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Design of Wood Aircraft Structures

MUNITIONS BOARD
AIRCRAFT COMMITTEE

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CHAPTER 3. METHODS OF STRUCTURAL ANALYSIS

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CHAPTER I

GENERAL

1.0. Purpose and Use of Bulletin

1.00. Introduction. This bulletin has been prepared for use in the design of both military and commercial aircraft, and contains material which is acceptable to the U. S. Air Force, Navy Bureau of Aeronautics, and the Civil Aeronautics Administration. It should, of course, be understood that methods and procedures other than those outlined herein are also acceptable, provided they are properly substantiated and approved by the appropriate agency. The applicability and interpretation of the provisions of this bulletin as contract or certification requirements will in each case be defined by the procuring or certificating agency.

1.01. Scope of Bulletin. The technical material in this bulletin is contained in chapters 2, 3, and 4, and pertains to three related phases of the structural design of wood aircraft.

Chapter 2 presents information on the strength and elastic properties of structural elements constructed of wood and plywood. This information supersedes that contained in the June 1944 edition of ANC–18, "Design of Wood Aircraft Structures."

Chapter 3 contains suggested methods of structural analysis for the design of various aircraft components. Although these methods are in many cases the same as those used for metal structures, special considerations have been introduced which take into account the orthotropic properties of wood.

Chapter 4 presents recommendations on the detail structural design of wood aircraft and contains some examples of how various manufacturers have treated the solution of specific detail design problems.

1.02. Acknowledgment. The Panel on Sandwich Construction of the Subcommittee on Air-Force-Navy-Civil Aircraft Design Criteria and the Forest Products Laboratory express their appreciation to aircraft manufacturers and others for the valuable assistance given in connection with various parts of this bulletin.

1.1. Nomenclature

This section presents the definitions of standard structural symbols which are used in the bulletin. In addition, sections 1.10 and 1.11 are presented to clarify the differentiation between the definitions for strength and elastic properties of plywood elements and those for like properties of plywood panels. These sections also outline the use of table 2–13.

1.10. Definitions for Plywood Elements—Beams, Prisms, and Columns in Compression, Strips in Tension. A plywood element is any rectangular piece of plywood that is supported, loaded, or restrained on two opposite edges only. In defining the various strength and elastic property terms for plywood elements the face grain direction has been used as a reference; for example, the subscript w denotes a direction parallel to (with) the face grain, while the subscript x denotes a direction perpendicular to (across) the face grain. This is illustrated by figure 1–1. The strength and elastic properties given in table 2–13 of the bulletin are for plywood elements.

1.11 Definitions for Plywood Panels. A plywood panel is any rectangular piece of plywood that is supported, loaded, or restrained on more than two edges. In defining the various strength and related property terms for plywood panels, the

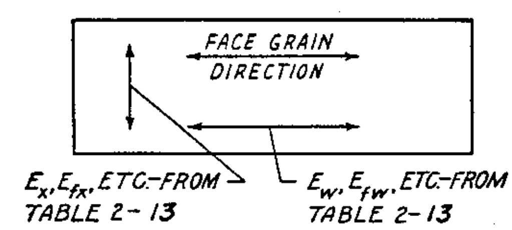

Figure 1–1. Plywood element (supported, loaded, or restrained on two opposite edges only).

side of length a rather than the face grain direction has been used as the reference. For any panel having tension or compression loads (either alone or accompanied by shear) the side of length a is the loaded side. For panels having only shear loads (with no tension or compression), the side a may be taken as either side (sec. 2.715). For panels having normal loads, side a is the shorter side. The subscripts a and 1 denote a direction parallel to the side of length a, and the subscripts b and 2 denote a direction perpendicular to the side of length a. This is illustrated by figure 1-2.

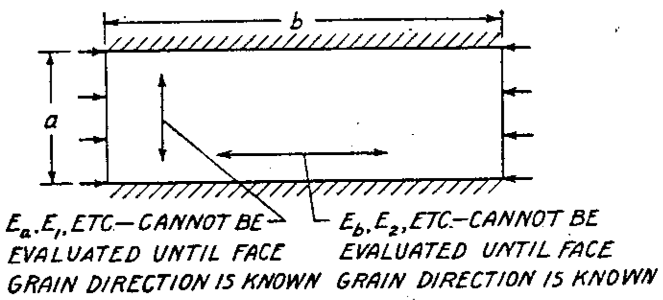

Figure 1-2. Plywood panel (supported, loaded, or restrained on more than two edges).

Since, in panels, the directions in which E_a, E_b, E_1, E_2, etc., are to be measured are related to the directions of the sides of lengths a and b, it is necessary to relate these directions to the face grain direction before the terms can be evaluated from table 2-13. It may be stated, therefore, that:

(1) When the face grain direction of a plywood panel is parallel to the side of length a, the values of E_a, E_b, E_1, E_2, etc., may be taken from the columns for E_w, E_x, E_{fw}, E_{fx}, etc., respectively, in table 2-13. This is illustrated by figure 1-3.

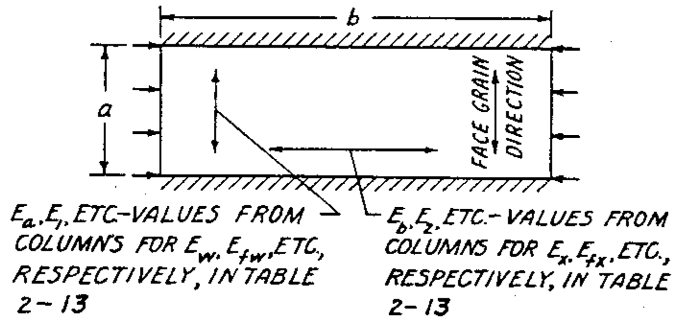

Figure 1-3. Plywood panel (face grain direction parallel to side of length a).

(2) When the face grain direction of a plywood panel is perpendicular to the side of length a, the values of E_a, E_b, E_1, E_2, etc., may be taken from the columns for E_x, E_w, E_{fx}, E_{fw}, etc., respectively, in table 2-13. This is illustrated by figure 1-4.

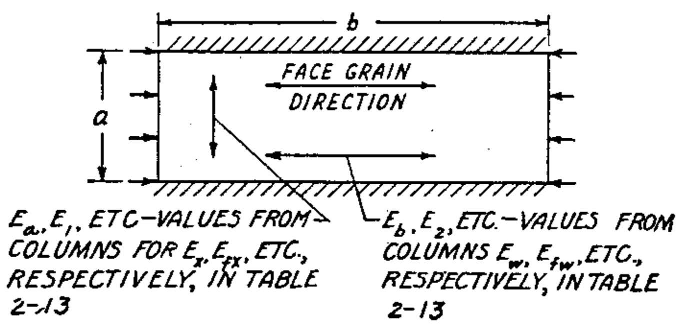

Figure 1-4. Plywood panel (face grain direction perpendicular to side of length a.

1.12. Standard Structural Symbols for Chapter 2. In general, symbols that are used only in the section where they are defined are not included in this nomenclature.

A —area of cross section, square inches (total).

A_L —area of plies with grain direction parallel to the direction of applied stress.

A_T —area of plies with grain direction perpendicular to the direction of applied stress (surfaces of plies parallel to plane of glue joint tangential to the annual growth rings, as for rotary-cut or flat-sliced veneer, flat-sawn lumber).

a —the length of the loaded side of a plywood panel for compression or tension loads, and the length of either side for shear loads (sec. 2.715); subscript denoting parallel to side of length a for plywood panels.

A_R —area of plies with grain direction perpendicular to the direction of applied stress (surfaces of plies parallel to plane of glue joint radial to the annual growth rings, as for quarter-sliced veneer, quarter-sawn lumber).

B

C —circumference.

D —diameter.

D_w —depending on direction of stiffeners, $\frac{E_{fw}t^3}{12\lambda_f}$ or $\frac{E_{fx}t^3}{12\lambda_f}$

D_{wc} —same as D_w except that the stiffener is considered to be an extra ply of the plywood.

D_{we} —same as D_w but these are effective values applicable to the stiffened panel as a whole.

D_x —depending on direction of stiffeners, $\frac{E_{fx}t^3}{12\lambda_f}$ or $\frac{E_{fw}t^3}{12\lambda_f}$

D_{xc} —same as D_x except that the stiffener is considered to be an extra ply of the plywood.

D_{xe} —same as D_x but these are effective values applicable to the stiffened panel as a whole.

D_{wx} $\frac{G_{fwx}t^3}{12}$

D_{wxc} —same as D_{wx} except that the stiffener is considered to be an extra ply of the plywood.

D_{wxe} —same as D_{wx} but these are effective values applicable to the stiffened panel as a whole.

b —the length of the unloaded side of a plywood panel for compression or tension loads, and the length of either side for shear loads (sec. 2.715); subscript denoting parallel to side of length b for plywood panels; subscript denoting "bending" for solid wood.

br —subscript denoting "bearing."

c —end-fixity coefficient for columns; subscript denoting "compression"; distance from neutral axis to extreme fiber.

c' —distance from neutral axis to the extreme fiber having grain direction parallel to the applied stress (plywood).

cr —subscript denoting "critical."

d —depth or height.

E_L —modulus of elasticity of wood in the direction parallel to the grain, as determined from a static bending test. (This value is listed in table 2–4.)

E_R —modulus of elasticity of wood in the direction radial to the annual growth rings.

E_T —modulus of elasticity of wood in the direction tangential to the annual growth rings.

E_{Lc} —modulus of elasticity of wood in the direction parallel to the grain, as determined from a compression test (value *not* listed in table 2–3, but approximately equal to 1.1 E_L).

E_a —effective modulus of elasticity of plywood in tension or compression measured parallel to the side of length a of plywood panels.

E_b —effective modulus of elasticity of plywood in tension or compression measured perpendicular to the side of length a of plywood panels.

E_g —E_a or E_b as required.

E_w —effective modulus of elasticity of plywood in tension or compression measured parallel to (*with*) the grain direction of the face plies.

E_x —effective modulus of elasticity of plywood in tension or compression measured perpendicular to (*across*) the grain direction of the face plies.

E_{fw} —effective modulus of elasticity of plywood in flexure (*bending*) measured parallel to (*with*) the grain direction of the face plies.

E_{fx} —effective modulus of elasticity of plywood in flexure (*bending*) measured perpendicular to (*across*) the grain direction of the face plies.

E'_{fx} —same as E_{fx}, except that outermost ply on tension side is neglected (not to be used in deflection formulas.)

e_L —unit strain (tension or compression) in the L direction.

e_R —unit strain (tension or compression) in the R direction.

e_T —unit strain (tension or compression) in the T direction.

e_{LT} —unit strain (shear); the change in angle between lines originally drawn in the L and T directions.

e_{LR} —unit strain (shear); the change in angle between lines originally drawn in the L and R directions.

e_{TR} —unit strain (shear); the change in angle between lines originally drawn in the T and R directions.

E_s —E_L of a stiffener.

E_1 —effective modulus of elasticity of plywood in flexure (*bending*) measured parallel to the side of length a of plywood panels, or parallel to the axis of plywood cylinders.

E_2 —effective modulus of elasticity of plywood in flexure (*bending*) measured perpendicular to the side of length a of plywood panels.

F —allowable stress; stress determined from test.

F_b —allowable bending stress.

F_{bu} —modulus of rupture in bending for solid wood parallel to grain.

F_{bp} —fiber stress at proportional limit in bending for solid wood parallel to grain.

F_{brp} —bearing stress at proportional limit parallel to the grain for solid wood.

F_{brT} —allowable ultimate bearing stress perpendicular to grain for solid wood (either radial or tangential to the annual growth rings).

F_{bru} —allowable ultimate bearing stress parallel to grain.

F_c —allowable compressive stress.

F_{ccr} —critical compressive stress for the buckling of rectangular plywood panels.

F_{cp} —stress at proportional limit in compression parallel to grain for solid wood.

F_{cpT} —stress at proportional limit in compression perpendicular to grain for solid wood (either radial or tangential to the annual growth rings).

F_{cpw} —stress at proportional limit in compression for plywood having the face grain direction parallel to (*with*) the applied stress.

F_{cpx} —stress at proportional limit in compression for plywood having the face grain direction perpendicular to (*across*) the applied stress.

f —internal (or calculated) stress; subscript denoting "flexure" (*bending*) for plywood.

f_b —internal (or calculated) primary bending stress.

f_{br} —internal (or calculated) bearing stress.

f_c —internal (or calculated) compressive stress.

f_{cL} —internal (or calculated) compressive stress in a longitudinal ply; i. e., any ply with its grain direction parallel to the applied stress.

$F_{cp\theta}$ —stress at proportional limit in compression for plywood having the face grain direction at an angle θ to the applied stress.

F_{cu} —ultimate compressive stress parallel to the grain for solid wood.

F_{cuT} —compressive strength perpendicular to grain for solid wood (either radial or tangential to the annual growth rings) (sec. 2.1000).

F_{cuw} —ultimate compressive stress for plywood having the face grain direction parallel to (*with*) the applied stress.

F_{cux} —ultimate compressive stress for plywood having the face grain direction perpendicular to (*across*) the applied stress.

$F_{cu\theta}$ —ultimate compressive stress for plywood having the face grain direction at an angle θ to the applied stress.

F_s —allowable shearing stress.

f_s —internal (or calculated) shearing stress.

F_{scr} —critical shear stress for the buckling of rectangular plywood panels.

F_{st} —modulus of rupture in torsion.

F_{su} —ultimate shear stress parallel to grain for solid wood.

$F_{s\theta c}$ —ultimate shear stress for plywood, wherein θ designates the angle between the face grain direction and the shear stress in a plywood element so loaded in shear that the face grain is stressed in compression.

$F_{s\theta t}$ —ultimate shear stress for plywood, wherein θ designates the angle between the face grain direction and the shear stress in a plywood element so loaded in shear that the face grain is stressed in tension.

F_{swx} —ultimate shear stress for plywood elements for the case where the face grain is at 0° and 90° to the shear stress.

F_t —allowable tension stress.

f_t —internal (or calculated) tensile stress.

f_{tL} —internal (or calculated) tensile stress in a longitudinal ply (any ply with its grain direction parallel to the applied stress).

F_{tu} —ultimate tensile stress parallel to grain for solid wood.

F_{tuT} —tensile strength perpendicular to grain for solid wood (either radial or tangential to the annual growth rings).

F_{tuw} —ultimate tensile stress for plywood having the face grain direction parallel to (*with*) the applied stress.

F_{tux} —ultimate tensile stress for plywood having the face grain direction perpendicular to (*across*) the applied stress.

$F_{tu\theta}$ —ultimate tensile stress for plywood having the face grain direction at an angle θ to the applied stress.

G —mean modulus of rigidity taken as 1/16 of E_L.

G_{LT} —modulus of rigidity associated with shear deformations in the LT plane resulting from shear stresses in the LR and RT planes.

G_{LR} —modulus of rigidity associated with shear deformations in the LR plane resulting from shear stresses in the LT and RT planes.

G_{TR} —modulus of rigidity associated with shear deformations in the TR plane resulting from shear stresses in the LT and LR planes.

H —a constant, generally theoretical.

I —moment of inertia.

I_p —polar moment of inertia.

J —torsion constant (I_p for round tubes).

K —a constant, generally empirical.

L —length; span; subscript denoting the direction parallel to the grain.

L' $=\frac{L}{\sqrt{c}}$ where c is the end-fixity coefficient.

M —applied bending moment.

N —

P —applied load (total, not unit load).

Q —static moment of a cross section.

R —subscript denoting the direction radial to the annual growth rings and perpendicular to the grain direction.

S —shear force.

T —applied torsional moment, torque; subscript denoting the direction tangential to the annual growth rings and perpendicular to the grain direction.

g —length of side of panel and equal to a or b as is required.

h —height or depth.

i —subscript denoting "i^{th} ply."

j —stiffness factor $\sqrt{EI/P}$

k —stiffness factor

$$\frac{E_{fw}\mu_{fxw}+2\lambda_f G_{fwx}}{\sqrt{E_{fw}E_{fx}}}$$

l —not used, to avoid confusion with the numeral 1.

m —number of half waves.

n —number of plies, number of stiffeners.

p —subscript denoting "polar"; subscript denoting "proportional limit"; load per unit area.

psi —pounds per square inch.

q —shear flow, pounds per inch.

r —radius; adjusted ratio length to width $\frac{b}{a}\left(\frac{E_1}{E_2}\right)^{1/4}$

s —distance c to c of adjacent stiffeners; subscript denoting "shear".

t —thickness; subscript denoting "tension".

t_c —thickness of central ply.

t_f —thickness of face ply.

U —

W —

X —

Y —

Z —section modulus, I/c

Z_p —polar section modulus, I_p/c.

u —subscript denoting "ultimate".

w —deflection of plywood panels; load per linear inch; subscript denoting parallel to face grain of plywood.

x —subscript denoting perpendicular to face grain of plywood.

y —distance from the neutral axis to any given fiber.

z —

z_n —distance between center of panel and neutral axis of panel stiffener combination.

β —the angle between side of length b and the face grain direction as used in the determination of buckling criteria for panels (sec. 2.71).

δ —deflection.

θ —usually the acute angle in degrees between the face grain direction and the direction of the applied stress; angle of twist in radians in a length (L).

μ_{LT} —Poisson's ratio of contraction along the direction T to extension along the direction L due to a normal tensile stress on the $_{RT}$ plane; similarly, μ_{LR}, μ_{RT}, μ_{TR}, μ_{RL}, and μ_{TL}.

ρ —radius of gyration.

ϕ —usually the acute angle in degrees between the face grain direction and the axis of extension.

CHAPTER 2

STRENGTH OF WOOD AND PLYWOOD ELEMENTS

2.0. Physical Characteristics and Factors Affecting the Strength of Wood

2.00. Anisotropy of Wood. Wood, unlike most other commonly used structural materials, is not isotropic. It is a complex structural material, consisting essentially of fibers of cellulose cemented together by lignin. It is the shape, size, and arrangement of these fibers, together with their physical and chemical composition that govern the strength of wood, and account for the large difference in properties along and across the grain (ref. 2–20).

The fibers are long and hollow tubes tapering toward the ends, which are closed. Besides these vertical fibers, which are oriented with their longer dimension lengthwise of the tree and comprise the principal part of what is called wood, all species, except palms and yuccas, contain horizontal strips of cells known as rays, which are oriented radially and are an important part of the tree's food transfer and storage system. Among different species the rays differ widely in their size and prevalence.

From the strength standpoint, this arrangement of fibers results in an anisotropic structure, that accounts for three Young's moduli differing by as much as 150 to 1, three shear moduli differing by as much as 20 to 1, six Poisson's ratios differing by as much as 40 to 1, and other properties differing by various amounts. Not all of these wood properties have, as yet, been thoroughly evaluated.

Figure 2–1 shows a diagrammatic sketch of the cellular structure of wood. Each year's growth is represented by one annual ring. The portion of the growth occurring in the spring consists of relatively thin-walled fibers, while that occurring during the later portion of the growing season consists of fibers having somewhat heavier walls. Thus, there is, for most woods, a definite line of demarcation between the growth occurring in successive years. The relation between the cellular structure of the wood and the three principal axes—longitudinal (L), tangential (T), and radial (R)—is indicated on the sketch. Figure 2–2 shows the relation between these axes and (*a*) the log, (*b*) a flat-sawn board or rotary-cut veneer, and (*c*) an edge-grain board or quarter-sliced veneer.

2.01. Density or Apparent Specific Gravity. The substance of which wood is composed is actually heavier than water, its specific gravity being nearly the same for all species and averaging about 1.5. Since a certain proportion of the volume of wood is occupied by cell cavities, the apparent specific gravity of the wood of most species is less than unity.

Relations between various strength properties and specific gravity have been developed (table 2–1) and are useful in estimating the strength of a piece of wood of known specific gravity. Considerable variability from these general relations is found, so that while they cannot be expected to give exact strength values, they do give good estimates of strength. Minimum permissible specific gravity values are listed in section 2.10.

The exponential values shown in table 2–1 apply to variation within a species. That is, they are to be used in determining the relation between the strength properties of pieces of the same species but of different specific gravity. For expressing the relation between the average strength properties of different species, the exponential values are somewhat lower. Such values are shown in table 14 of U. S. Department of Agriculture Technical Bulletin 479 (ref. 2–57).

2.02. Moisture Content. Wood in the natural state in the living tree has considerable water associated with it. After being converted to lumber or other usable form, or during conversion,

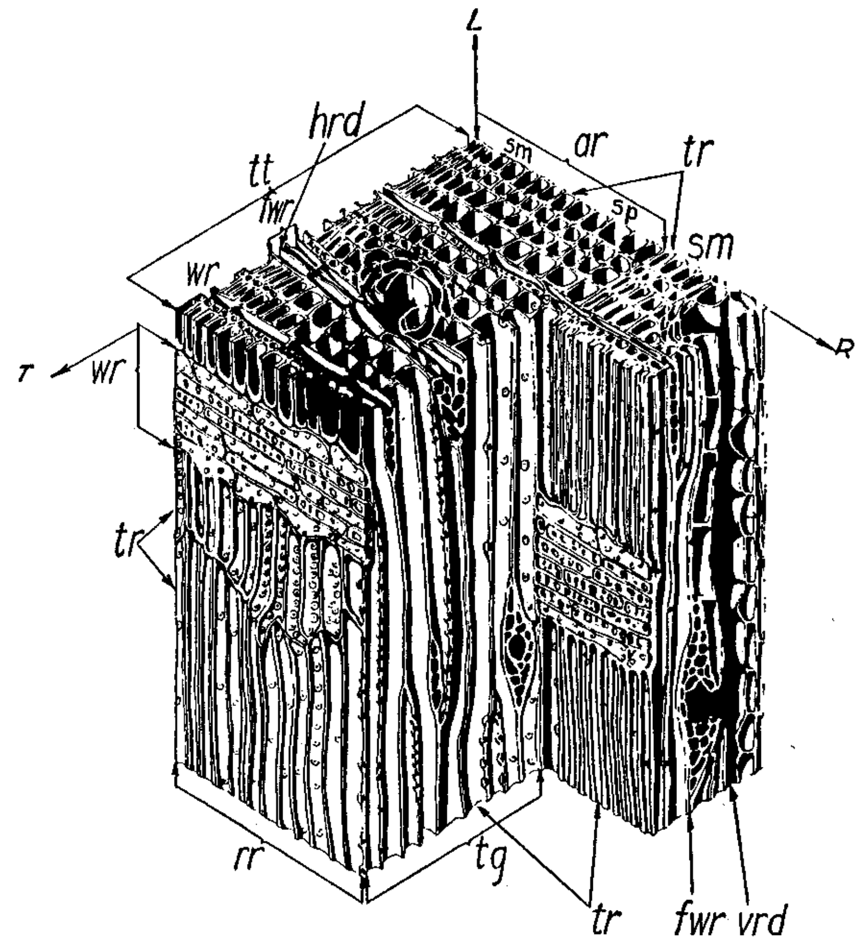

Figure 2–1. Wood cellular structure. Drawing of a highly magnified block softwood measuring about one-fortieth inch vertically: tt, transverse surface; rr, radial surface; tg, tangential surface; ar, annual rings; sm, summerwood; sp, springwood; tr, tracheids, or fibers; hrd, horizontal resin duct; fwr, fusiform wood ray; wr, wood rays; L, direction (longitudinal) of grain; R, direction radial to annual rings and perpendicular to grain direction; T, direction tangential to annual rings and perpendicular to grain direction; vrd, vertical resin duct.

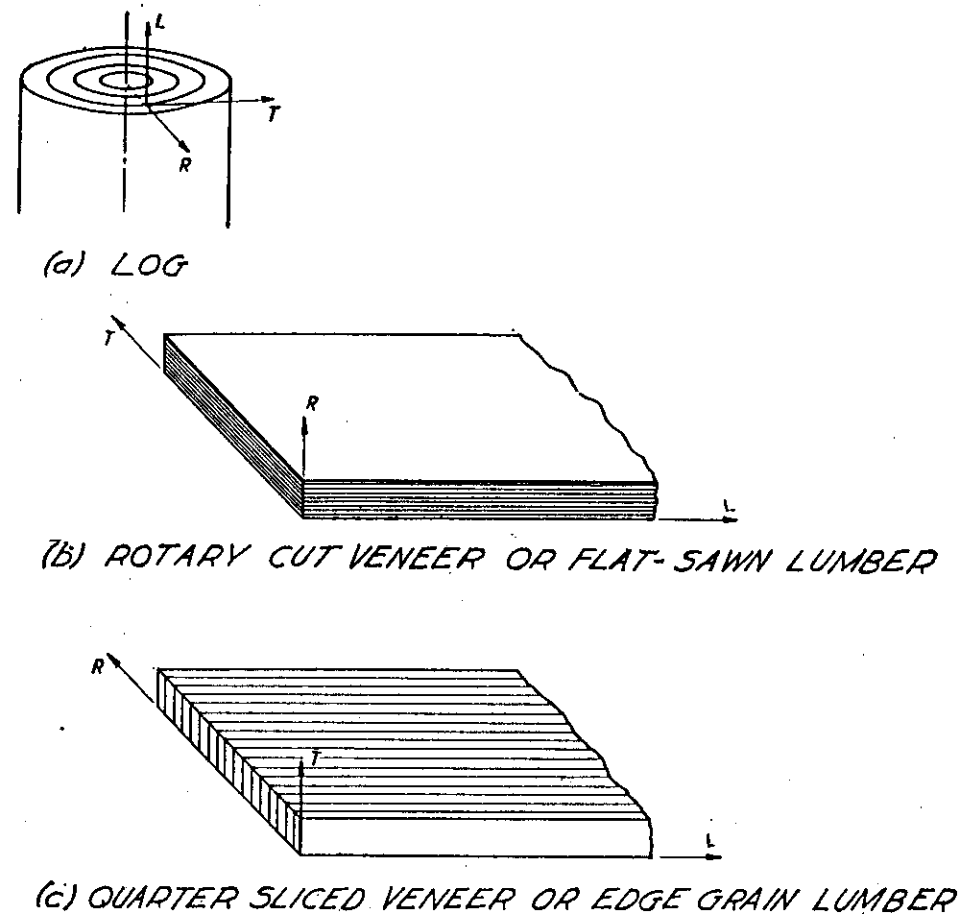

Figure 2–2. Principal directions in wood and plywood.

wood is commonly dried so that most of the water is removed.

The water is associated with the wood in two ways, either absorbed in the cell walls, or as free water in the cell cavities. During drying, the free water in the cell cavities is removed first, then that absorbed in the cell walls. The point at which all the water has been removed from the cell cavities while the cell walls remain saturated is known as the fiber-saturation point. For most species, the moisture content at fiber saturation is from 22 to 30 percent of the weight of the dry wood.

Lowering the moisture content to the fiber-saturation point results in no changes in dimension or in strength properties. Lowering the moisture content below the fiber-saturation point, however, results in shrinkage and an increase in strength properties.

Wood is a hygroscopic material, continually giving off or taking on moisture in accordance with the relative humidity and temperature to which it is exposed. Thus, while the strength of a piece of wood may be increased to a relatively high value by drying to a low moisture content, some of that increase may be lost if, in use, it is exposed to atmospheric conditions that tend to increase the moisture content. While paint and other coatings may be employed to retard the rate of absorption of moisture by wood, they do not change its hygroscopic properties, thus a piece of wood may be expected to come to the same moisture content under the same exposure conditions whether painted or unpainted. The time required will vary, depending upon whether or not it is coated. It is desirable, therefore, to design a structure on the basis of the strength corresponding to the conditions of use.

Moisture content is generally expressed as a percentage of the dry weight of the wood. The percentage variation of wood strength properties for 1 percent change in moisture content is given in table 2–2. Since this variation is an exponential function (ref. 2–85), it is necessary that strength adjustments based on the percentage changes given in the table be made successively for each 1 percent change in moisture content until the total change has been covered. Figure 2–3 is a chart by means of which the ratio between the adjusted strength and the original strength may be determined approximately if the proper correction factor is obtained from table 2–2 and the difference in moisture content for which correction is desired is known. For positive correction factors in table 2–2, the original strength is multiplied by the strength ratio factor determined from figure 2–3 for adjustments involving decrease in moisture content, and divided by the strength ratio factor for those involving increase in moisture content. For negative factors in table 2–2, the original strength is divided by the strength ratio factor for adjustments involving decrease in moisture, and multiplied for adjustments involving increase in moisture.

Table 2–1. Variation of wood strength properties with specific gravity [1]

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

S =strength at specific gravity g

S'=strength at specific gravity g' (usually average values from column (2) of tables 2–6 and 2–7)

	n
Static bending:	
Fiber stress at proportional limit	1. 50
Modulus of rupture	1. 50
Modulus of elasticity	1. 25
Work to maximum load	2. 00
Total work	2. 25
Impact bending:	
Fiber stress at proportional limit	1. 50
Modulus of elasticity	1. 25
Height of drop	2. 00
Compression parallel to grain:	
Fiber stress at proportional limit	1. 25
Maximum crushing strength	1. 25
Modulus of elasticity	1. 25
Compression perpendicular to grain:	
Fiber stress at proportional limit	2. 50
Hardness—end, radial, tangential	2. 50

[1] Values in this table apply only to variations within a species. See section 2.01.

2.03. Shrinkage. Reduction of moisture content below the fiber-saturation point results in a change in dimension of the wood. Shrinkage in the longitudinal direction is generally negligible, but in the other two directions it is considerable. In general, radial shrinkage is less than tangential, the ratio between the two varying with the species.

A quarter-sawed board will, therefore, shrink less in width but more in thickness than a flat-sawed board. The smaller the ratio of radial to tangential shrinkage, the more advantage is to be gained through minimizing shrinkage in width by using a quarter-sawed board. The smaller the difference between radial and tangential shrinkage, the less, ordinarily, is the tendency to check in drying and to cup with changes in moisture content.

In general, woods of high specific gravity shrink and swell more for a given change in moisture content than do woods of low specific gravity.

2.04. TEMPERATURE. The strength of wood is greatly influenced by its temperature, but the magnitude of the effect depends upon the moisture content of the wood and the time of exposure.

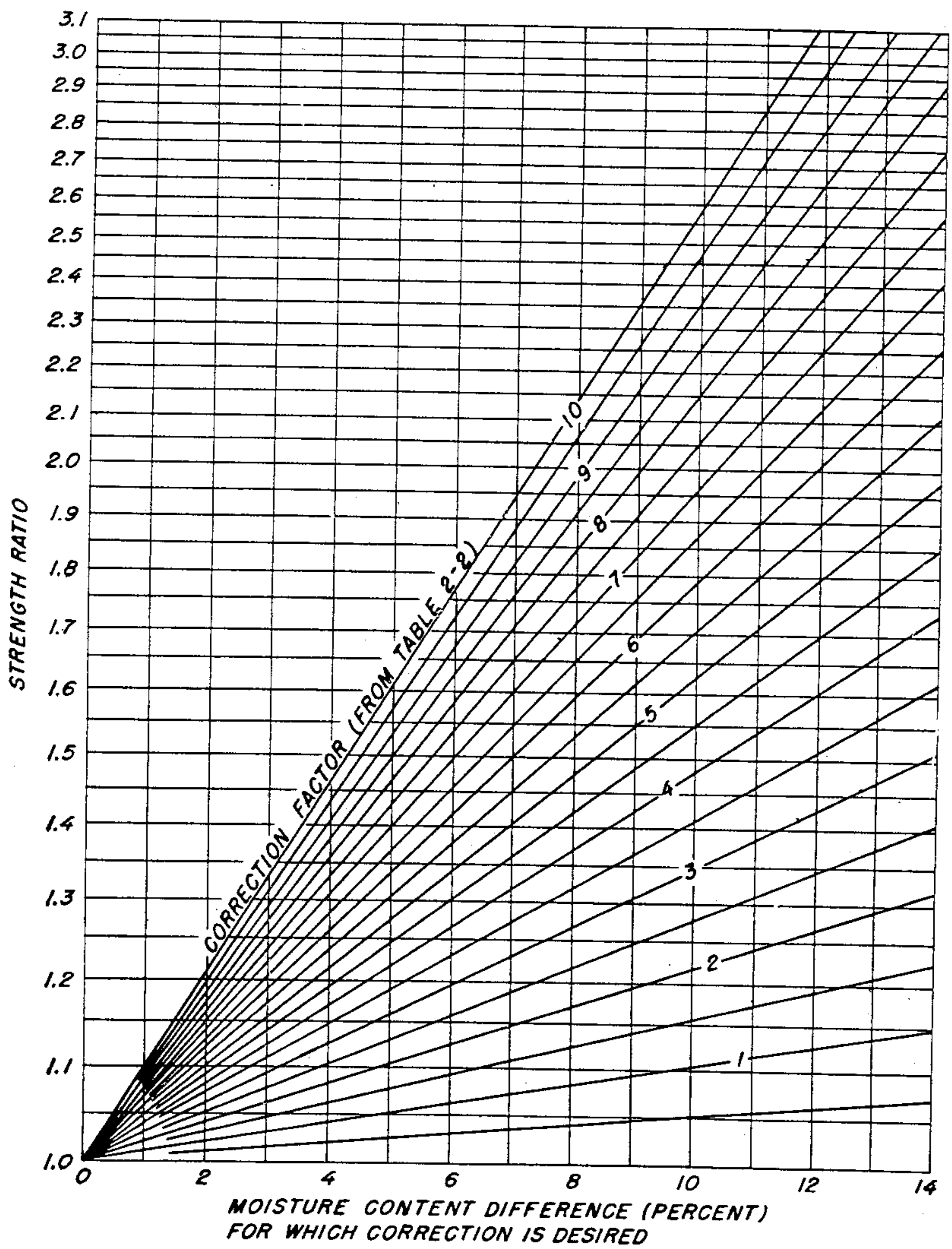

Figure 2-3. Strength ratio chart for use in making strength-moisture adjustments.

Table 2-2. Percentage increase in wood strength properties for 1 percent decrease in moisture content [1]

Species	Static bending: Fiber stress at proportional limit	Static bending: Modulus of rupture	Static bending: Modulus of elasticity	Static bending: Work to maximum load [2]	Compression parallel to grain, maximum crushing strength	Compression perpendicular to grain	Shearing strength parallel to grain	Hardness (side)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Hardwoods: [3]								
Ash, black	8. 9	6. 4	3. 6	1. 8	8. 3	6. 8	5. 1	4. 1
Ash, commercial white	4. 1	3. 5	1. 4	. 4	4. 7	4. 8	2. 9	2. 4
Basswood, American	6. 8	4. 8	2. 9	2. 6	6. 5	6. 6	4. 2	4. 2
Beech, American	6. 0	4. 7	1. 8	2. 0	6. 2	5. 3	3. 8	3. 6
Birch, sweet	6. 4	5. 0	2. 3	1. 2	7. 1	7. 2	5. 0	3. 6
Birch, yellow	6. 0	4. 8	2. 0	1. 7	6. 1	5. 6	3. 6	3. 3
Cherry, black	6. 6	3. 6	1. 1	1. 0	6. 0	5. 5	3. 5	3. 1
Cottonwood	5. 8	4. 1	2. 5	. 1	6. 6	5. 7	2. 6	1. 8
Elm, rock	4. 7	3. 8	2. 1	−. 3	5. 3	6. 1	3. 5	2. 8
Hickory (true hickories)	4. 9	4. 8	2. 8	−. 7	5. 9	6. 6	3. 9	-------
Khaya ("African mahogany")	3. 2	2. 5	1. 6	−. 6	3. 2	3. 0	. 4	3. 1
Mahogany	2. 6	1. 3	. 8	−2. 9	2. 5	3. 9	-------	1. 0
Maple, sugar	5. 2	4. 4	1. 4	1. 9	5. 7	7. 1	3. 9	3. 4
Oak, commercial white and red	4. 6	4. 4	2. 4	1. 7	5. 9	4. 4	3. 5	1. 8
Sweetgum	6. 7	4. 7	2. 2	1. 5	6. 1	5. 4	3. 5	2. 4
Walnut, black	5. 8	3. 7	1. 4	−2. 6	4. 8	6. 3	1. 0	1. 0
Yellow-poplar	5. 0	4. 6	2. 7	1. 9	6. 7	4. 8	3. 3	2. 4
Softwoods (conifers): [3]								
Baldcypress	4. 6	4. 0	1. 6	1. 8	4. 9	5. 1	1. 7	2. 3
Douglas-fir	4. 5	3. 7	1. 8	1. 9	5. 5	5. 0	1. 7	2. 9
Fir, noble	5. 1	4. 7	1. 9	3. 2	6. 1	5. 5	2. 3	3. 1
Hemlock, western	4. 7	3. 4	1. 4	. 7	5. 0	3. 7	2. 5	2. 0
Incense cedar, California	3. 4	2. 1	1. 8	−1. 4	4. 3	4. 0	. 4	1. 5
Pine, eastern white	5. 6	4. 8	2. 0	2. 1	5. 7	5. 6	2. 2	2. 2
Pine, red	8. 0	5. 7	2. 2	4. 7	7. 5	7. 2	3. 9	4. 5
Pine, sugar	4. 4	3. 9	2. 1	. 1	5. 4	4. 4	3. 7	1. 9
Pine, western white	5. 3	5. 1	2. 2	4. 8	6. 5	5. 2	2. 5	1. 5
Redcedar, western	4. 3	3. 4	1. 6	1. 3	5. 1	5. 1	1. 6	2. 3
Spruce, red and Sitka	4. 7	3. 9	1. 7	2. 0	5. 3	4. 3	2. 6	2. 4
Spruce, white	5. 8	4. 8	1. 9	2. 1	6. 5	5. 7	3. 7	3. 3
White-cedar, northern	5. 4	3. 6	1. 8	−1. 5	5. 9	2. 3	2. 8	3. 0
White-cedar, Port Orford	5. 7	5. 2	1. 6	1. 7	6. 2	6. 7	2. 2	2. 8

[1] Corrections to the strength properties should be made successively for each 1 percent change in moisture content until the total change has been covered. For each 1 percent decrease in moisture content, the strength is multiplied by $(1+P)$, where P is the percentage correction factor shown in the table, expressed as a decimal. For each 1 percent increase in moisture content, the strength is divided by $(1+P)$.

[2] Negative values indicate a decrease in work to maximum load for a decrease in moisture content.

[3] For tension values see section 2.5411.

Although considerable literature exists relating to permanent strength reductions resulting from prolonged or cyclic exposure to temperature extremes (ref. 2–46, 2–57, 2–84) few investigations have been made with respect to transient or reversible effects resulting from differences in temperature (ref. 2–2, 2–26, 2–28, 2–36, 2–58, 2–73, 2–76, 2–81).

Broadly, it would appear from data now available that prolonged exposure to temperatures above about 150° F. may result in a permanent loss of strength, and that within the range 0° F. to 150° F. the reduction in static strength properties (excluding modulus of elasticity) with increase in temperature for wood at about 12 percent moisture content, will approximate one-half percent per degree Fahrenheit. The effect on impact properties is variable and cannot be generalized. Some data on the mechanical properties of wood of different moisture contents over the temperature range of $-328°$ F. to $+392°$ F. are given in NACA Technical Memorandum No. 984, reference 2–37.

2.05. Fatigue Properties. The fatigue characteristics of wood have been explored to only a limited extent (ref. 2–38, 2–39, 2–41). Tests of the Forest Products Laboratory indicate that wood is less sensitive to rapidly repeated loads than are the more crystalline structural materials, resulting in a higher endurance limit in proportion to the ultimate strength. Tension parallel-to-grain and glue joint shear tests of Douglas-fir and white oak, and tension perpendicular-to-grain tests of Douglas-fir showed an endurance load for 30 million cycles of about 40 percent of standard test strength for both solid wood and scarf-jointed specimens when the minimum repeated load was 10 percent of the maximum repeated load for each cycle. These tests were conducted at about 12 percent moisture content, at a temperature of 75° F.

Tests of small cantilever bending specimens of solid wood and plywood, subjected to fully reversed stresses under the same temperature-humidity conditions as above, indicate an endurance load of about 30 percent of the modulus of rupture of standard static tests after 30 million cycles of repeated stress.

Very little data are available on the effects of notches, bolt holes, or connectors in fatigue. Some data on the effect of notches on fatigue properties of rotating beam specimens are given in reference 2–87.

2.06. Plastic Properties. Though it is known that wood, in common with other materials of construction, exhibits plastic as well as elastic properties, quantitative evaluations of the plastic characteristics of wood are limited in scope (ref. 2–34). Thus, while recognizing that when load is applied to a wood structural member the immediate or elastic deformation subsequently will be increased by plastic yield or creep, there is, at present, no accurate means of evaluating the rate of progress of such plastic yield, nor of predicting the time at which failure may be expected to occur.

Preliminary investigations at the Forest Products Laboratory (ref. 2–66, 2–86) involve creep tests with stresses up to 3,000 pounds per square inch in tension and compression, up to 400 pounds per square inch in shear, and at stress levels approaching the short-time ultimate strength in bending. They indicate creep characteristics very much alike in these strength properties at the lower stress levels. There is reason to believe that creep properties differ between tension and compression as stress values approach the short-time ultimate strength in compression, but the difference has not been fully explored. From these considerations, supported by a few test results, it is believed that joints and fastenings have similar creep properties insofar as their strength is controlled by the strength of the wood.

It is evident from the studies thus far completed that creep under constant load is quite rapid at first, and continues for long periods at a decreasing rate, depending upon the ratio of the applied load to that which would cause immediate failure. No critical point in time has been found at which the rate of creep suddenly changes or at which all creep ceases. Neither has there been found a stress threshold below which no creep takes place.

The studies in bending and compression have indicated that with stresses at, or less than, 60 percent of the strength in a standard laboratory test, the ratio of creep to initial strain is approximately constant. Since strain in this range is proportional to stress, it may be said that creep is proportional to stress. Both in compression and bending, creep at 5 minutes is generally less than 2 percent, and at 1 hour is about 4 percent of the initial strain or deflection. Where stresses in bending exceed 60 percent of laboratory test strength, creep percentages are higher than the above values.

It is known that temperature and moisture changes influence plastic properties, but the extent of such effects is not known.

When load is removed from wood, the elastic strain is recovered immediately. There is, in addition, a recovery of a portion of the plastic strain, relatively rapid at first, and continuing more and more slowly for considerable periods of time. Little is known of the nature and extent of recovery, or of permanent set characteristics, hysteresis, or damping capacity (see sec. 2.095).

In bending, successive repetitions of the same load separated by periods of recovery cause successively increased deformations which finally lead to failure. From data now available it appears that the sum of the periods under intermittent load, until failure occurs, is somewhat greater than the duration to failure under constant load at the same stress level.

2.07. Impact Properties. The rate at which load is applied to a wood member, as well as the time during which it acts, has an important effect on its ability to carry load (secs. 2.06 and 2.10).

Under extremely rapid loading conditions, such as are obtained in impact tests where failure may occur in a fraction of a second, a wood member would be expected to withstand a force much greater than in a standard test. Exact relationships of failing stresses under static and impact loadings are not well known as, in impact tests, measurement is generally made of the absorbed energy rather than the stress imposed.

A beam subjected to impact loading in the standard drop hammer impact bending test (ref. 2–57) may deflect about twice as much before failure as under static test conditions. The stress required to produce failure under such impact conditions is, therefore, correspondingly, about twice as great as for static conditions.

The shock resistance of wood may be measured by a single-blow impact test such as the "toughness" test described in USDA Tech. Bul. 479 (ref. 2–57) where average toughness values for common species are listed, together with minimum acceptance requirements for a number of aircraft woods.

Recent data of the Forest Products Laboratory (ref. 2–10, 2–14) show that the toughness of wood is considerably influenced by its moisture content. Above the fiber-saturation point, approximately 30 percent moisture content, toughness is apparently independent of changes in moisture. For drier material the toughness, in general, decreases slowly from the green value to a minimum at about 12 to 18 percent moisture content, and then increases substantially with further decrease in moisture. These conclusions are in general agreement with extensive toughness and Izod tests by the Australian Forest Products Laboratory (ref. 2–35) but it has been found that results vary greatly among species, and no adequate general formula can be devised to represent toughness-moisture relations for all species.

2.08. EFFECT OF LIQUIDS. Some liquids, when absorbed by wood, adversely affect the strength properties, others do not. In general, nonpolar, nonswelling liquids that do not react with wood chemically do not affect the strength (ref. 2–19). For example, saturated, straight-chain hydrocarbon oils, such as gasoline, kerosene, and most lubricating oils, and aromatic hydrocarbons, such as benzene and toluene, have no significant effect on the strength of wood and they do not raise the grain.

Turpentine, mineral paint thinners, and linseed oil will by analogy cause practically no effect upon the strength properties nor will cleaning fluids such as carbon tetrachloride.

Low molecular-weight, simple alcohols such as methyl (wood alcohol), ethyl (grain alcohol), and propyl alcohol and polyhydric alcohols such as ethylene glycol (antifreeze) and glycerine swell wood appreciably and cause a considerable loss in strength properties, varying from half to almost the full strength loss caused by water. In general, the crushing strength is decreased somewhat less than it would be if swollen to the same extent in water (ref. 2–19, 2–60).

Lacquer solvents, such as acetone, methyl and ethyl acetates, and ethylene glycol monoethyl ether will reduce the strength about half as much as water.

Low molecular-weight organic acids, such as acetic acid, will reduce the strength about three-fourths as much as water. The high molecular-weight fatty acids will have a much smaller but positive effect.

These various liquids reduce the strength of wood only while they remain in the wood. Volatile liquids, hence, have only a short, temporary effect upon the strength. Low volatility liquids like glycerine will reduce the strength over considerable periods of time. These are apparently the only liquids with which the aircraft industry need be concerned. Some hydraulic fluids containing glycerine or ethylene glycol have an experimentally demonstrated detrimental effect upon the strength of wood (ref. 2–11).

Another group of liquids, strong mineral acids and bases, have a permanent effect upon the strength of woods as a result of chemical degradation of the wood. This degradation varies with species. The only comprehensive data available on the subject are given in the tables 2–3 and 2–4.

2.09. MISCELLANEOUS PHYSICAL PROPERTIES.

2.091. *Coefficient of expansion.* The isotropic nature of wood results in differing coefficients of thermal expansion (α) along its radial, tangential, and fiber axes. This anisotropy, modified by the treatments involved, remains a basic property of all the derived structural products of wood, in which the fiber arrangement is not destroyed.

The thermal expansion of wood is so small as to

Table 2–3. Deterioration due to four weeks soaking in acids and bases at room temperature measured by the modulus of rupture relative to that for matched water-soaked specimens. Concentrations, 2 to 10 percent (ref. 2–36)

Species	Hydrochloric acid	Sulfuric acid	Nitric acid	Sodium hydroxide	Ammonium hydroxide
Larch	[1] 1.09–0.81	1.11–1.00	1.07–0.95	0.96–0.52	1.06–0.92
Pine	1.08– .84	1.13–0.84	1.07– .93	.96– .51	1.00– .79
Spruce	1.00– .82	1.02– .94	.98– .96	.93– .44	.98– .75
Beech	.96– .55	.97– .87	.83– .71	.59– .31	.67– .43
Oak	.93– .52	.97– .82	.83– .65	.58– .29	.65– .36
Basswood	.88– .48	.87– .81	.76– .57	.55– .21	.61– .33

[1] Values greater than unity due to the fact that acid is more slowly absorbed by the wood than water.

Table 2–4. Loss in breaking load in percent due to soaking in acids at room temperature relative to matched water-soaked specimens (ref. 2–1)

Species	Hydrochloric acid 82 days		Sulfuric acid 82 days		Acetic acid 135 days	
	5 percent concentration	15 percent concentration	10 percent concentration	20 percent concentration	50 percent concentration	80 percent concentration
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Teak	31	50	17	31	43	39
Oak	54	76	48	40	39	26
Pine	18	46	11	16	20	0

be unimportant in ordinary usage, for example, a 1 percent increase in moisture content swells yellow birch as much as does an 80° C. thermal expansion. Only meager data are available on the coefficients of thermal expansion of wood and wood-base materials, and investigators are not in close agreement in their values although there is general agreement that the expansion across the grain is much greater than that along the grain (ref. 2–20).

A comprehensive study of the thermal expansion of wood and wood-base products has been completed recently at the Forest Products Laboratory, and the results have been published (ref. 2–82). In this work the variation of the coefficients of linear thermal expansion with specific gravity was determined on a series of solid, oven-dry specimens of 9 different species of untreated wood. The effects of radial compression, resin-treating, and cross-banding on the values of the coefficients were determined on birch laminates. The values of the coefficients for papreg and hydrolyzed-wood plastic were also determined.

The average coefficients of linear thermal expansion (α) per ° C. of nine species of solid wood (ref. 2–82) from +50 to −50° C. for the average specific gravity of the species are given in the following tabulation:

Species	Average specific gravity [1]	$\alpha_t \times 10^6$	$\alpha_r \times 10^6$	$\alpha l \times 10^6$
Yellow Birch	0.66	38.3	30.7	3.36
Sugar Maple	.68	35.3	26.8	3.82
Yellow-poplar	.43	29.7	27.8	3.17
Cottonwood	.43	32.6	23.2	2.89
Balsa	[2] .17	[3] 24.1	[3] 16.3	--------
Douglas-fir [3]	.51	42.7	27.9	3.16
Sitka spruce	.42	32.3	23.8	3.15
White fir	.40	32.6	21.8	3.34
Redwood	.42	35.1	23.6	4.28

[1] Average specific gravity (based on weight and volume when oven dry) taken from tables of properties in U. S. D. A. Tech. Bull. No. 479 (ref 2-57) or for specimens included in this study.

[2] Specific gravity average of values for two specimens tested.

[3] α measured from +50 to 0° C. only.

The coefficients of linear thermal expansion in the tangential (α_t) and radial directions (α_r) may be calculated for specific gravities other than those tabulated by use of the following equation:

$$\alpha = \alpha_o \frac{G}{G_o} \qquad (2:1)$$

where

α=coefficient of linear thermal expansion (α_t or α_r) at specific gravity G

α_o=coefficient of linear thermal expansion (α_t or α_r) listed
G_o=specific gravity listed
G=specific gravity desired

The coefficient of linear thermal expansion parallel to the grain (αl) is independent of specific gravity, and is unaffected by radial or tangential compression.

The dependency of the coefficient of linear thermal expansion on resin content in a solid piece is expressed by:

$$\alpha_c=\frac{E_w\alpha_w(1-n_r)+E_r\alpha_r n_r}{E_w(1-n_r)+E_r n_r} \qquad (2:2)$$

where

α_c=coefficient of linear thermal expansion (α) of the wood-resin system
α_w=of wood alone
α_r=of resin alone.
E=modulus of elasticity (subscripts have the same meaning as for α)
n_r=fraction of solid cross-section of sample consisting of resin

General formulas were developed at the Forest Products Laboratory that permit calculation of the coefficients of linear thermal expansion of wood laminates in any grain direction of the specimen, from the original and final specific gravities, the percentage by weight of resin and glue present, the percentage of cross-banding, and the slope of grain relative to any three axes of reference. Solution of the formulas, however, should be attempted only after reference to the original publication (ref. 2–82).

2.092. *Thermal conductivity.* The thermal conductivity of wood is dependent on a number of factors of varying degrees of importance. Some of the more significant variables affecting the rate of heat flow in wood are the following: density and moisture content of the wood; direction of heat flow with respect to the grain; kind, quantity, and distribution of extractives or chemical substances; relative density and proportion of springwood and summerwood; defects, like checks, knots, and cross-grain structure.

The Forest Products Laboratory has made careful determinations of the thermal conductivity of wood at various moisture contents. These tests, which covered 32 species, have furnished sufficient data on the relationship between conductivity, specific gravity, and moisture content to make it possible to compute the approximate thermal conductivity for any wood for which the specific gravity is known and for which the moisture content can be determined or assumed. Such conductivities have many practical applications, such as in estimating the thermal resistance or insulating value of various woods; thermal resistance being the reciprocal or inverse value of conductivity.

It is common engineering practice to express heat conductivity, represented by K, as the amount of heat in British thermal units that will pass in 1 hour through 1 square foot of the material 1 inch thick per degree Fahrenheit temperature difference between the faces.

Although it is not practicable (ref. 2–45) to compute the exact conductivity of wood of given density and moisture content because of the number of variables involved, the following equations permit calculation of conductivity closely enough for practical purposes:

For wood having a moisture content under 40 percent:

$$K=S(1.39+0.028M)+0.165 \qquad (2:3)$$

For wood having a moisture content of 40 percent or more:

$$K=S(1.39+0.038M)+0.165 \qquad (2:4)$$

Where

K=conductivity
S=specific gravity based on volume at current moisture and weight when oven-dry
M=moisture content

Conductivities of wood aircraft parts will ordinarily be computed by means of equation (2:3) using 15 percent for the moisture content of aircraft to be used in the continental United States and 20 percent for the moisture content of aircraft to be used under tropical conditions (sec. 2.10). The use of species average values of specific gravity may be considered sufficiently correct for most purposes.

Experiments on Douglas-fir plywood with veneer ⅛-inch or more in thickness (ref. 2–45) indicate that the thin film of glue between the wood surfaces has no important effect on conductivity, as would be expected, because of the very slight thickness of the glue coating in comparison with the total thickness.

Tests (ref. 2–45) indicate there is a small increase in conductivity with increase in temperature difference but, for temperature conditions normally encountered, the variation in conductivity is not significant.

2.093. *Ignition temperature.* Limited data are available concerning minimum temperatures required to produce charring or ignition of wood. Results obtained by different investigators for ignition temperatures show wide discrepancies. The different values reported may be due to the specific test conditions associated with the methods employed, and also to the different interpretations among investigators as to what constitutes ignition temperature (ref. 2–4). Assuming conditions favorable to the completion of the ignition process, the ignition temperature has been defined (ref. 2–4) as the temperature in the combustible at which the rate of heat developed by the reactions inducing ignition just exceeds the rate at which heat is dissipated by all causes, under the given conditions.

It is thus obvious that, unlike flammable liquids, which have reasonably definite ignition temperatures, the ignition temperature of wood, even if a standard interpretation of the phenomenon were determined upon, would vary widely depending upon the size, density, moisture content, and type, distribution, and quantity of extractives present in the specimen under test, and upon the time and rate of heating, the amount of air available, and the rate of air flow.

The importance of the time factor has been emphasized by the Forest Products Laboratory (ref. 2–49) but no specific tests have been made relating ignition temperatures to long exposures at the lower ranges of elevated temperature. The Underwriters' Laboratories (ref. 2–80) have cited an example of ignition occurring after long-continued exposure (about 15 yrs.) to a temperature of approximately 190° F.

2.094. *Electrical properties.* The resistance that wood offers to the passage of direct current depends primarily upon the moisture content of the wood (ref. 2–72). In the green state the resistivity of wood is relatively low and increases slowly with decrease in moisture until the fiber-saturation point is reached at about 30 percent moisture content, and all free water has been removed. The change of resistivity within the green range is about 50-fold. When wood is dried below the fiber-saturation point, however, its resistivity increases rapidly, about a million-fold from the fiber-saturation point to the oven dry condition. The logarithm of resistivity is approximately inversely proportional to moisture content. At values of moisture content approaching zero the resistivity becomes very great, of the order of 10^{16} ohm-centimeters (ref. 2–83), and dry wood is a very good electrical insulator. In conditions of use, however, wood will not remain dry, but will absorb moisture until it reaches a condition of equilibrium corresponding with the ambient atmosphere. The resistivity of wood at a typical moisture content of 9.3 percent is 10^{10} ohm-centimeters.

When alternating voltage is applied to wood the effects depend upon both moisture content and frequency. At frequencies up to a few hundred cycles per second the behavior of wood is practically the same as for direct currents. At much higher frequencies, from a million cycles per second upward, the electrical properties of wood are essentially its properties when acting as a dielectric material. In this role it is interposed between two metallic plates or sheets to form a condenser. Wood is an imperfect dielectric and, therefore, some of the electrical energy required to charge the condenser will be lost to the wood where it appears as heat.

Losses in the wood depend principally upon its moisture content and the frequency of the applied voltage, and the losses increase with both moisture content, especially above about 10 percent, and frequency. Wood is a very poor insulator or dielectric at high frequencies. The alternating current electrical properties of wood are concerned principally with high-frequency dielectric heating for gluing purposes (ref. 2–5, 2–74).

2.095. *Damping capacity.* Damping capacity may be defined as the ability of a solid to convert mechanical energy of vibration into internal energy. This causes vibrations to die out. Published information on the subject (ref. 2–33) is mainly concerned with metals, and only occasional references are made to wood.

The damping capacity of timber has been investigated by Greenhill (ref. 2–29). His investigations indicate that "if a truly elastic material is subjected to a cycle of stress, the stress-strain curve will be a straight line. If, however, the material undergoes reversible plastic deformation during the cycle, the stress-strain curve will be a hysteresis loop. The area enclosed by this loop represents the amount of energy expended during each complete stress cycle. Specimens subjected to cycles of stress below the fatigue limit can dissipate an unlimited quantity of energy as heat without any damage.

"When a solid is subjected to a periodic force, the damping capacity prevents the amplitude of vibration from becoming infinite when the frequency of the applied force approaches a natural frequency of the solid. Damping capacity is of considerable importance in certain branches of engineering and, consistent with other properties, it is generally agreed that materials of high damping capacity are superior to those of low damping capacity. Take, for example, the wings of aeroplanes. Under certain circumstances these are subject to resonant vibrations, the amplitude of which depends essentially on the damping properties of the materials of construction. The same thing applies with special force to the blades of aeroplane propellers which are liable to vibrate violently at certain critical speeds of rotation. The amplitudes of vibration are great or small according to the material of which the blades are made. It is stated by experts that the endurance of the blades depends far more on the damping capacity of the material than on its fatigue strength."

Damping capacity has been expressed numerically in various ways. Greenhill and Kimball (ref. 2–29, 2–33) have used logarithmic decrement (δ), and Kimball has summarized various formulas used by different investigators for determination of this factor. Briefly, if ΔW is the energy dissipated per cycle of vibration, and W the maximum energy of the cycle, the ratio $\Delta W/W$, called the "specific energy loss" or the "damping capacity," gives a measure of the damping characteristics of the material. The logarithmic decrement δ is equal to one-half the damping capacity, or $\Delta W/2W$.

Values of the logarithmic decrement δ for wood and a few other materials are given in table 2–5.

Table 2–5. Damping capacity—logarithmic decrements (δ) for internal friction in solids

Investigator	Material	Method	Stress-percent of maximum	Logarithmic decrement
Forest Products Laboratory	Wood—Parallel laminated birch	Compression	84	0.002
	do	do	88	.012
	do	do	93	.063
	do	Flexure		.073
Do	Staypak—Yellow birch	Compression	86	.0013
	do	do	89	.0465
	do	do	92	.1435
	do	Flexure		.128
Do	Compreg—Yellow birch, high-impact type	Compression	83	.173
	do	do	89	.232
	do	Flexure		.238
Do	Compreg—Yellow birch, low-impact type	Compression	74	.045
	do	do	87	.157
	do	do	90	.172
	do	Flexure		.108
Do	Compreg—Maple	Compression	89	.0002
	do	do	94	.149
	do	do	93	.218
	do	Flexure		.121
	do	do		.239
Greenhill (Ref. 2–29)	Wood—Sitka spruce	Flexure		.035
	do	Torsion		.0521
Kimball and Lovell (Ref. 2–33).	Wood—Maple	Revolving defl. rods.		.021
	Nickel steel	do		.0023
	Mild steel	do		.0049
	Aluminum	do		.0034
	Nickel	do		.0032
	Celluloid	do		.0450
A. Gemant	Wood	Flexure		.027
W. Jackson (Ref. 2–33)	Nickel steel	do		.0017
	Copper	do		.0032

Data other than those from Greenhill and the Forest Products Laboratory are from a compilation included in reference 2–33.

Greenhill (ref. 2–29) found that the effect of increasing the moisture content of wood is to increase its damping capacity, the relation being practically linear within the range of 8 to 19 percent moisture content examined.

Upon removal of stress, full recovery of strain does not take place in most materials even though the stress imposed may be less than that corresponding to the apparent elastic limit of the material. Tests at the Forest Products Laboratory have shown that, with a compression load applied repeatedly to a specimen of papreg, the set or permanent deformation was increased, but the amount of set added for each load cycle diminished. A straight-line relationship was found when accumulative permanent set was plotted on an arithmetical scale against the number of load cycles plotted on a logarithmic scale. It was found that the higher the load, the greater was the permanent set after the first and all succeeding load cycles.

2.1. Basic Strength and Elastic Properties of Wood

2.10. Design Values, Tables 2–6 and 2–7. Strength properties of various species for use in calculating the strength of aircraft elements are presented in tables 2–6 and 2–7. Their applicability to the purpose is considered to have been substantiated by experience. The assumptions (see footnotes to tables 2–6 and 2–7) made in deriving the values in tables 2–6 and 2–7 from the results of standard tests (sec. 2.12) have been reexamined in the light of recent data with respect to the distribution of strength values in wood for aircraft construction and the moisture content of airplane parts, together with data relating to "duration of stress" in order to clarify the basis of design (ref. 2–12, 2–13).

The values in table 2–6 are based on a moisture content of 15 percent and are considered applicable for design of structural parts of aircraft that are to be used in the continental United States. Values in table 2–7 are based on a moisture content of 20 percent and should be used for design of structural parts of aircraft to be used under tropical conditions where high relative humidity, approximately 90 percent or over, is prevalent for long periods of time, or more or less continuously.

When tests of physical properties are made on additional species or on specially selected wood the results may be made comparable to those in tables 2–6 and 2–7 by adjusting them to 15 or 20 percent moisture content, respectively, in accordance with table 2–2, together with the appropriate use of the factors described in the footnotes to tables 2–6 and 2–7.

For notes on acceptable procedures for static tests and the correction of test results, see sections 2.12 and 3.01.

2.100. *Supplemental notes.*

2.1000. *Compression perpendicular to grain.* Wood does not exhibit a definite ultimate strength in compression perpendicular to the grain, particularly when the load is applied over only a part of the surface, as it is by fittings. Beyond the proportional limit the load continues to increase slowly until the deformation becomes several times as great as at the proportional limit and the crushing is so severe as to damage the wood seriously in other properties. A "probability" factor was applied to average values of stress at proportional limit to take account of variability, and the result was increased by 50 percent to get design values comparable to those for bending, compression parallel to grain, and shear as shown in tables 2–6 and 2–7.

2.1001. *Compression parallel to grain.* Available data indicate that the proportional limit for hardwoods is about 75 percent and for softwoods about 80 percent of the maximum crushing strength. Accordingly, design values for fiber stress at proportional limit were obtained by multiplying maximum crushing-strength values by a factor of 0.75 for hardwoods and 0.80 for softwoods, and adjusting for a difference in the factors for the "rate and duration of load."

2.11. Notes on the Use of Values in Tables 2–6 and 2–7.

2.110. *Relation of design values in tables 2–6 and 2–7 to slope of grain.* The values given in tables 2–6 and 2–7 apply for grain slopes as steep as the following:

(*a*) For compression parallel to grain—1 in 12.

(*b*) For bending and for tension parallel to grain—1 in 15.

When material is used in which the steepest grain slope is steeper than the above limits, the design values of tables 2–6 and 2–7 must be reduced according to the percentages in table 2–8.

Table 2-6.—Strength values of various woods, based on 15 percent moisture content,[1] to be used in design of aircraft for use in the continental United States (see sections 2.10 and 2.11 for explanations relative to the basis for, and use of, the values in this table)

Species of wood: common and botanical names	Specific gravity based on volume and weight when oven dry		Weight at 15 percent moisture content	Shrinkage from green to oven-dry condition based on dimensions when green		Static bending				Compression parallel to grain		Compression perpendicular to grain [4,7] (F_{cuT})	Shearing strength parallel to grain [4,8] (F_{su})	Hardness, side; load required to imbed 0.444-inch ball to one-half its diameter	Tension	
	Average [2]	Minimum permitted [3]		Radial	Tangential	Fiber stress at proportional limit [4] (F_{bp})	Modulus of rupture [4] (F_{bu})	Modulus of elasticity [4,5] (E_L)	Work to maximum load	Fiber stress at proportional limit [6] (F_{cp})	Maximum crushing strength [4] (F_{cu})				Strength parallel to grain (F_{tu})	Strength perpendicular to grain [9] (F_{tuT})
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
HARDWOODS (BROAD-LEAVED SPECIES)			Lb. per cu. ft.	Percent	Percent	P. s. i.	P. s. i.	1,000 p. s. i.	In.-lb. per cu. ft.	P. s. i.	P. s. i.	P. s. i.	P. s. i.	Lb.	Tension strength parallel to grain taken as equal to modulus of rupture. See section 2.111.	P. s. i.
Ash, black (*Fraxinus nigra*)	0.53	0.48	35	5.0	7.8	5,200	10,600	1,310	14.2	3,220	4,600	910	1,190	750		320
Ash, commercial white (*Fraxinus spp.*) [10]	.62	.56	41	4.5	7.2	7,200	13,200	1,400	14.9	4,270	6,100	1,680	1,590	1,180		380
Basswood, American (*Tilia glabra*)	.40	.36	25	6.6	9.3	4,500	7,700	1,220	6.6	2,680	3,800	450	770	360		170
Beach, American (*Fagus grandifolia*)	.67	.60	43	5.1	11.0	6,900	13,200	1,480	14.2	4,180	6,000	1,300	1,590	1,170		460
Birch, Alaska (*Betula neoalaskana*)	.59	.53	38	6.5	9.9	6,000	11,800	1,580	13.2	4,070	5,800	850	1,120	750		240
Birch, paper (*Betula papyrifera*)	.60	.54	38	6.3	8.6	5,300	10,600	1,340	16.1	3,130	4,500	740	980	810		
Birch (*Betula spp.*) [11,12]	.68	.58	44	6.8	8.8	7,600	15,100	1,850	18.6	4,590	6,500	1,380	1,630	1,230		390
Cherry, black (*Prunus serotina*)	.53	.48	36	3.7	7.1	6,900	11,300	1,310	11.7	4,090	5,800	880	1,360	870		280
Cottonwood, Eastern (*Populus deltoides*)	.43	.39	28	3.9	9.2	4,500	7,700	1,150	7.3	2,770	4,000	490	760	400		270
Elm, American (*Ulmus americana*)	.55	.50	35	4.2	9.5	6,000	10,600	1,160	12.7	3,220	4,600	880	1,200	770		320
Elm, rock (*Ulmus thomasii*)	.66	.60	43	4.8	8.1	6,500	13,500	1,310	19.3	4,130	5,900	1,550	1,530	1,210		
Hickory (true hickories) (*Hicoria spp.*) [13]	.80	.71	50	7.4	11.4	8,700	17,100	1,780	26.1	5,080	7,200	2,250	1,660	...		...
Khaya ("African mahogany") (*Khaya spp.*) [12]	.48	.42	32	4.1	5.8	5,800	9,800	1,200	7.9	3,480	5,000	1,320	1,110	720		230
Locust, black (*Robinia pseudoacacia*)	.71	.64	49	4.4	6.9	10,900	18,100	1,810	17.6	6,300	9,000	2,450	2,010	1,670		340
Magnolia, Southern (*Magnolia grandiflora*)	.53	.48	35	5.4	6.6	5,500	10,100	1,200	13.4	3,140	4,500	1,100	1,230	940		350
Mahogany (*Swietenia spp.*) [12,14]	.52	.46	35	3.5	4.8	6,800	11,700	1,370	7.4	4,330	6,200	1,370	1,060	740		170
Maple, silver (*Acer saccharinum*)	.51	.46	33	3.0	7.2	4,900	8,100	990	8.9	2,970	4,200	930	1,200	670		260
Maple, sugar (*Acer saccharum*)	.68	.60	43	4.9	9.5	7,600	14,100	1,590	15.7	4,540	6,500	1,790	1,830	1,310		
Oak, commercial white and red (*Quercus spp.*) [15]	.69	.62	44	4.8	9.4	6,600	12,300	1,460	13.2	3,990	5,700	1,450	1,470	1,230		380
Pecan (*Hicoria pecan*)	.69	.62	46	4.9	8.9	7,400	12,800	1,480	14.0	4,540	6,500	2,120	1,690	1,680		
Sweetgum (*Liquidambar styraciflua*) [12]	.54	.48	35	5.2	9.9	6,200	11,200	1,340	10.8	3,380	4,800	770	1,170	640		360
Sycamore, American (*Platanus occidentalis*)	.54	.49	35	5.1	7.6	5,100	9,100	1,200	8.2	3,160	4,500	890	1,180	730		350
Tupelo, water (*Nyssa aquatica*)	.52	.47	35	4.2	7.6	5,900	9,100	1,090	7.2	3,520	5,000	1,120	1,310	830		340
Walnut, black (*Juglans nigra*)	.56	.52	38	5.2	7.1	8,300	13,300	1,460	11.5	4,510	6,400	1,270	1,180	980		330
Yellow-poplar (*Liriodendron tulipifera*) [12,16]	.44	.38	29	4.0	7.1	4,600	8,600	1,250	6.4	2,880	4,100	620	930	420		250

See footnotes at end of table.

Table 2–6.—Strength values of various woods, based on 15 percent moisture content,[1] to be used in design of aircraft for use in the continental United States (see sections 2.10 and 2.11 for explanations relative to the basis for, and use of, the values in this table)—Continued

Species of wood: common and botanical names	Specific gravity based on volume and weight when oven dry		Weight at 15 percent moisture content	Shrinkage from green to oven-dry condition based on dimensions when green		Static bending				Compression parallel to grain		Compression perpendicular to grain [4] [7] (F_{cuT})	Shearing strength parallel to grain [4] [8] (F_{su})	Hardness, side; load required to imbed 0.444-inch ball to one-half its diameter	Tension	
	Average [2]	Minimum permitted [3]		Radial	Tangential	Fiber stress at proportional limit [4] (F_{bp})	Modulus of rupture [4] (F_{bu})	Modulus of elasticity [4] [5] (E_L)	Work to maximum load	Fiber stress at proportional limit [6] (F_{cp})	Maximum crushing strength [4] (F_{cu})				Strength parallel to grain (F_{tu})	Strength perpendicular to grain [9] (F_{tuT})
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
SOFTWOODS (CONIFERS)																
			Lb. per cu. ft.	*Percent*	*Percent*	*P. s. i.*	*P. s. i.*	*1,000 p. s. i.*	*In.-lb. per cu. ft*	*P. s. i.*	*P. s. i.*	*P. s. i.*	*P. s. i.*	*Lb.*		*P. s. i.*
Baldcypress (*Taxodium distichum*)	0.48	0.43	32	3.8	6.2	5,900	9,600	1,240	7.7	4,020	5,400	940	840	480	Tension strength parallel to grain taken as equal to modules of rupture. See section 2.111.	140
Cedar, Alaska (*Chamaecyparis nootkatensis*)	.46	.41	31	2.8	6.0	5,700	9,900	1,220	10.1	3,840	5,100	810	930	540		180
Douglas-fir (normal) (*Pseudotsuga taxifolia*)[12] [16]	.50	.45	33	5.0	7.8	5,900	10,900	1,480	8.1	4,220	5,600	1,020	950	610		140
Douglas-fir (light) [12] [16]	.43	.38	28	.....	.....	4,900	9,000	1,210	.....	3,390	4,500	770	.....	.....		...
Fir, California red (*Abies magnifica*)	.42	.38	28	4.5	7.9	5,100	9,400	1,320	8.2	3,480	4,700	680	890	460		190
Fir, noble (*Abies nobilis*)[12]	.42	.36	28	4.5	8.3	5,600	9,800	1,470	8.0	3,590	4,800	700	880	380		110
Fir, Pacific (*Abies amabilis*)	.42	.38	27	4.5	10.0	5,000	8,400	1,320	8.3	3,370	4,500	530	830	400		.....
Fir, white (*Abies concolor*)	.40	.36	26	3.2	7.0	5,300	8,400	1,170	6.3	3,200	4,400	650	780	410		130
Hemlock, Western (*Tsuga heterophylla*)[12]	.45	.40	30	4.3	7.9	6,200	11,000	1,510	7.3	4,080	5,500	730	860	540		150
Incense-cedar, California (*Libocedrus decurrens*)	.36	.32	25	3.3	5.2	5,000	7,600	900	5.6	3,350	4,500	790	760	450		140
Larch, Western (*Larix occidentalis*)	.59	.53	37	4.2	8.1	6,700	11,000	1,480	7.8	4,780	6,400	1,150	1,110	680		140
Pine, Eastern white (*Pinus strobus*)	.37	.34	25	2.1	6.1	4,600	7,600	1,060	6.3	2,960	4,000	520	740	350		150
Pine, ponderosa (*Pinus ponderosa*)	.42	.33	28	3.9	6.3	5,000	8,100	1,070	6.2	3,160	4,200	750	900	410		190
Pine, red (*Pinus resinosa*)	.51	.46	33	4.6	7.2	7,000	10,800	1,530	8.7	4,320	5,800	820	970	510		190
Pine, sugar (*Pinus lambertiana*)	.38	.34	26	2.9	5.6	4,700	7,300	1,020	5.5	2,970	4,000	630	830	360		160
Pine, Western white (*Pinus monticola*)	.42	.38	28	4.1	7.4	5,000	8,300	1,280	7.7	3,400	4,600	560	700	360		.....
Redcedar, Western (*Thuja plicata*)	.34	.31	23	2.4	5.0	4,400	7,100	960	5.6	3,160	4,200	640	720	330		110
Spruce, Sitka (*Picea sitchensis* [12]	.41	.36	28	4.2	7.5	5,300	9,400	1,380	8.7	3,530	4,700	740	990	470		170
Spruce, red (*Picea rubra*)	.41	.36	28	3.8	7.8	5,600	9,300	1,320	8.1	3,670	4,900	630	890	460		160
Spruce, white (*Picea glauca*)	.45	.36	29	4.7	8.2	5,100	8,700	1,150	7.2	3,310	4,400	590	850	440		160
White-cedar, Northern (*Thuja occidentalis*)	.32	.29	22	2.1	4.7	3,900	6,000	690	5.0	2,430	3,300	430	700	290		120
White-cedar, Port Orford (*Chamaecyparis lawsoniana*)[12] [16]	.43	.40	29	4.6	6.9	6,700	10,200	1,430	8.6	4,110	5,500	810	790	510		160

[1] A moisture content value of 15 percent has been used in design of wood aircraft for use in the continental United States for many years. This value was substantiated as a normally expected service condition by reference 2-12. For design of aircraft to be used under tropical conditions see table 2-7 and section 2.10.

[2] Values in column 2 for birch, khaya, mahogany, sweetgum, yellow-poplar, Douglas-fir, noble fir, Western hemlock, Sitka spruce, and Port Orford white cedar are averages for material having a specific gravity equal to or greater than the minimum permitted for each species, as listed in column 3. For species other than those listed above, values in column 2 are general species averages, without excluding material below the minimum permitted.

[3] Values in column 3 for minimum permitted specific gravity are those listed in table 2-3 of ANC-18, June, 1944, corresponding to applicable Army-Navy-Aeronautical specifications as of that date. The continued applicability of these values is considered as being substantiated by experience.

[4] The values in columns 7, 8, 9, 12, 13, and 14 are species mean values adjusted to 15 percent moisture content (see footnote 1) and multiplied by two factors: (1) A "probability" factor to allow for variability of wood, and (2) a "rate and duration of load" factor to allow for the effect of estimated loading conditions for aircraft in service. The "probability" factor is based on composite cumulative frequency curves (figs. 1 and 2, ref. 2-13). Factors were determined for each property at an "inclusion" limit of 25 percent; that is, they represent strength values, expressed as percentages of the respective means, below which not more than 25 percent of aircraft-grade material would be expected to fall.

The "rate and duration of load" factors for ultimates are those applicable to a loading time of 1 second and a duration of 1.5 seconds, while those for proportional limits relate to a loading time of 3 seconds and a duration of 15 seconds (data from ref. 2-3). Values for modulus of elasticity in static bending, for compression perpendicular to grain, and for shear are assumed to be unaffected by rate and duration of load. Factors used for the several properties are:

Test	*Property*	*"Probability" Factor*	*"Rate and Duration of Load" Factor*
Static bending	Fiber stress at proportional limit.	0.89	1.05
Static bending	Modulus of rupture	.92	1.10
Static bending	Modulus of elasticity	.91	1.00
Compression parallel to grain	Fiber stress at proportional limit.	(See footnote 6).	1.00
Compression parallel to grain	Maximum crushing strength	.91	1.07
Compression perpendicular to grain.	Fiber stress at proportional limit.	.81	1.00
Shear parallel to grain	Maximum shearing strength	.88	1.00

[5] The values given in column 9 are based on the average apparent modulus of elasticity (E_e) as obtained by substituting results from tests of 2- by 2-inch beams on a 28-inch span or 1- by 1-inch beams on a 14-inch span with load at the center in the formula $E_e = PL^3/48\delta I$. The use of these values of E_e in the usual formulas will give the deflection of beams of ordinary length with but small error. For exactness in the computation of deflections of I and box beams, particularly for short spans, the formula that takes into account shear deformations (see National Advisory Committee for Aeronautics Report No. 180, ref. 2-59) should be used. This formula involves E_t, the true modulus of elasticity in bending, and G, the modulus of rigidity in shear. Values of E_t may be obtained by adding 10 percent to the values of E_e as given in the table. If the I or box beam has the grain of the web parallel to the axis of the beam, or parallel and perpendicular thereto as in some plywood webs, the value of G may be taken as $E_t/16$ or $E_e/14.5$. If the web is of plywood with the grain at 45° to the axis of the beam G may be taken as $E_t/5$ or $E_e/4.5$.

[6] Design values for fiber stress at proportional limit in compression parallel to grain were obtained by multiplying the values of maximum crushing strength in the next column by 0.75 for hardwoods and 0.80 for conifers, and by the ratio of the "rate and duration of load" factors, namely, 1.00/1.07.

[7] Wood does not exhibit a definite ultimate strength in compression perpendicular to grain, particularly when the load is applied over only a part of the surface, as at fittings. Beyond the proportional limit, the load continues to increase slowly until the deformation becomes several times as great as at the proportional limit (see fig. 2-4) and the crushing is so severe as to damage the wood seriously in other properties. In calculating values in column 13, a "rate and duration of load" factor of 1.00 was assumed, and the average proportional limit stress, modified by the appropriate "probability" factor (see footnote 4) was increased by 50 percent to get design values.

[8] Values in this column are, for use in computing resistance to longitudinal shear. They were obtained by multiplying average values by a "probability" factor (see footnote 4) to allow for variability. Tests have shown that because of the favorable influence upon the distribution of stresses resulting from limiting shearing deformations the maximum strength-weight ratio and minimum variability in strength are attained when I and box beams are so proportioned that the ultimate shearing strength is not developed and failure by shear does not occur.

[9] Values in column 17 are one-half the average values at 15 percent moisture content.

[10] Includes white ash (*F. americana*), green ash (*F. pennsylvanica lanceolata*), and blue ash (*F. quadrangulata*).

[11] Includes sweet birch (*B. lenta*) and yellow birch (*B. lutea*).

[12] Values for these species in columns 2, 4, 7, 8, 9, 11, 12, and 13 are based on material conforming to aircraft specifications for minimum permitted specific gravity and rings per inch (see footnote 2 and reference 2-13). Values in columns 5, 6, 10, 14, 15, and 17, and all values for other species, are based on general averages for the species without excluding material below the minimum permitted specific gravity or with less than the required number of rings per inch.

[13] Includes shellbark hickory (*H. laciniosa*), mockernut hickory (*H. alba*), pignut hickory (*H. glabra*), and shagbark hickory (*H. ovata*).

[14] Includes only material from Central America.

[15] Includes white oak (*Q. alba*), bur oak (*Q. macrocarpa*), swamp chestnut oak (*Q. prinus*), post oak (*Q. stellata*), Northern red oak (*Q. borealis*), Southern red oak (*Q. rubra*), laurel oak (*Q. laurifolia*), water oak (*Q. nigra*), swamp red oak (*Q. pagodaefolia*), willow oak (*Q. phellos*), and yellow oak (*Q. velutina*).

[16] These species will be found in the Army-Navy-Aeronautical specifications under the following names: White-cedar, Port Orford—(AN-C-72) cedar, aircraft Port Orford; Douglas-fir—(AN-F-7) fir, aircraft Douglas; yellow-poplar (AN-P-17) poplar, aircraft yellow.

Table 2·7. Strength values of various woods based on 20 percent moisture content [1] to be used in design of aircraft for use in tropical regions having continued high relative humidity (approximately 90 percent or over) (see sections 2.10 and 2.11 for explanations relative to the basis for, and use of, the values in this table)

Species of wood: common and botanical names	Specific gravity based on volume and weight when oven dry: Average [2]	Specific gravity: Minimum permitted [3]	Weight at 20 percent moisture content	Shrinkage from green to oven-dry condition based on dimensions when green: Radial	Shrinkage: Tangential	Static bending: Fiber stress at proportional limit [4] (F_{bp})	Static bending: Modulus of rupture (F_{bu})	Static bending: Modulus of elasticity [4,5] (E_L)	Static bending: Work to maximum load	Compression parallel to grain: Fiber stress at proportional limit [6] (F_{cp})	Compression parallel to grain: Maximum crushing strength [4] (F_{cu})	Compression perpendicular to grain [4,7] (F_{cuT})	Shearing strength parallel to grain [4,8] (F_{su})	Hardness, side; load required to imbed 0.444-inch ball to one-half its diameter	Tension: Strength parallel to grain (F_{tu})	Tension: Strength perpendicular to grain [9] (F_{tuT})
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
HARDWOODS (BROAD-LEAVED SPECIES)			*Lb. per cu. ft.*	*Percent*	*Percent*	*P. s. i.*	*P. s. i.*	*1,000 p. s. i.*	*In.-lb. per cu. ft.*	*P. s. i.*	*P. s. i.*	*P. s. i.*	*P. s. i.*	*Lb.*		*P. s. i.*
Ash, black (*Fraxinus nigra*)	0.53	0.48	35	5.0	7.8	3,400	7,800	1,090	13.0	2,160	3,100	680	930	610	equal to modulus of rupture. See sec. 2.111.	276
Ash, commercial white (*Fraxinus spp.*) [10]	.62	.56	41	4.5	7.2	5,900	11,100	1,310	14.6	3,390	4,800	1,330	1,380	1,050		328
Basswood, American (*Tilia glabra*)	.40	.36	25	6.6	9.3	3,200	6,100	1,060	5.8	1,960	2,800	330	620	290		152
Beech, American (*Fagus grandifolia*)	.67	.60	44	5.1	11.0	5,100	10,500	1,350	12.9	3,090	4,400	1,010	1,320	980		402
Birch, Alaska (*Betula neoalaskana*)	.59	.53	38	6.5	9.9	4,500	9,000	1,380	12.3	2,800	4,000	650	930	640		146
Birch, paper (*Betula papyrifera*)	.60	.54	38	6.3	8.6	3,700	8,100	1,180	16.1	2,160	3,100	530	840	660		...
Birch (*Betula spp.*) [11,12]	.68	.58	44	6.8	8.8	5,600	11,900	1,660	17.3	3,330	4,800	1,020	1,320	1,040		294
Cherry, black (*Prunus serotina*)	.53	.48	36	3.7	7.1	5,100	9,400	1,240	12.3	3,060	4,400	670	1,140	750		284
Cottonwood, Eastern (*Populus deltoides*)	.43	.39	29	3.9	9.2	3,400	6,300	1,020	7.3	2,010	2,900	370	670	370		230
Elm, American (*Ulmus americana*)	.55	.50	36	4.2	9.5	4,600	8,600	1,080	12.2	2,470	3,500	670	1,020	680		308
Elm, rock (*Ulmus thomasii*)	.66	.60	44	4.8	8.1	5,200	11,200	1,180	19.6	3,180	4,500	1,160	1,290	1,060		...
Hickory (true hickories) (*Hicoria spp.*) [13]	.80	.71	50	7.4	11.4	6,800	13,600	1,550	27.1	3,820	5,500	1,640	1,380	...		...
Khaya ("African mahogany") (*Khaya spp.*) [12]	.48	.42	33	4.1	5.8	5,000	8,700	1,160	8.2	2,970	4,200	1,140	1,090	620		218
Locust, black (*Robinia pseudoacacia*)	.71	.64	50	4.4	6.9	9,300	15,700	1,740	16.3	5,330	7,600	2,020	1,740	1,610		362
Magnolia, Southern (*Magnolia grandiflora*)	.53	.48	36	5.4	6.6	4,200	8,200	1,090	14.5	2,330	3,300	850	1,050	820		326
Mahogany (*Swietenia spp.*) [12,14]	.52	.46	36	3.5	4.8	6,000	10,900	1,320	8.6	3,820	5,500	1,130	1,150	700		173
Maple, silver (*Acer saccharinum*)	.51	.46	34	3.0	7.2	3,700	6,800	910	10.0	2,180	3,100	700	1,040	630		272
Maple, sugar (*Acer saccharum*)	.68	.60	44	4.9	9.5	5,900	11,400	1,480	14.3	3,440	4,900	1,270	1,510	1,110		...
Oak, commercial white and red (*Quercus spp.*) [15]	.69	.62	45	4.8	9.4	5,300	10,000	1,290	12.1	3,000	4,300	1,170	1,240	1,120		372
Pecan (*Hicoria pecan*)	.69	.62	46	4.9	8.9	5,900	11,100	1,340	14.3	3,420	4,900	1,520	1,470	1,460		...
Sweetgum (*Liquidambar styraciflua*) [12]	.54	.48	35	5.2	9.9	4,500	8,900	1,210	10.0	2,510	3,600	600	990	570		296
Sycamore, American (*Platanus occidentalis*)	.54	.49	35	5.1	7.6	3,800	7,600	1,060	7.8	2,450	3,500	680	1,000	660		330
Tupelo, water (*Nyssa aquatica*)	.52	.47	35	4.2	7.6	4,700	8,100	1,010	7.8	2,790	4,000	880	1,160	760		316
Walnut, black (*Juglans nigra*)	.56	.52	39	5.2	7.1	6,300	11,100	1,360	13.2	3,550	5,100	930	1,120	930		304
Yellow-poplar (*Liriodendron tulipifera*) [12,16]	.44	.38	30	4.0	7.1	3,600	6,900	1,100	5.9	2,070	3,000	490	790	370		237

SOFTWOODS (CONIFERS)															Tension strength parallel to grain taken as	
Baldcypress (*Taxodium distichum*)	.48	.43	33	3.8	6.2	4,700	7,900	1,150	7.1	3,170	4,200	740	770	430		146
Cedar, Alaska (*Chamaecyparis nootkatenis*)	.46	.41	32	2.8	6.0	4,400	7,900	1,110	9.6	2,840	3,800	640	820	490		169
Douglas-fir (normal) (*Pseudotsuga taxifolia*)[12 16]	.50	.45	34	5.0	7.8	4,700	9,100	1,350	7.4	3,230	4,300	800	870	530		130
Douglas-fir (light)[12 16]	.43	.38	29	...	...	4,000	7,500	1,110	...	2,590	3,500	600	...	...		...
Fir, California red (*Abies magnifica*)	.42	.38	29	4.5	7.9	3,900	7,400	1,190	7.1	2,610	3,500	530	780	400		190
Fir, noble (*Abies nobilis*)[12]	.42	.36	28	4.5	8.3	4,300	7,800	1,340	6.8	2,670	3,600	530	790	320		114
Fir, Pacific silver (*Abies amabilis*)	.42	.38	27	4.5	10.0	4,000	6,800	1,220	6.9	2,490	3,300	420	690	350		...
Fir, white (*Abies concolor*)	.40	.36	27	3.2	7.0	4,300	6,800	1,040	5.6	2,480	3,300	530	710	370		140
Hemlock, Western (*Tsuga heterophylla*)[12]	.45	.40	30	4.3	7.9	4,900	9,400	1,410	7.1	3,190	4,300	610	760	490		154
Incense-cedar, California (*Libocedrus decurrens*)	.36	.32	26	3.3	5.2	4,200	6,900	820	6.0	2,720	3,600	650	750	410		140
Larch, Western (*Larix occidentalis*)	.59	.53	38	4.2	8.1	5,600	9,500	1,360	7.5	3,810	5,100	930	970	580		131
Pine, Eastern white (*Pinus strobus*)	.37	.34	26	2.1	6.1	3,500	6,000	970	5.7	2,240	3,000	390	660	320		135
Pine, ponderosa (*Pinus ponderosa*)	.42	.38	29	3.9	6.3	3,700	6,300	960	5.6	2,280	3,000	550	720	350		162
Pine, red (*Pinus resunosa*)	.51	.46	34	4.6	7.2	4,800	8,200	1,370	7.0	3,000	4,000	580	800	410		131
Pine, sugar (*Pinus lambertiana*)	.38	.34	27	2.9	5.6	3,800	6,000	920	5.4	2,290	3,100	510	690	330		148
Pine, Western white (*Pinus monticola*)	.42	.38	28	4.1	7.4	3,900	6,500	1,150	6.1	2,480	3,300	440	620	330		...
Redcedar, Western (*Thuja plicata*)	.34	.31	24	2.4	5.0	3,500	6,000	890	5.3	2,450	3,300	500	670	290		114
Spruce, Sitka (*Picea sitchensis*)[12]	.41	.36	28	4.2	7.5	4,200	7,700	1,270	7.6	2,760	3,700	580	860	420		151
Spruce, red (*Picea rubra*)	.41	.36	29	3.8	7.8	4,400	7,700	1,210	7.5	2,810	3,800	530	790	410		135
Spruce, white (*Picea glauca*)	.45	.36	29	4.7	8.2	3,900	6,900	1,040	6.5	2,420	3,200	440	710	370		128
White-cedar, Northern (*Thuja occidentalis*)	.32	.29	22	2.1	4.7	3,000	5,000	630	5.4	1,830	2,400	380	610	250		120
White-cedar, Port Orford (*Chamaecyparis lawsoniana*)[12 16]	.43	.40	30	4.6	6.9	5,100	7,900	1,320	7.9	3,040	4,100	580	710	440		116

See footnotes on page 26.

FOOTNOTES FOR TABLE 2-7.

[1] A moisture content value of 20 percent has been used in determining the values in table 2-7. This moisture content represents an equilibrium with high relative humidity, approximately 90 percent or over, corresponding to conditions in tropical areas where high humidity is prevalent for long periods of time, or more or less continuously. For design of aircraft to be used within the continental United States see table 2-6 and section 2.10.

[2] Values in column 2 for birch, khaya, maghogany, sweetgum, yellow-poplar, Douglas-fir, noble fir, Western hemlock, Sitka spruce, and Port Orford white-cedar are averages for material having a specific gravity equal to or greater than the minimum permitted for each species, as listed in column 3. For species other than those listed above, values in column 2 are general species averages, without excluding material below the minimum permitted.

[3] Values in column 3 for minimum permitted specific gravity are those listed in table 2-3 of ANC-18, June, 1944, corresponding to applicable Army-Navy-Aeronautical specifications as of that date. The continued applicability of these values is considered as being substantiated by experience.

[4] The values in columns 7, 8, 9, 12, 13, and 14 are species mean values adjusted to 20 percent moisture content (see footnote 1) and multiplied by two factors: (1) A "probability" factor to allow for variability of wood, and (2) a "rate and duration of load" factor to allow for the effect of estimated loading conditions for aircraft in service. The "probability" factor is based on composite cumulative frequency curves (figs. 1 and 2, ref. 2-13). Factors were determined for each property at an "inclusion" limit of 25 percent; that is, they represent strength values, expressed as percentages of the respective means, below which not more than 25 percent of aircraft-grade material would be expected to fall.

The "rate and duration of load" factors for ultimates are those applicable to a loading time of 1 second and a duration of 1.5 seconds, while those for proportional limits relate to a loading time of 3 seconds and a duration of 15 seconds (data from ref. 2-3). Values for modulus of elasticity in static bending, for compression perpendicular to grain, and for shear are assumed to be unaffected by rate and duration of load. Factors used for the several properties are:

Test	*Property*	*"Probability" Factor*	*"Rate and Duration of Load" Factor*
Static bending	Fiber stress at proportional limit.	0.89	1.05
Static bending	Modulus of rupture	.92	1.10
Static bending	Modulus of elasticity	.91	1.00
Compression parallel to grain	Fiber stress at proportional limit.	(See footnote 6)	1.00
Compression parallel to grain	Maximum crushing strength.	.91	1.07
Compression perpendicular to grain.	Fiber stress at proportional limit.	.81	1.00
Shear parallel to grain	Maximum shearing strength	.88	1.00

[5] The values given in column 9 are based on the average apparent modulus of elasticity (E_c) as obtained by substituting results from tests of 2- by 2-inch beams on a 28-inch span or 1- by 1-inch beams on a 14-inch span with load at the center in the formula $E_c = PL^3/48\delta I$. The use of these values of E_c in the usual formulas will give the deflection of beams of ordinary length with but small error. For exactness in the computation of deflections of I and box beams, particularly for short spans, the formula that takes into account shear deformations (see National Advisory Committee for Aeronautics Report No. 180, ref. 2-59) should be used. This formula involves E_t, the true modulus of elasticity in bending, and G, the modulus of rigidity in shear. Values of E_t may be obtained by adding 10 percent to the values of E_c as given in the table. If the I or box beam has the grain of the web parallel to the axis of the beam, or parallel and perpendicular thereto as in some plywood webs, the value of G may be taken as $E_t/16$ or $E_c/14.5$. If the web is of plywood with the grain at 45° to the axis of the beam G may be taken as $E_t/5$ or $E_c/4.5$.

[6] Design values for fiber stress at proportional limit in compression parallel to grain were obtained by multiplying the values of maximum crushing strength in the next column by 0.75 for hardwoods and 0.80 for conifers, and by the ratio of the "rate and duration of load" factors, namely, 1.00/1.07.

[7] Wood does not exhibit a definite ultimate strength in compression perpendicular to grain, particularly when the load is applied over only a part of the surface, as at fittings. Beyond the proportional limit, the load continues to increase slowly until the deformation becomes several times as great as at the proportional limit (see figure 2-1) and the crushing is so severe as to damage the wood seriously in other properties. In calculating values in column 13, a "rate and duration of load" factor of 1.00 was assumed, and the average proportional limit stress, modified by the appropriate "probability" factor (see footnote 4) was increased by 50 percent to get design values.

[8] Values in this column are for use in computing resistance to longitudinal shear. They were obtained by multiplying average values by a "probability" factor (see footnote 4) to allow for variability. Tests have shown that because of the favorable influence upon the distribution of stresses resulting from limiting shearing deformations the maximum strength-weight ratio and minimum variability in strength are attained when I and box beams are so proportioned that the ultimate shearing strength is not developed and failure by shear does not occur.

[9] Values in column 17 are one-half the average values at 20 percent moisture content.

[10] Includes white ash (*F. americana*), green ash (*F. pennsylvanica lanceolata*), and blue ash (*F. quadrangulata*).

[11] Includes sweet birch (*B. lenta*) and yellow birch (*B. lutea*).

[12] Values for these species in columns 2, 4, 7, 8, 9, 11, 12, and 13 are based on material conforming to aircraft specifications for minimum permitted specific gravity and rings per inch (see footnote 2 and ref. 2-13). Values in columns 5, 6, 10, 14, 15, and 17, and all values for other species, are based on general averages for the species without excluding material below the minimum permitted specific gravity or with less than the required number of rings per inch.

[13] Includes shellbark hickory (*H. laciniosa*), mockernut hickory (*H. alba*), pignut hickory (*H. glabra*), and shagbark hickory (*H. ovata*).

[14] Includes only material from Central America.

[15] Includes white oak (*Q. alba*), bur oak (*Q. macrocarpa*), swamp chestnut oak (*Q. prinus*), post oak (*Q. stellata*), Northern red oak (*Q. borealis*), Southern red oak (*Q. rubra*), laurel oak (*Q. laurifolia*), water oak (*Q. nigra*), swamp red oak (*Q. pagodaefolia*), willow oak (*Q. phellos*), and yellow oak (*Q. velutina*).

[16] These species will be found in the Army-Navy-Aeronautical specifications under the following names: White-cedar, Port Orford—(AN-C-72) cedar, aircraft Port Orford; Douglas-fir (AN-F-7) fir, aircraft Douglas; yellow-poplar (AN-P-17) poplar, aircraft yellow.

2.111. *Tension parallel to grain.* Relatively few data are available on the tensile strength of various species parallel to grain. In the absence of sufficient tensile-test data upon which to base tension design values, the values used in design for modulus of rupture are used also for tension. While it is recognized that this is somewhat conservative, the pronounced effect of stress concentration, slope of grain (table 2–8) and other factors upon tensile strength makes the use of conservative values desirable.

Pending further investigation of the effects of stress concentration at bolt holes, it is recommended that the stress in the area remaining to resist tension at the critical section through a bolt hole not exceed two-thirds the modulus of rupture in static bending when cross-banded reinforcing plates are used; otherwise one-half the modulus of rupture shall not be exceeded.

2.112. *Tension perpendicular to grain.* Values of strength of various species in tension perpendicular to grain have been included for use as a guide in estimating the adequacy of glued joints subjected to such stresses. For example, the joints between the upper wing skin and wing framework are subjected to tensile stresses perpendicular to the grain by reason of the lift forces exerted on the upper skin surface.

Caution must be exercised in the use of these values, since little experience is available to serve as a guide in relating these design values to the average property. Considering the variability of this property, however, the possible discontinuity or lack of uniformity of glue joints, and the probable concentration of stress along the edges of such joints, the average test values for each species have been multiplied by a factor of 0.5 to obtain the values given in tables 2–6 and 2–7.

Table 2–8. Reduction in wood strength for various grain slopes

Maximum slope of grain in the member	Corresponding design value, percent of value in table 2–6				
	Static bending			Compression parallel to grain	Tension parallel to grain
	Fiber stress at proportional limit	Modulus of rupture	Modulus of elasticity	Maximum crushing strength	Modulus of rupture
1 in 15	100	100	100	....	100
1 in 12	98	88	97	100	85
1 in 10	87	78	91	98	75
1 in 8	78	67	84	94	60

2.12. Standard Test Procedures.

2.120. *Static bending.* In the static-bending test, the resistance of a beam to slowly applied loads is measured. The beam is 2 by 2 inches in cross section and 30 inches long and is supported on roller bearings which rest on knife edges 28 inches apart. Load is applied at the center of the length through a hard maple block 3$^{13}/_{16}$ inches wide, having a compound curvature. The curvature has a radius of 3 inches over the central 2⅛ inches of arc, and is joined by an arc of 2-inch radius on each side. The standard placement is with the annual rings of the specimen horizontal and the loading block bearing on the side of the piece nearest the pith. A constant rate of deflection (0.1 inch per minute) is maintained until the specimen fails. Load and deflection are read simultaneously at suitable intervals.

Figure 2–4 (a) shows a static-bending test set-up, and typical load-deflection curves for Sitka spruce and yellow birch.

Data on a number of properties are obtained from this test. These are discussed as follows:

2.1200. *Modulus of elasticity* (E_L). The modulus of elasticity is determined from the slope of the straight line portion of the graph, the steeper the line, the higher being the modulus. Modulus of elasticity is computed by

$$E_L=\frac{P_pL^3}{48\delta_pI}=\frac{P_pL^3}{4\delta_pbd^3} \qquad (2:5)$$

The standard static bending test is made under such conditions that shear deformations are responsible for approximately 10 percent of the deflection. Values of E_L from tests made under such conditions and calculated by the formula shown do not, therefore, represent the true modulus of elasticity of the material, but an "apparent" modulus of elasticity.

The use of these values of apparent modulus of elasticity in the usual formulas will give the deflection of simple beams of ordinary length with but little error. For I- and box beams, where more exact computations are desired, and formulas are used that take into account the effect of shear deformations, a "true" value of the modulus of elasticity is necessary and may be had by adding 10 percent to the values in tables 2–6 and 2–7.

2.1201. *Fiber stress at proportional limit* (F_{bp}). The plotted points from which the early portions of the curves of figure 2–4 (a) were drawn lie approximately on a straight line, showing that the deflection is proportional to the load. As the test progresses however, this proportionality between load and deflection ceases to exist. The

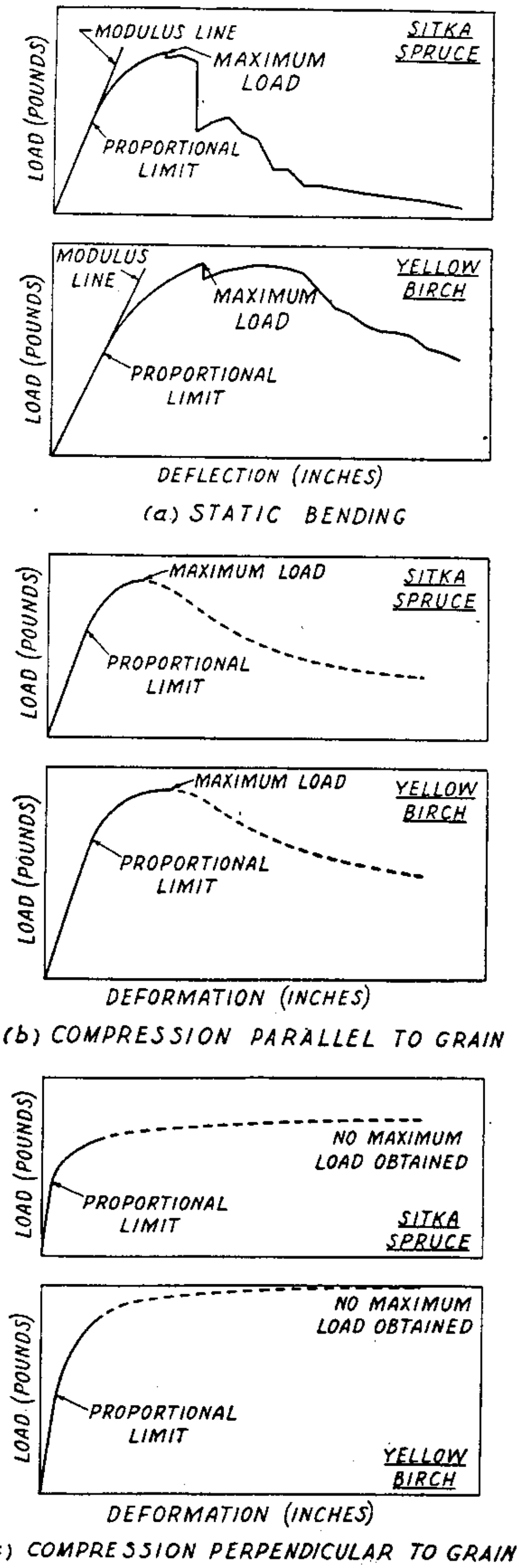

Figure 2-4. Standard test methods and typical load-deflection curves

point at which this occurs is known as the proportional limit. The corresponding stress in the extreme fibers of the beam is known as "fiber stress at proportional limit." Fiber stress at proportional limit is computed by

$$F_{bp}=\frac{P_pL}{4}\frac{c}{I}=\frac{1.5P_pL}{bd^2} \qquad (2:6)$$

2.1202. *Modulus of rupture* (F_{bu}). Modulus of rupture is computed by the same formula as was used in computing fiber stress at proportional limit, except that maximum load is used in place of load at proportional limit. Since the formula used is based upon an assumption of linear variation of stress across the cross section of the beam, modulus of rupture is not truly a stress existing at time of rupture, but is useful in finding the load-carrying capacity of a beam.

2.1203. *Work to maximum load.* The energy absorbed by the specimen up to the maximum load is represented by the area under the load-deflection curve from the origin to a vertical line through the abscissa representing the maximum deflection at which the maximum load is sustained. It is expressed, in tables 2–6 and 2–7, in inch-pounds per cubic inch of specimen. Work to maximum load is computed by

$$\text{Work to } P_{max.}=\frac{\text{area under curve to } P_{max.}}{b\times d\times L} \qquad (2:7)$$

2.121. *Compression parallel to grain.* In the compression-parallel-to-grain test, a 2- by 2- by 8-inch block is compressed in the direction of its length at a constant rate (0.024 inch per minute). The load is applied through a spherical bearing block, preferably of the suspended self-aligning type, to insure uniform distribution stress. On some of the specimens, the load and the deformation in a 6-inch central gage length are read simultaneously until the proportional limit is passed. The test is discontinued when the maximum load is passed and the failure appears.

Figure 2–4 (b) shows a test set-up, and typical load-deflection curves for Sitka spruce and yellow birch. Data on a number of properties are obtained from this test. These are discussed as follows:

2.1210. *Modulus of elasticity* (E_{Lc}). The modulus of elasticity is determined from the slope of the straight-line portion of the graph, the steeper the line the higher the modulus. The modulus of elasticity is computed by

$$E_{Lc}=\frac{P_p}{Ae_L} \quad (2:8)$$

The value of the modulus of elasticity so determined corresponds to the "true" value of modulus of elasticity discussed under static bending. Values of the modulus of elasticity from compression-parallel-to-grain tests are not published but may be approximated by adding 10 percent to the apparent values shown under static bending in table 2–6.

A multiplying factor of 1.1 has been inserted in various formulas throughout this bulletin to convert E_L values, as shown in tables 2–6 and 2–7 to E_{Lc} values required in formulas involving direct stress.

2.1211. *Fiber stress at proportional limit* (F_{cp}). The plotted points from which early portions of the curves of figure 2–4 (b) were drawn lie approximately on a straight line, showing that the deformation within the gage length is proportional to the load. The point at which this proportionality ceases to exist is known as the proportional limit and the stress corresponding to the load at proportional limit is the fiber stress at proportional limit. It is calculated by

$$F_{cp}=\frac{P_p}{A} \quad (2:9)$$

2.1212. *Maximum crushing strength* (F_{cu}). The maximum crushing strength is computed by the same formula as used in computing fiber stress at proportional limit except that maximum load is used in place of load at proportional limit.

2.122. *Compression perpendicular to grain.* The specimen for the compression-perpendicular-to-grain test is 2 by 2 inches in cross section and 6 inches long. Pressure is applied through a steel plate 2 inches wide placed across the center of the specimen and at right angles to its length. Hence, the plate covers one-third of the surface. The standard placement of the specimen is with the growth rings vertical. The standard rate of descent of the movable head is 0.024 inch per minute. Simultaneous readings of load and compression are taken until the test is discontinued at 0.1-inch compression.

Figure 2–4 (c) shows a test set-up, and typical load-deflection curves for Sitka spruce and yellow birch.

The principal property determined is the stress at proportional limit (F_{cpT}) which is calculated by

$$F_{cpT}=\frac{\text{Load at proportional limit}}{\text{Width of plate}\times\text{width of specimen}} \quad (2:10)$$

Tests indicate that the stress at proportional limit when the growth rings are placed horizontal does not differ greatly from that when the growth rings are vertical. For design purposes, therefore, the values of strength in compression perpendicular to grain as given in tables 2–6 and 2–7 may be used regardless of ring placement.

2.123. *Shear parallel to grain* (F_{su}). The shear-parallel-to-grain test is made by applying force to a 2- by 2-inch lip projecting ¾ inch from a block 2½ inches long. The block is placed in a special tool having a plate that is seated on the lip and moved downward at a rate of 0.015 inch per minute. The specimen is supported at the base so that a ⅛-inch offset exists between the outer edge of the support and the inner edge of the loading plate.

The shear tool has an adjustable seat in the plate to insure uniform lateral distribution of the load. Specimens are so cut that a radial surface of failure is obtained in some and a tangential surface of failure in others.

The property obtained from the test is the maximum shearing strength parallel to grain. It is computed by

$$F_{su}=\frac{P_{max.}}{A} \quad (2:11)$$

The value of F_{su} as found when the surface of failure is in a tangential plane does not differ greatly from that found when the surface of failure is in a radial plane, and the two values have been combined to give the values shown in column 14 of tables 2–6 and 2–7.

2.124. *Hardness.* Hardness is measured by the load required to embed a 0.444-inch ball to one-half its diameter in the wood. (The diameter of the ball is such that its projected area is one square centimeter.) The rate of penetration of the ball is 0.25 inch per minute. Two penetrations are made on each end, two on a radial, and two on a tangential surface of the specimen. A special tool makes it easy to determine when the proper penetration of the ball has been reached. The accompanying load is recorded as the hardness value.

Values of radial and tangential hardness as

Table 2-9. Elastic constants of various species

Species	Specific gravity [1]	Moisture content [1]	Young's modulus ratios		Modulus of rigidity ratios			Poisson's ratios						Source of data
			E_T/E_L	E_R/E_L	G_{LR}/E_L	G_{LT}/E_L	G_{RT}/E_L	μ_{LR}	μ_{LT}	μ_{RT}	μ_{TR}	μ_{RL}	μ_{TL}	
		Percent												
Balsa [2]	0. 131	9. 4	0. 015	0. 046	0. 054	0. 037	0. 005	0. 229	0. 488	0. 665	0. 231	0. 018	0. 009	Reference 2–3.
Douglas-fir	. 506	7. 5	. 061	. 090				. 295	. 441	. 447	. 368	. 030	. 023	Reference 2–26.
Do	. 506	12. 9	. 050	. 068				. 292	. 449	. 390	. 374	. 036	. 029	Do.
Do	. 506	19. 9	. 032	. 056				. 274	. 496	. 560	. 396	. 018	. 019	Do.
Do	. 45	11. 2			. 064	. 078	. 007							Reference 2–4.
Khaya	. 45	11. 3	. 050	. 111	. 088	. 059	. 021	. 297	. 641	. 604	. 264	. 033	. 032	Reference 2–2.
Mahogany	. 50	11. 7	. 064	. 107	. 086	. 066	. 028	. 314	. 533	. 600	. 326	. 033	. 034	Reference 2–2.
Quipo [3]	. 137	11. 2	. 055	. 182	. 082	. 055	. 032	. 216	. 666	. 455	. 128	. 047	. 032	Reference 2–3.
Sitka spruce	. 378	7. 1	. 050	. 089				. 375	. 436	. 468	. 248	. 034	. 022	Reference 2–10.
Do	. 378	12. 8	. 043	. 078				. 372	. 467	. 435	. 245	. 040	. 025	Do.
Do	. 378	16. 3	. 036	. 064				. 374	. 504	. 527	. 278	. 030	. 020	Do.
Do	. 378	21. 6	. 029	. 053				. 371	. 539	. 512	. 278	. 022	. 017	Do.
Do	. 39	6. 8			. 070	. 068	. 004							Reference 2–5.
Do	. 39	11. 1			. 064	. 061	. 003							Do.
Sweetgum	. 536	11. 2	. 050	. 115				. 325	. 403	. 682	. 309	. 044	. 023	Reference 2–25.
Do	. 530	10. 2			. 089	. 061	. 021							
Yellow birch	. 64	13. 3	. 050	. 078				. 426	. 451	. 697	. 426	. 043	. 024	Reference 11.
Do	. 65	12. 6			. 074	. 068	. 017							Do.
Yellow-poplar	. 376	10. 7	. 043	. 092	. 075	. 069	. 011	. 318	. 392	. 703	. 329	. 030	. 019	Reference 2–12.
Ash	. 801	13. 6	. 064	. 109	. 057	. 041	. 0165	. 533	. 653	. 656	. 386	. 0582	. 0421	Reference 2–21.
Walnut	. 593	11. 0	. 056	. 106	. 085	. 062	. 0209	. 495	. 632	. 718	. 367	. 0520	. 0360	Do.

[1] Specific gravity based on volume at test and weight when oven dry. The values shown to 2 decimal places, and corresponding moisture values, are tentative, and subject to revision.

[2] The balsa in these tests varied in specific gravity from 0.06 to 0.22, in which range E_L is given approximately by the equation E_L=5,500,000×specific gravity−200,000.

[3] The quipo in these tests varied in specific gravity from 0.08 to 0.20, in which range E_L is given approximately by the equation E_L=3,260,000×specific gravity−170,000.

determined by the standard test have been averaged to give the values of side hardness in tables 2–6 and 2–7.

2.125. *Tension perpendicular to grain* (F_{tuT}). The tension-perpendicular-to-grain test is made to determine the resistance of wood across the grain to slowly applied tensile loads. The test specimen is 2 by 2 inches in cross section, and 2½ inches in overall length, with a length at midheight of 1 inch. The load is applied with special grips, the rate of movement of the movable head of the testing machine being 0.25 inch per minute. Some specimens are cut to give a radial and others to give a tangential surface of failure.

The only property obtained from this test is the maximum tensile strength perpendicular to grain. It is calculated from the formula

$$F_{tuT}=\frac{P_{max.}}{A} \qquad (2:12)$$

Tests indicate that the plane of failure being tangential or radial makes little difference in the strength in tension perpendicular to grain. Results from both types of specimens have, therefore, been combined to give the values shown in tables 2–6 and 2–7.

2.13. Elastic Properties Not Included in Tables 2–6 and 2–7. Certain elastic properties useful in design are not included in tables 2–6 and 2–7. The data in tables 2–6 and 2–7 are, in general, based on large numbers of tests, while the data on the additional elastic properties are based on relatively few tests. Available data on these properties are included in table 2–9.

2.130. *Moduli of elasticity perpendicular to grain* (E_T, E_R). The modulus of elasticity of wood perpendicular to the grain is designated as E_T when the direction is tangential to the annual growth rings, and E_R when the direction is radial to the annual growth rings. Tests have been made to evaluate these elastic properties for only a few species (table 2–9). The ratios $\frac{E_T}{E_L}$ and $\frac{E_R}{E_L}$ vary greatly among species and are considerably affected by differences in specific gravity and moisture content. For species not listed in the table, a rough approximation of the values for E_T and E_R may be made by assuming values of $\frac{E_T}{E_L}$ and $\frac{E_R}{E_L}$ as 0.05 and 0.10, respectively. Values of E_L are given in tables 2–6 and 2–7.

2.131. *Moduli of rigidity* (G_{LT}, G_{LR}, G_{RT}). The modulus of elasticity in shear, or the modulus of rigidity as it is called, must be associated with shear deformation in one of the three mutually perpendicular planes defined by the L, T, and R directions, and with shear stresses in the other two. The symbol for modulus of rigidity has subscripts denoting the plane of deformation. Thus the modulus of rigidity G_{LT} refers to shear deformations in the LT plane resulting from shear stresses in the LR and RT planes. Values of these moduli for a few species are given in table 2–9. The ratios of G_{LT}, G_R, and G_{RT} to E_L vary among species and appear to be considerably affected by differences in specific gravity and moisture content. For species not listed in the table, it is recommended the approximate ratios $\frac{G_{LT}}{E_L}=0.06$, $\frac{G_{LR}}{E_L}=0.075$, and $\frac{G_{RT}}{E_L}=0.018$ be used in evaluating the various moduli of rigidity. The two letters of the subscript may be interchanged without changing the meaning of G.

2.132. *Poisson's ratios* (μ). The Poisson's ratio relating to the contraction in the T direction under a tensile stress acting in the L direction, and thus normal to the RT plane, is designated as μ_{LT}; μ_{LR}, μ_{RT}, μ_{RL}, μ_{TR}, and μ_{TL} have similar significance, the first letter of the subscript in each relating to the direction of stress and the second to the direction of the lateral deformation.

Thus, the two letters of the subscript may not be interchanged without changing the meaning. The Poisson's ratios appear to be independent of specific gravity but are variously affected by differences in moisture content. Information on Poisson's ratios for wood is meager and values for only a few species are given in table 2–9.

2.14. Stress-Strain Relations. For most practical purposes wood can be considered to be an orthotropic material having orthotropic axes L, T, and R (see sec. 2.00). If the directions of the applied stresses are parallel to a plane containing two of these axes, the methods described in sections 2.56 to 2.5602, inclusive, can be applied. The general equations for stresses applied in any direction can be obtained from reference 2–53.

2.15. Strength Under Multiaxial Stress. If the directions of the applied stresses are parallel to a plane containing two of the orthotropic axes, the methods described in section 2.610 to 2.613, inclusive, for plywood can be applied. The ultimate shear stress associated with relative shear displacements of the L and R axes and the L and T axes are each equal to the ultimate shear stress parallel to the grain (F_{su}). The ultimate shear stress associated with relative shear displacements of the R and T axes is for hardwoods approximately one-half and for coniferous woods one-third of F_{su} (ref. 2–48). The ultimate compressive stress associated with the T and R axes are each equal to the compressive strength perpendicular to the grain (F_{cuT}) and the ultimate tensile stress associated with these axes are each equal to the tensile strength perpendicular to the grain (F_{tuT}).

The general equation defining the condition of failure for stresses applied in any direction is similar to equation (2:51) except that its left hand member contains six terms instead of three. If the ultimate stresses are given the values indicated in the preceding paragraph this equation can be written in the following form:

$$\left(\frac{f_L}{F_L}\right)^2+\left(\frac{f_T}{F_T}\right)^2+\left(\frac{f_R}{F_R}\right)^2+\frac{(f_{LT})^2+(f_{LR})^2+(Kf_{RT})^2}{(F_{su})^2}=1 \qquad (2:13)$$

in which f_L, f_T, and f_R are the three internal direct stresses in the directions of the axes L, T, and R, respectively, and f_{LT}, f_{LR}, and f_{RT} are the three internal shear stresses associated with shear displacements of the L and T axes, the L and R axes, and the R and T axes, respectively. Also F_L, F_T, and F_R are the three ultimate stresses associated with the directions of the L, T, and R axes, respectively, and may be tensile or compressive; thus F_L is tensile if f_L is tensile and compressive if f_L is compressive and similarly for F_T and F_R. Thus F_L is equal to F_{cu} or F_{tu}; F_T is equal to F_{cuT} or F_{tuT}; and F_R is equal to F_{cuT} or F_{tuT}. The value of K is 2 for hardwoods and 3 for coniferous woods.

Equation (2:13) can be handled in the manner described in section 2.613 and in reference 2–67 using the transformation equations for three dimensions given in reference 2–53.

The methods described in this section have not been verified by test but their verification for plywood indicates that they probably will yield reasonable values. Also equation 2:44 has been compared with results of tests on solid wood in which the specimens were constrained by the testing equipment and good agreement was found, however, shear stress associated with relative shear displacements of the R and T axes was not involved in these tests.

2.16. STRESS CONCENTRATIONS. Wood has plastic as well as elastic properties (see sec. 2.06 on creep) and, therefore, stress concentrations in tension, compression, or shear are greatly relieved with the passage of time. In compression and shear, creep is very rapid for stresses near the ultimate value and, therefore, values of stress concentration calculated by means of the mathematical theory of elasticity are rarely attained. Creep at high stress in tension, however, is not nearly so rapid and calculated values of stress concentration may be approximately correct if the load is suddenly applied. This fact should be given careful consideration in the design of wood and plywood tension members, and stress concentrations should be avoided.

2.161. *Stress concentrations around a hole in a tension or compression member.* Figure 2–5 shows a panel of wood pierced by an elliptical hole which is small compared to the size of the panel. Axes y and z are orthotropic axes of the wood as well as axes of the ellipse. When a tensile stress (f_a) is applied as shown in the figure, tensile stress concentrations occur at the ends of axis a. The value of the stress at these points is given by equation (2:14):

$$f=f_a\left(\frac{a}{b}\sqrt{\frac{E_y}{G_{yz}}-2\mu_{yz}+2\sqrt{\frac{E_y}{E_z}}}+1\right) \qquad (2:14)$$

in which f_a denotes the value of the applied stress, subscript y denotes the orthotropic axis which is parallel to the stress, and subscript z denotes the other orthotropic axis which lies in the plane of the panel. These subscripts may represent the L, T, or R directions depending upon the directions of the grain and annual rings in the panel. Equation (2:14) applies also to a compressive stress.

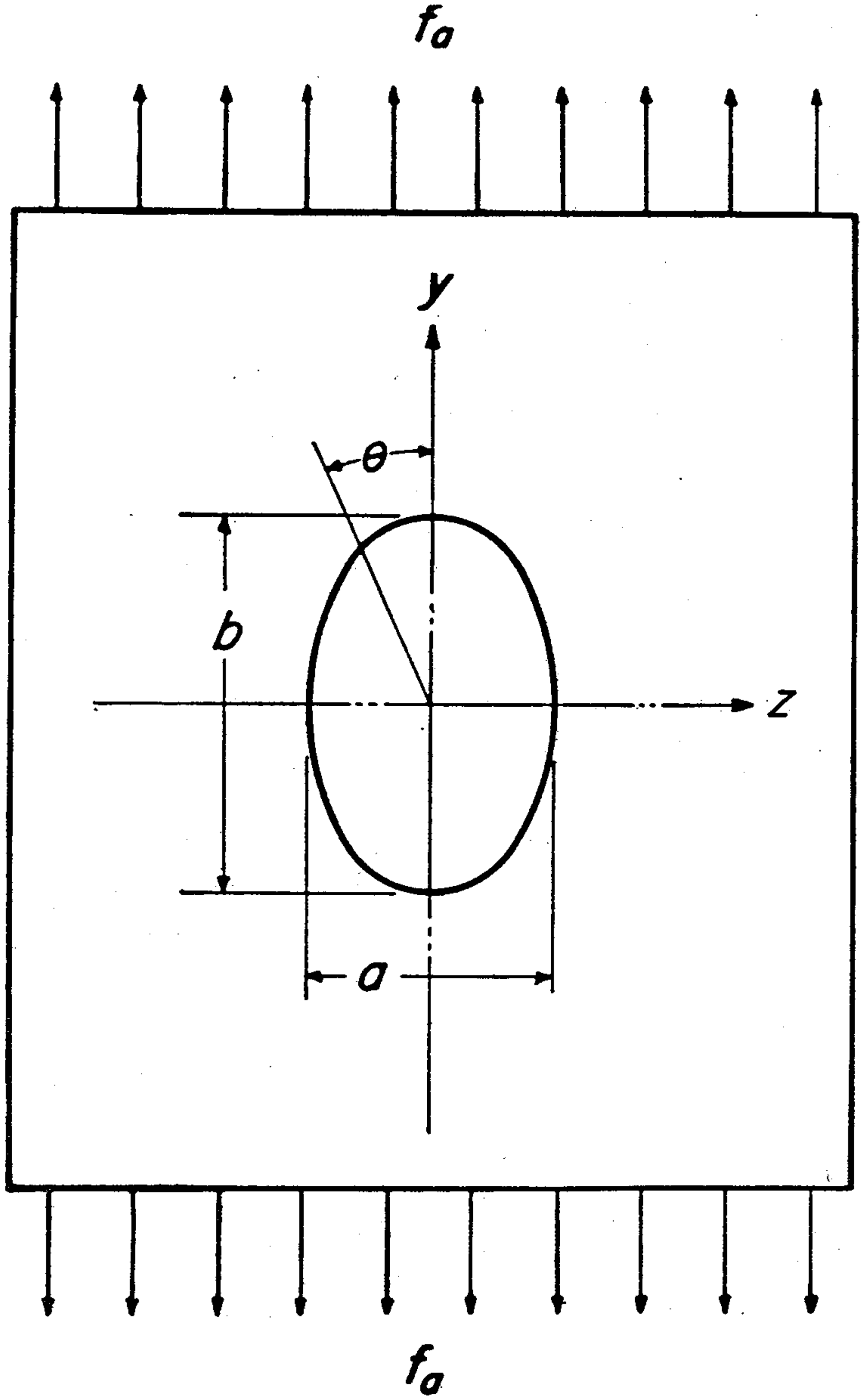

Figure 2–5. A wood or plywood panel pierced by an elliptical hole.

The shear stress on the periphery of the ellipse associated with relative shear displacements of axes y and z is given by equation (2:15):

$$f_s=f_a \frac{\frac{a}{b}\sqrt{\frac{E_y}{E_z}}\cos^2\theta-\left[\sqrt{\frac{E_y}{G_{yz}}-2\mu_{yz}+2\sqrt{\frac{E_y}{E_z}}}+\frac{b}{a}\right]\sin^2\theta}{\left(\frac{a}{b}\right)^2\frac{E_y}{E_z}\cos^4\theta+\left[\frac{E_y}{G_{yz}}-2\mu_{yz}\right]\sin^2\theta+\cos^2\theta\left(\frac{b}{a}\right)^2\sin^4\theta}\sin\theta\cos\theta \qquad (2:15)$$

By use of equation (2:15) the shear stress can be plotted against θ and its maximum value found. For a plane sawed Sitka spruce panel pierced by a circular hole ($a=b$) a maximum value of $0.71\,f_a$ was found at $\theta=78°$ (see ref. 2–69).

Equations (2:14) and (2:15) can be used for plywood if the subscripts y and z are replaced by the subscripts b and a, respectively.

2.162. *Stress concentration due to a hole which is not small compared to the size of the member.* Stress concentrations in isotropic materials around holes that are not small compared to the size of the members pierced by them have been determined by photoelastic methods and are well known. It is impossible to use such methods in connection with wood, however, an estimate of the stress concentrations can be obtained by use of equation (2:14).

For an isotropic material equation (2:14) reduces to equation (2:16)

$$f=f_a\left(2\,\frac{a}{b}+1\right) \qquad (2:16)$$

An approximate corrective factor for use with the stress concentrations obtained for isotropic materials to obtain those for wood, or plywood, can be obtained by dividing values obtained by equation (2:14) by those obtained by equation (2:16). Of course such corrections do not apply to the shear stresses such as those obtained by equation (2:15).

2.2. Columns

2.20. Primary Failure. The allowable stresses for solid wood columns are given by the following formulas:

Long columns

$$F_c=\frac{10\,E_L}{\left(\frac{L'}{\rho}\right)^2}\text{ psi}$$

$$\left(\frac{L'}{\rho}\right)_{cr}=\sqrt{\frac{15\,E_L}{F_{cu}}} \qquad (2:17)$$

Short columns (ref. 2–97)

$$F_c=F_{cu}\left[1-\frac{1}{3}\left(\frac{L'}{K\rho}\right)^4\right]\text{ psi} \qquad (2:18)$$

where

$$K=\left(\frac{L'}{\rho}\right)_{cr}$$

These formulas are reproduced graphically in figure 2–6 for solid wood struts of a number of species.

2.21. Local Buckling and Twisting Failure. The formulas given in section 2.20 do not apply when columns with thin outstanding flanges or low torsional rigidity are subject to local buckling or twisting failure. For such cases, the allowable stresses are given by the following formulas:

Local buckling (torsionally rigid columns)

$$F_c=0.07\,E_L\left(\frac{t}{b}\right)^2\text{ psi}\left(\text{when }\frac{b}{t}>6\right) \qquad (2:19)$$

Twisting failure (torsionally weak columns)

$$F_c=0.044\,E_L\left(\frac{t}{b}\right)^2\text{ psi}\left(\text{when }\frac{b}{t}>5\right) \qquad (2:20)$$

When the width-thickness ratio (b/t) of the outstanding flange is less than the values noted, the column formulas of section 2.20 should be used. Failure due to local buckling or twisting can occur only when the critical stress for these types of failure is less than the stress required to cause primary failure. For unconventional shapes, tests should be conducted to determine suitable column curves (ref. 2–79).

2.22. Lateral Buckling. When subjected to axial compressive loads, beams will act as columns tending to fail through lateral buckling. The usual column formulas (2:17 and 2:18) will apply except that when two beams are interconnected by ribs so that they will deflect together (laterally), the total end load carried by both beams will be the sum of the critical end loads for the individual beams.

The column lengths will usually be the length of a drag bay in a conventional wing. A restraint

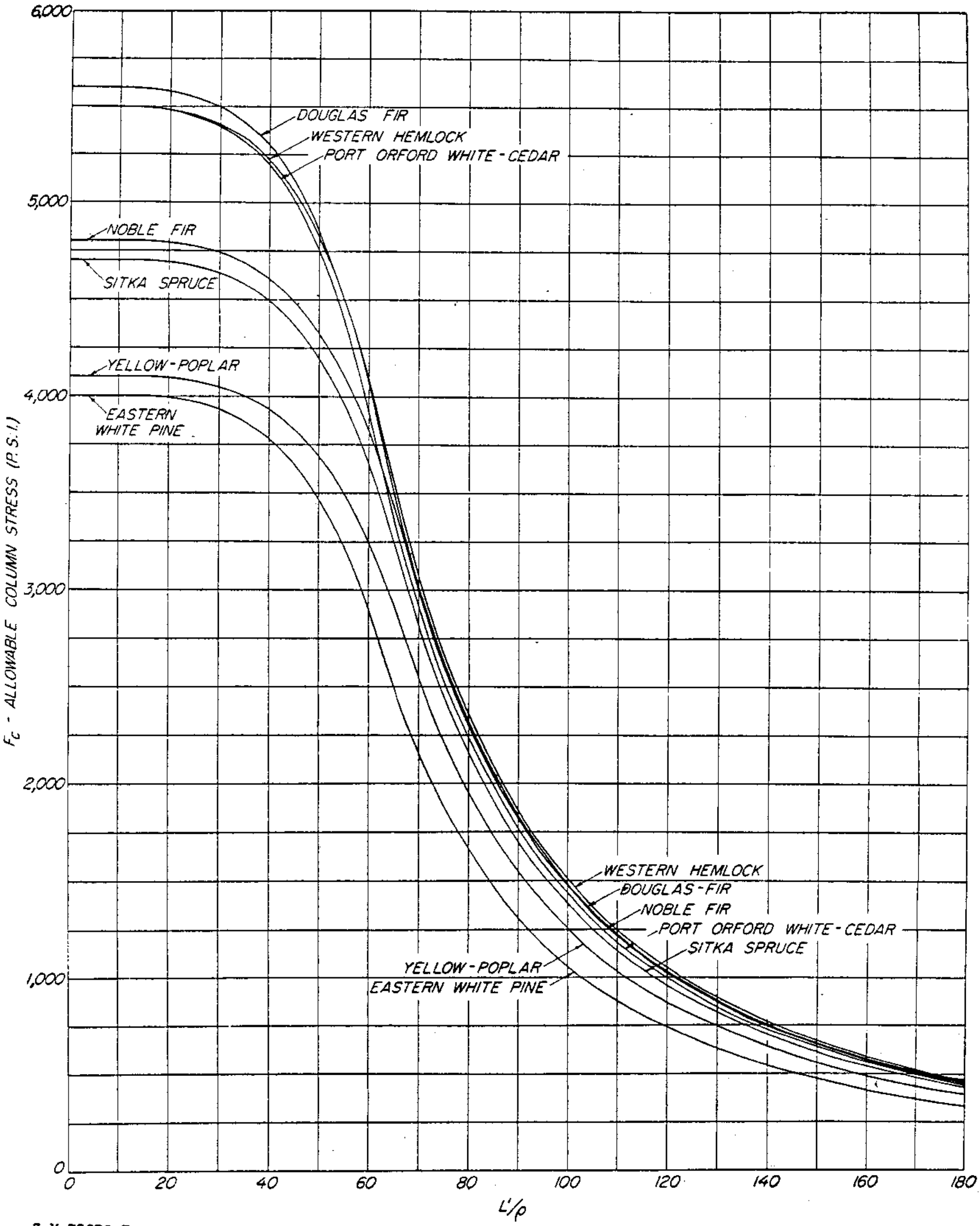

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Figure 2–6. Allowable column stresses for solid wood struts.

coefficient of 1.0 will be applicable unless the construction is such that additional restraint is afforded by the leading edge or similar parts. Certain rules for such conditions will be found in the requirements of the certificating or procuring agencies.

2.3. Beams

2.30. Form Factors. When other than solid rectangular cross sections are used for beams (I-beams or box beams), the static-bending strength properties given in table 2-6 must be multiplied by a "form factor" for design purposes. This form factor is the ratio of either the fiber stress at proportional limit or the modulus of rupture (in bending) of the particular section to the same property of a standard 2-inch square specimen of that material. The proportional limit form factor (FF_p) is given by the formula:

$$FF_p=0.58+0.42\left(K\frac{b-b'}{b}+\frac{b'}{b}\right) \quad (2:21)$$

and the modulus of rupture form factor (FF_u) by the formula:

$$FF_u=0.50+0.50\left(K\frac{b-b'}{b}+\frac{b'}{b}\right) \quad (2:22)$$

where

b' = total web thickness

b = total flange width (including any web(s))

K = constant obtained from figure 2-7

Formulas 2:21 and 2:22 cannot be used to determine the form factors of sections in which the top and bottom edges of the beam are not perpendicular to the vertical axis of the beam. In such cases, it is first necessary to convert the section to an equivalent section whose height equals the mean height of the original section, and whose width and flange areas equal those of the original section, as shown in figure 2-7. The fact that the two beams of each pair shown in figure 2-7 developed practically the same maximum load in test demonstrates the validity of this conversion (ref. 2-56 and 2-62).

Tests have indicated that the modulus of rupture which can be developed by a beam of rectangular cross section decreases with the height. Sufficient data are not available to permit exact evaluation of the reduction as the height increases, but where deep beams of rectangular cross section are to be used, thought should be given to the reduction of the value for modulus of rupture given in tables 2-6 and 2-7.

2.31. Torsional Instability. It is possible for deep thin beams to fail through torsional instability at loads less than those indicated by the usual beam formula. Reference 2-63 gives formulas for calculating the strength of such beams for various conditions of end restraint. However, in view of the difficulty of accurately evaluating the modulus of rigidity and end fixity, it is always advisable to conduct static tests of a typical specimen. This will apply to cases in which the ratio of the moment of inertia about the horizontal axis to the moment of inertia about the vertical axis exceeds approximately 25 (ref. 2-62 and 2-63).

2.32. Combined Loadings.

2.320. *General.* Because of the variation of the strength properties of wood with the direction of loading with respect to the grain, no general rules for combined loadings can be presented, other than those for combined bending and compression given in section 2.321, and those for combined bending and tension given in section 2.322. When unusual loading combinations exist, static tests should be conducted to determine the desired information.

2.321. *Bending and compression.* When subjected to combined bending and compression, the allowable stress for spruce, Western hemlock, and noble fir beams at 15 percent moisture content can be determined from figure 2-8 and that for Douglas-fir beams from figure 2-9. The charts are based on a method of analysis developed by the Forest Products Laboratory (ref. 2-63 and 2-78).

The curves of figures 2-8 and 2-9 are based on the use of a fourth-power parabola for columns of intermediate length. On these figures the horizontal family of curves indicates the proportional limit under combined bending and compression; the vertical family, the effect of various slenderness ratios on bending. The allowable stress, F_{bc}, under combined load is found as follows:

(1) For the cross section of a given beam, find the proportional limit in bending and the modulus of rupture from the ratios of compression-flange thickness to total depth and of web thickness to total width, locating such points as A and B.

(2) Project points A and B to the central line, obtaining such points as C and D.

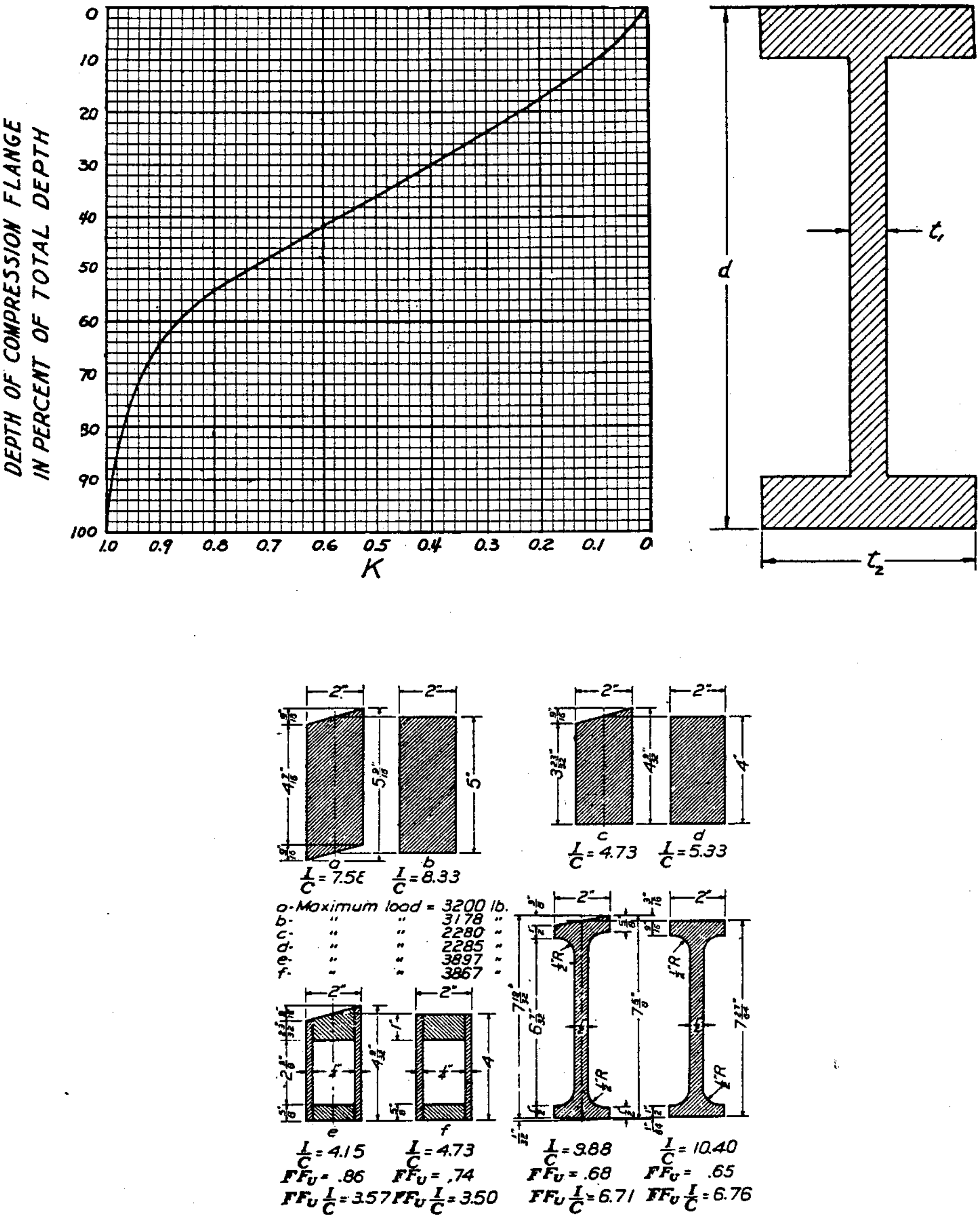

Figure 2–7. Form-factor curve and equivalent beam sections.

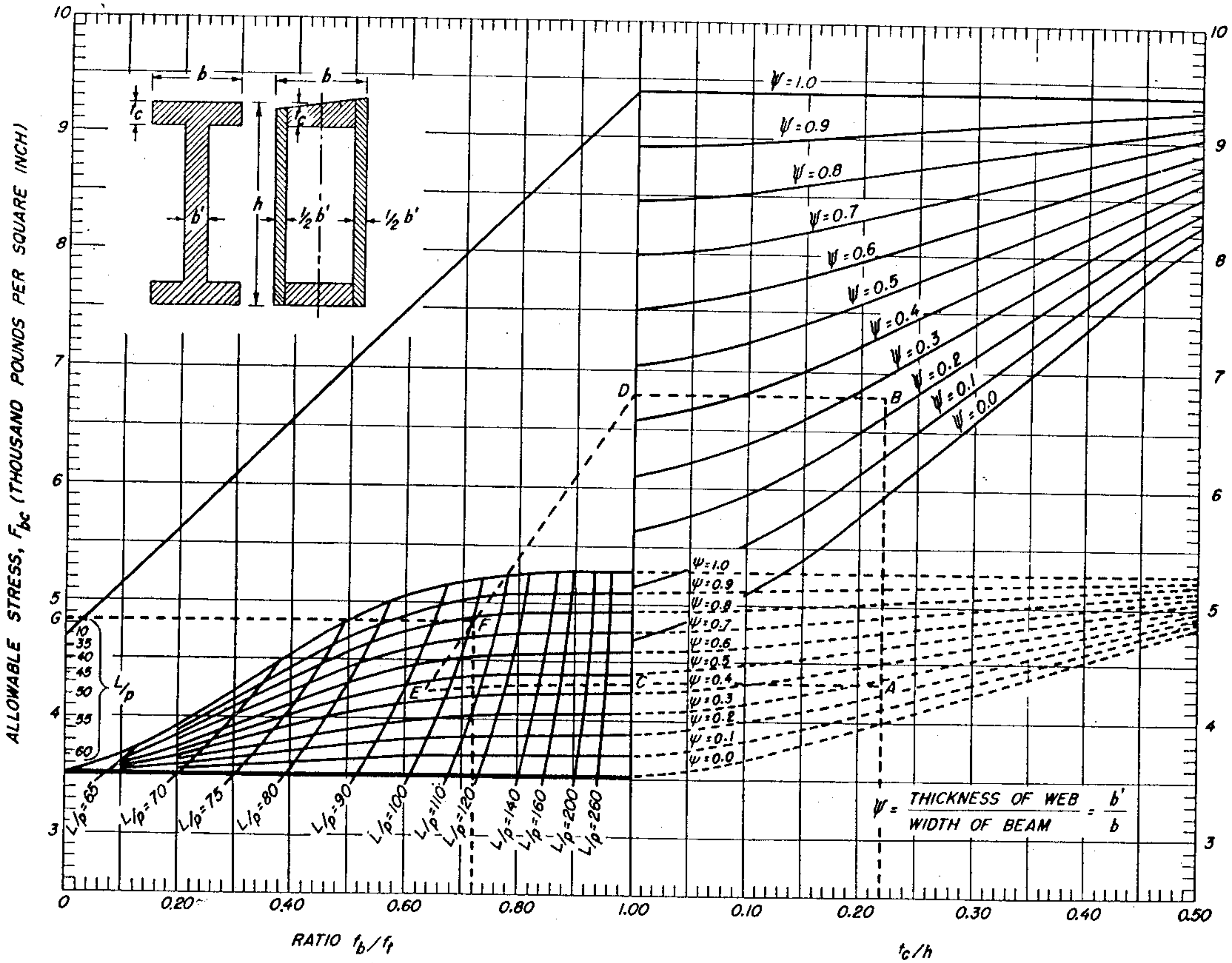

Figure 2–8. Allowable stresses for Sitka spruce spars subjected to combined bending and compression at 15 percent moisture content.

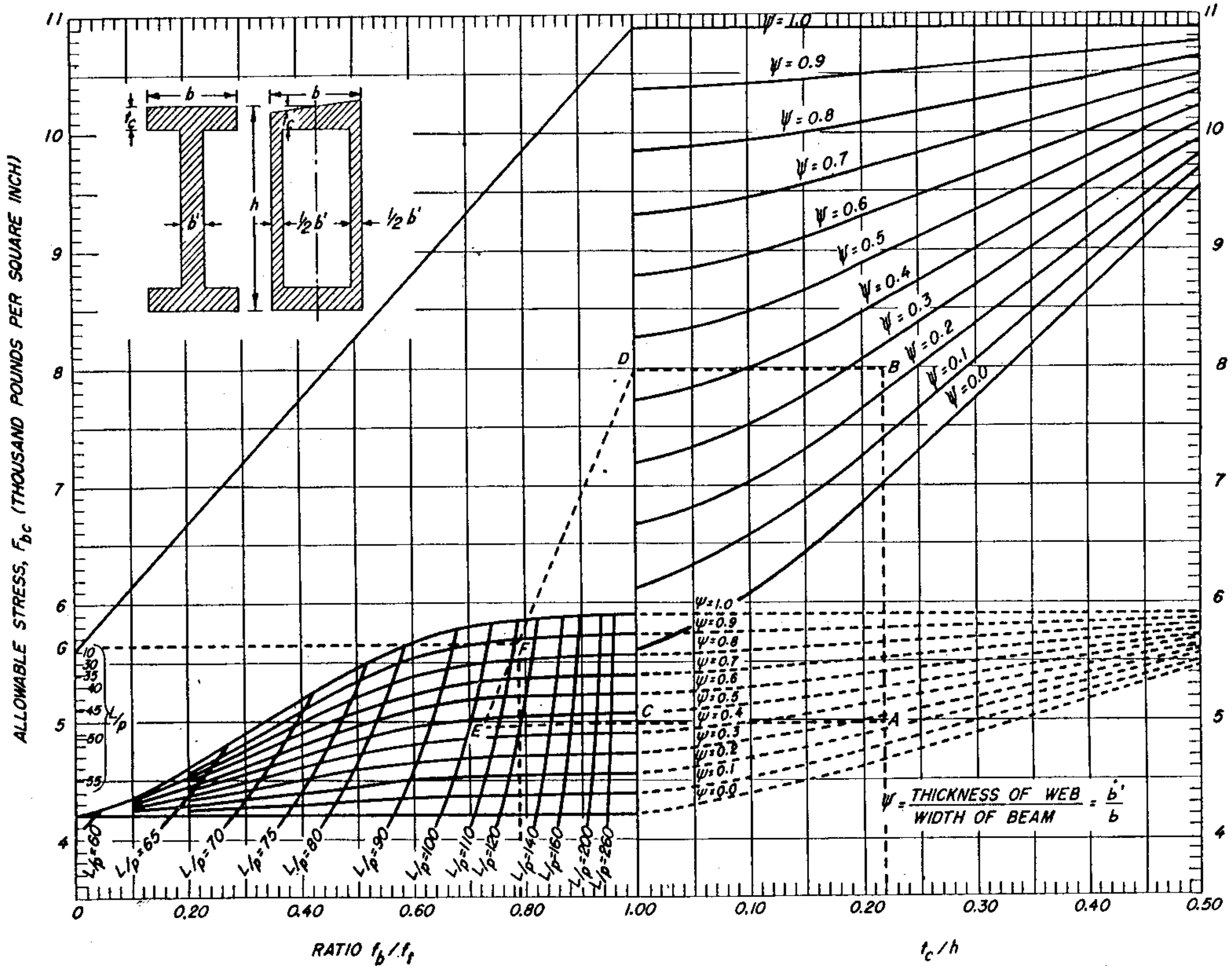

Figure 2–9. Allowable stresses for Douglas-fir spars subjected to combined bending and compression at 15 percent moisture content.

(3) Locate a point, such as E, indicating the proportional limit of the given section under combined bending and compression. This point will be at the intersection of the curve of the "horizontal" family through C and the curve of the slenderness ratio corresponding to the distance between points of inflection.

(4) Draw line ED.

(5) Locate point F on line ED, with an abscissa equal to the computed ratio of bending to total stress. The ordinate of F represents the desired value of the allowable stress.

The following rules should be observed in the use of figures 2–8 and 2–9:

(1) The length to be used in computing the slenderness ratio, L/ρ should be determined as follows:

(*a*) If there are no points of inflection between supports, L should be taken as the distance between supports.

(*b*) If there are two points of inflection between supports, L should be taken as the distance between these points of inflection when calculating the allowable strength of any section included therein.

(*c*) When calculating the allowable strength of a section between a point of inflection and an intermediate support of a continuous beam, L should be taken as the distance between the points of inflection adjacent to the support on either side.

(*d*) When investigating a section adjacent to an end support, L should be taken as twice the distance between the support and the adjacent point of inflection, except that it need not exceed the distance between supports.

(2) In computing the value of ρ for use in determining the slenderness ratio, L/ρ, filler blocks should be neglected and, in the case of tapered spars, the average value should be used.

(3) In computing the modulus of rupture and the proportional limit in bending, the properites of the section under investigation should be used. Filler blocks may be included in the section for this purpose. When computing the form factor of box spars the total thicknesses of both webs should be used.

2.322. *Bending and tension.* When tensile axial loads exist, the maximum computed stress on the tension flange should not exceed the modulus of rupture of a solid beam in pure bending. Unless the tensile load is relatively large, the compression flange should also be checked, using the modulus of rupture corrected for form factor.

2.33. SHEAR WEBS. See section 2.73.

2.34. BEAM SECTION EFFICIENCY. In order to obtain the maximum bending efficiency of either I or box beams, the unequal flange dimensions can be determined by first designing a symmetrical beam of equal flanges. The amount of material to be transferred from the tension side to the compression side, keeping the total cross-sectional area, height, and width constant, is given by the following equation (ref. 2–62):

$$x=\frac{Abh^2-\sqrt{A^2b^2h^4-4AI_sbhwD}}{2wDbh} \qquad (2{:}23)$$

where

A = total area of the cross section
b = total width
h = total depth
w = width of flange
D = clear distance between flanges
I_s = moment of inertia of the symmetrical section
x = thickness to be taken from tension flange and added to compression flange

In using this equation, the following procedure is to be followed:

(*a*) Determine the section modulus required.

(*b*) Determine the sizes of flanges of equal size to give the required section modulus.

(*c*) Using equation (2:23), compute the thickness of material to be transferred from the tension flange to the compression flange. The procedure thus far will result in a section modulus greater than required. To obtain a beam of the required section modulus, either (*d*) or (*e*) may be followed.

(*d*) Calculate the ratio of depth of tension flange to compression flange and design a section having flanges with this ratio and the required section modulus, or

(*e*) Carry out steps (*a*), (*b*), and (*c*) starting with a symmetrical section having a section modulus less than that required until an unsymmetrical section having the required section modulus is obtained.

(*f*) Beams designed according to the foregoing procedure should always be checked for adequacy of glue area between webs and tension flange. This consideration may govern the thickness of the tension flange.

2.4. Torsion

2.40. GENERAL. The torsional deformation of wood is related to the three moduli of rigidity, G_{LT}, G_{LR}, and G_{RT}. When a member is twisted about an axis parallel to the grain, G_{RT} is not involved; when twisted about an axis radial to the grain direction, G_{LT} is not involved; when twisted about an axis tangential to the grain direction, G_{LR} is not involved. No general relationship has been found for the relative magnitudes of G_{LR}, G_{LT}, and G_{RT} (table 2–9).

2.41. TORSIONAL PROPERTIES. The "mean modulus of rigidity" (G) taken as 1/16 of E_L, may be safely used in the standard formulas for computing the torsional rigidities and internal shear stresses of solid wood members twisted about an axis parallel to the grain direction. Torsion formulas for a number of simple sections are given in table 2–10. For solid-wood members the allowable ultimate torsional shear stress (F_{st}) may be taken as the allowable shear stress parallel to the grain (column 14 in tables 2–6 and 2–7) multiplied by 1.18: that is, $F_{st}=1.18\ F_{su}$. The allowable torsional shear stress at the proportional limit may be taken as two-thirds of F_{st}. The torsional strength and rigidity of box beams having plywood webs are given in section 2.75.

Table 2–10. Formulas for torsion on symmetrical sections

Section	Angle of twist in radians	Maximum shear stress
Circle	$\theta=\frac{32TL}{G\pi D^4}$	$f_s=\frac{16T}{\pi D^3}$
Circular tube	$\theta=\frac{TL}{GI_p}$	$f_s=\frac{TD}{2I_p}$
Ellipse [1]	$\theta=\frac{TL(a+b)}{G\pi a^3b^3}$	$f_s=\frac{2T}{\pi ab^2}$ at ends of short diameter
Square [2]	$\theta=\frac{TL}{2.25Ga^4}$ (approx.)	$f_s=\frac{3T}{5a^3}$ (approx.)
Rectangle [3]	$\theta=\frac{40I_pTL}{A^4G}$ (approx.)	$f_s=\frac{T(15a+9b)}{40a^2b^2}$ at midpoint of long side

[1] $2a$=major axis: $2b$=minor axis.
[2] $2a$=side of square.
[3] $2a$=long side, $2b$=short side.

2.5. Basic Strength and Elastic Properties of Plywood

2.50. GENERAL. Plywood is usually made with an odd number of sheets or plies of veneer with the grain direction of adjacent plies at right angles. Depending upon the method by which the veneer is cut, it is known as rotary-cut, sliced, or sawed veneer. Generally, the construction is symmetrical; that is, plies of the same species, thickness, and grain direction are placed in pairs at equal distances from the central ply. Lack of symmetry results in twisting and warping of the finished panel. The disparity between the properties of wood in directions parallel to and across the grain is reduced by reason of the arrangement of the material in plywood. By placing some of the material with its strong direction (parallel to grain) at right angles to the remainder, the strengths in the two directions become more or less equalized. Since shrinkage of wood in the longitudinal direction is practically negligible, the transverse shrinkage of each ply is restrained by the adjacent plies. Thus, the shrinking and swelling of plywood for a given change in moisture content is less than for solid wood.

The tendency of plywood to split is considerably less than for solid wood as a result of the cross-banded construction. While many woods are cut into veneer, those species which have been approved for use in aircraft plywood are listed in table 2–11.

2.51. ANALYSIS OF PLYWOOD STRENGTH PROPERTIES. The analysis of the strength and elastic properties of plywood is complicated by the fact that the elastic moduli of adjacent layers are different. This is illustrated in figure 2–10 for bending of a three-ply panel. Assuming that strain is proportional to distance from the neutral axis, stresses on contiguous sides of a glue joint will be different by reason of the difference in the modulus of elasticity in adjacent layers. This results in a distribution of stress across the cross section as shown in figure 2–10 (c). Similar irregular stress distribution will be obtained for plywood subjected to other types of loading.

From this it may be seen that the strength and elastic properties of plywood are dependent not only upon the strength of the material and the dimensions of the member, as for a solid piece, but also upon the number of plies, their relative thickness, and the species used in the individual plies. In addition, plywood may be used with the direction of the face plies at angles other than 0° or 90° to the direction of principal stress and, in special cases, the grain direction of adjacent plies may be oriented at angles other than 90°.

In general, plywood for aircraft use has the grain direction (the longitudinal direction) of adjacent plies at right angles. The strength and elastic properties of the plywood are dependent upon the properties of solid wood along and across the grain as illustrated in figure 2–11.

Considerable information (tables 2–6 and 2–7) on the properties of wood parallel to the grain is available, but the data on properties across the grain are less complete. Sufficient data are available, however, so that the elastic properties of wood in the two directions can be related with reasonable accuracy to the plywood properties. On this basis formulas are given which will enable the designer, knowing the number, relative thickness and species of plies, to compute the properties of plywood from the data given in tables 2–6 and 2–7.

The formulas given are only for plywood having the grain direction of adjacent plies at right angles and are applicable only to certain directions of stress. The limitations on the angle between the face grain and the direction of principal stress have been noted in each section. The formulas are intended for use only in these cases, and the interpolation must not be used to obtain values for intermediate angles unless specific information on these angles is given. Computed values of certain of the strength and elastic properties for many of the commonly used species and constructions of plywood are given in section 2.54, based on strength of wood at 15 percent moisture content (table 2–6).

2.52. BASIC FORMULAS. For purposes of discussion, plywood structural shapes may be conveniently separated into two groups: (a) elements acting as prisms, columns, and beams, and (b) panels. The fundamental difference between these two groups is that, in group (a) the plywood is supported or restrained only on two opposite edges, while in group (b) the plywood is supported

Table 2–11. Veneer species for aircraft plywood

Group I (high density) [1] [2]	Group II (medium density) [2]	Group III (low density) [3]
American beech	Birch (Alaska and paper)	Basswood.
Birch (sweet and yellow)	Khaya species (so-called "African mahogany").	Yellow-poplar.
Maple (hard)	Southern magnolia	Port Orford White-cedar.
Pecan	Mahogany (from tropical America).	Spruce (red, Sitka, and white) (quarter-sliced).
	Maple (soft)	Ponderosa pine (quarter-sliced).
	Sweetgum	Sugar pine.
	Water tupelo	Noble fir (quarter-sliced).
	Black walnut	Western hemlock (quarter-sliced).
	Douglas-fir (quarter-sliced)	Redwood (quarter-sliced).
	American elm (quarter-sliced)	
	Sycamore	

[1] Where hardness, resistance to abrasion, and high strength of fastening are desired, Group I woods should be used for face stock.
[2] Where finish is desired, or where the plywood is to be steamed and bent into a form in which it is to remain, species of Group I and II should be used.
[3] Group III species are used principally for core stock and cross-banding. However, where high bending strength or freedom from buckling at minimum weight is desired, plywood made entirely from species of Group III is recommended.