Designation: D 3737 – 00a

Standard Practice for Establishing Stresses for Structural Glued Laminated Timber (Glulam)[1]

This standard is issued under the fixed designation D 3737; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers the procedures for establishing allowable design stresses for structural glued laminated timber. Properties considered include bending, tension and compression parallel to the grain, modulus of elasticity, horizontal shear, and compression perpendicular to the grain.

1.2 This practice is limited to the calculation of design stresses for glulam subject to the given procedures for the selection and arrangement of grades of lumber of the species considered.

1.3 Requirements for production, inspection, and certification are not included, but in order to justify the design stresses developed using procedures in this practice, manufacturer must conform to recognized manufacturing standards for glulam. Refer to ANSI/AITC A190.1 and CSA 0122.

1.4 Stresses established by use of this practice are based on dry conditions of use (12 % average with less than 16 % moisture content). Modifications for wet-use conditions are given in 9.2.

1.5 The values stated in inch-pound units are to be regarded as standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 198 Test Methods of Static Tests of Timber in Structural Sizes[2]

D 245 Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber[2]

D 2395 Test Methods for Specific Gravity of Wood and Wood-Base Materials[2]

D 2555 Test Methods for Establishing Clear Wood Strength Values[2]

D 2915 Practice for Evaluating Allowable Properties for Grades of Structural Lumber[2]

D 4761 Test Method for Mechanical Properties of Lumber and Wood-Base Structural Material[2]

E 105 Practice for Probability Sampling of Materials[3]

2.2 *Other Standards:*

ANSI/AITC A190.1 Structural Glued Laminated Timber[4]

CSA 0122 Structural Glued Laminated Timber[5]

3. Terminology

3.1 *Definitions:*

3.1.1 *E-rated lumber*—lumber graded for laminating by nondestructive measurement for a modulus of elasticity (*E*) and by visual inspection in accordance with the grading rules of the applicable grading or inspection agency.

3.1.2 *glulam*—a term used to denote structural glued laminated timber, which is a material glued up from suitably selected and prepared pieces of wood either in a straight or curved form with the grain of all pieces essentially parallel to the longitudinal axis of the member.

3.1.3 *horizontally laminated timber*—a glulam member designed to resist bending loads applied perpendicularly to the wide faces of the laminations.

3.1.4 *lamination*—a layer of lumber within the glued laminated timber.

3.1.5 *modulus of elasticity (E)*—for laminating, *E* is divided into two categories to distinguish mode of measurement and application.

3.1.6 *long-span E*—the *E* calculated from deflection measured in a flat-wise test of lumber with a center point loading and a span-depth ratio ($1/d$) of approximately 100.

3.1.7 *member E*—the design *E* of the finished glued laminated member as defined in this practice.

3.1.8 *vertically laminated timber*—a glulam member designed to resist bending loads applied parallel to the wide faces of the laminations.

3.1.9 *visually graded lumber*—lumber graded by visual inspection in accordance with the grading rules of the applicable grading or inspection agency.

3.2 *Symbols:*

[1] This practice is under the jurisdiction of ASTM Committee D7 on Wood and is the direct responsibility of Subcommittee D07.02 on Lumber and Engineered Wood Products.

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[2] *Annual Book of ASTM Standards*, Vol 04.10.

[3] *Annual Book of ASTM Standards*, Vol 14.02.

[4] Available from the American Institute of Timber Construction, 11818 S.E. Mill Plain Blvd., Suite 415, Vancouver, WA 98684.

[5] Available from the Canadian Standards Association, 178 Rexdale Blvd., Rexdale, Ontario, Canada, M9W 1R3.

GDE = ratio of the cross-sectional area of the local grain deviation (which may or may not be associated with a knot) at the edge of the lumber to the cross-sectional area of the lumber (see Fig. 1).
GDC = ratio of the cross-sectional area of the local grain deviation (which may or may not be associated with a knot) away from the edge of the lumber to the cross-sectional area of the lumber (see Fig. 1).
GDS = projected sum of all *GDE* and *GDC* values within a one-foot length of lumber as illustrated in Fig. 1.
KE = ratio of cross-sectional area of knot at the edge of the wide face of lumber to the cross-sectional area of the lumber (see Fig. 2).
KC = ratio of the cross-sectional area of knot located away from the edge of the lumber to the cross-sectional area of the lumber. When a knot at the edge of the wide face and a knot located away from the edge are in the same cross section, the combination of the two shall be used in determining *KC* (see Fig. 2).
SMF = stress modification factor of a beam.
$SR_{t\,1}$ = strength ratio of the tension lamination at the outermost fiber.

4. Requirements for Laminations

4.1 Separate laminations shall not exceed 2 in. (51 mm) in net thickness. Lumber may be end-jointed to form any length of lamination or placed edge-to-edge to form any width, or both. Lumber must be edge-glued unless it can be shown by calculations or experimental data that unglued edge joints meet the structural performance requirements of the glulam members for the intended use.

4.2 All lumber used shall be graded prior to laminating the member and suitably marked or segregated to identify its grade. When pieces are ripped, each piece shall be regraded and suitably marked or segregated.

4.3 The effect of decay or compression failure upon strength cannot be readily determined, thus these defects shall be prohibited from laminating grades insofar as existing inspection and grading technology permit. Firm white speck or light white pocket is permissible in grades of lumber that permit knots to occupy up to one third or more of the cross section provided their extent in combination with knots does not exceed that of the largest edge knot permitted. The exception is that firm white speck and light white pocket shall be excluded from end joints in tension members and the outer 10 % of the total depth on the tension side of bending members.

4.4 Compression wood in readily identifiable and damaging form shall be limited in laminating grades.

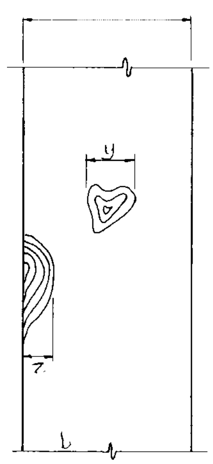
4.4.1 For dry conditions of use, grades permitting knots up to one half of the cross section may contain streaks of compression wood occupying as much as 20 % of the cross section. Streaks of compression wood up to one eighth of the cross section may be permitted in other grades.

4.4.2 For wet conditions of use, or for pressure-treated members, the conditions of 4.4.1 apply except that compression wood is limited to 5 % of the cross section in tension members and in the outer 10 % of the total depth on the tension side of bending members.

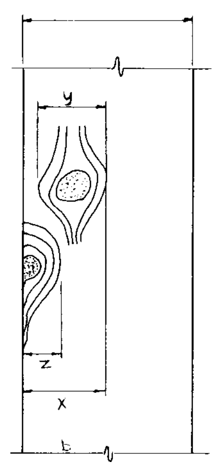
4.5 Lumber shall be free of shakes and splits that make an angle of less than 45° with the wide face of the piece. Pitch pockets shall be limited in size to the area of the largest knot permitted, and pitch streaks shall be limited to one sixth of the width of the lumber.

4.6 For wet-use conditions, significant amounts of wane are limited to that which will be removed upon final surfacing of the member. For dry-use conditions, wane up to one sixth the width of the lumber is permitted at each edge provided the allowable shear strength is adjusted to consider this unbonded region.

4.7 The range of moisture content of lumber for assembly



(*a*)

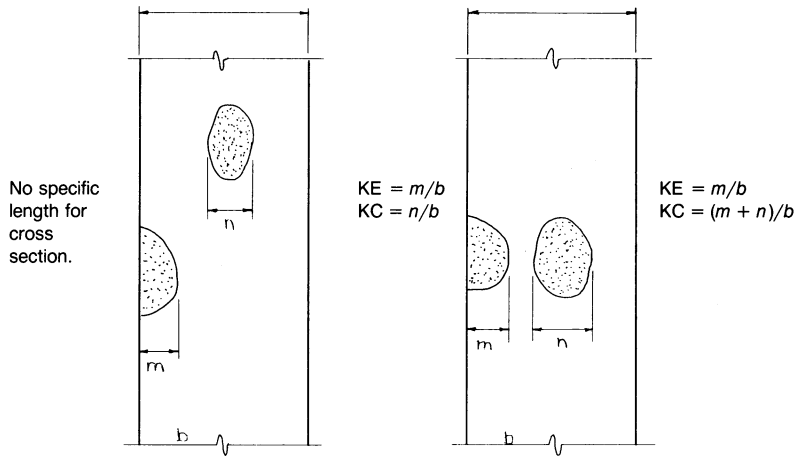


(*b*)

GDC = *y/b*
GDE = *z/b*
GDS = *x/b* where $x = y + z$
(*a*) Example of grain deviations not associated with a knot where the projected grain deviations do not overlap.

GDC = *y/b*
GDE = *z/b*
GDS = *x/b* where $x < y + z$
(*b*) Example of grain deviations associated with knots where the projected grain deviations overlap.

FIG. 1 Knot and Grain Deviation Measurement at the Outer 5 % on the Tension Side of a Member Occurring in a 1-ft Length



NOTE 1—When edge knots and centerline knots occur at the same cross section, the sum of the edge knots and centerline knots is used in calculating KC as shown in (b).

FIG. 2 Knot Measurement for the Next Inner 5 % on the Tension Side of a Bending Member

into a single member shall not exceed five percentage points, except when all of the lumber is 12 % or lower.

5. Knot Data

5.1 Data on knot properties for the grades of lumber to be used are needed in order to determine the design levels for the bending strength of members loaded perpendicular to the wide faces of the laminations (horizontally laminated members), along with compression parallel to the grain. Two different levels of sampling are recognized for collecting these knot data, one during development of a laminating grade and another during the actual use of grade in production of glulam members. Guidelines for sampling material are given in Practice E 105.

5.1.1 *Development*—During the development of the laminating grade, not less than 100 pieces or 1000 lineal ft (300 m) of lumber randomly chosen from a representative group shall be used as a sample for each grade of lumber. No special selection of the pieces should be made; the only requirement is that they meet the grade but not qualify for a higher grade.

5.1.2 *Use*—After the laminating grade has been put in use, not less than 200 pieces of a grade or 2000 lineal ft (600 m) shall be randomly chosen in at least 20 sampling visits to glulam manufacturers representing at least 75 % of the regional production of that grade. This type of survey must be conducted within 3 years of the development survey and used to modify if necessary, combinations based on the development survey. This second level of sampling should not be considered as effective for longer than 10 years. A change of grading rules involving liberalization of knot size limitation requires resampling.

5.1.3 Base knot measurement on a displacement technique. Measurements shall represent the projected cross-sectional area of knots as determined by an average width on the wide faces, or in the case of edge or spike knots, an estimated equivalent displacement.

5.1.4 Determine location and width of all knots larger than ¼ in. (6 mm) for the lumber in the survey.

5.2 Knot data for horizontally laminated combinations must include the average of the sum of all knot sizes within each 1-ft (0.30-m) length, taken at 0.2-ft (60-mm) intervals, and the determination of the 99.5-percentile knot size.

5.3 Knot data for glulam combinations loaded in compression parallel to grain must include the average and the standard deviation for the largest knot size within each 3-ft (0.9-m) length taken at 0.5-ft (0.15-m) interval.

5.4 *Requirements for Evaluation of New Knot Data*—New knot data is reviewed for acceptance to judge the adequacy of the new data to better represent the target populations. Where knot values are already in use, new data may be presented to substantiate, augment, or replace the existing data. The following requirements must be followed in consideration of the new data. A decision sequence (see Appendix X1) is recommended.

5.4.1 *Substantiation*—Where new data is demonstrably well representative of the population, but does not present significant differences stated in Appendix X1, and where existing data is fully documented and not in need of increased precision, the new data analysis may be considered for inclusion to permanent files as substantiation of the specific knot values to which it applies.

5.4.2 *Augment Existing Data*—Where new data is demonstrably well representative of the population, but does not present significant differences as stated in Appendix X1, and where existing data is documented and can be shown to be in need of additional precision, the new data may be combined with existing data to result in a more precise estimate of the respective population parameters.

5.4.3 *Replacement*—Before new knot data may be considered for replacement of existing data, appropriate statistical tests must show that the population was representatively sampled, and that the new data describes the population to be significantly different from the population represented in current use with respect to mean, and 99.5 percentile knot size. In the absence of a representative sample, data may be considered for replacement on the grounds that it represents a more adequate sample or is more completely documented than existing data, or both.

6. Stress Index Values

6.1 *Visually Graded Lumber*—Test Methods D 2555 provide information on clear wood strength properties and their expected variation for small, clear, straight-grained specimens of green lumber. Based on these properties, stress index values are calculated.

6.1.1 Determine the bending stress index by calculating the clear wood stress fifth percentile in accordance with Test Methods D 2555, multiplying by the appropriate factors in Table 1, and furthermore multiplying by 0.743 to adjust to a 12-in. (0.3-m) deep, uniformly loaded simple beam with a 21:1 span-to-depth ratio.

6.1.1.1 Tests of large beams of Douglas Fir-Larch, Southern Pine, and Hem-Fir indicate that the bending stress index based on test and analyses given in Table 2, may be used instead of the procedure in 6.1.1 for Douglas Fir-Larch, grown within the states of Wyoming, Montana, Washington, Idaho, Oregon, and California; for Southern Pine consisting of the four principal species: longleaf, slash, shortleaf, and loblolly; and for Hem-Fir consisting of Western Hemlock, California Red Fir, Grand Fir, Noble Fir, Pacific Silver Fir, and White Fir.

6.1.2 Determine a compression stress index parallel to the grain by calculating the clear wood stress fifth percentile in accordance with Test Methods D 2555 and multiplying by the appropriate factors from Table 1.

6.1.3 Determine a tension by using ⅝ of the bending stress index for 12-in. (0.3-m) deep members obtained in 6.1.1.

6.1.4 Obtain a clear wood modulus of elasticity from an average value for the species or species group from Test Methods D 2555. From that obtain a long-span modulus of elasticity by multiplying by the appropriate factors from Table 1. This factor adjusts values to a span-to-depth ratio of 100:1 and an assumed uniform loading.

6.1.4.1 The modulus of elasticity values in Table 2 are based on testing of large samples of lumber of the species groups listed in 6.1.1.1 and may be used instead of values determined by the method in 6.1.4.

6.1.5 Determine a horizontal shear stress index by calculating the clear wood stress fifth percentile in accordance with Test Methods D 2555 and multiplying by the appropriate factors from Table 1 except that for medium grain, close grain, and dense Douglas Fir-Larch and medium grain and dense Southern Pine as described in Practice D 245, horizontal shear stress of 165 psi (1.15 MPa) for Douglas Fir-Larch, and 200 psi (1.40 MPa) for Southern Pine shall be used for the two species. Coarse-grain material (that is, having less than four rings per inch and not meeting the medium-grain requirements), a value of 140 psi (0.95 MPa) shall be used for these two species groups.

TABLE 1 Adjustment Factors for Clear Wood Stresses (Test Methods D 2555)

Property	Multipliers for Average or Lower Exclusion Limit		Seasoning Factor for a 12 % Average Moisture Content
	Softwoods	Hardwoods	
Bending	0.476	0.435	1.35
Compression parallel to grain	0.526	0.476	1.75
Modulus of elasticity	1.095	1.095	1.20
Horizontal shear	0.244	0.222	1.13

6.1.5.1 As an alternative to 6.1.5, the horizontal shear stress index shall be permitted to be determined from flexural tests of full-size beams in accordance with the principles of Test Methods D 198 with specific loading details as shown in Annex A5. Laminating lumber used in the critical core area of the test beams subjected to maximum shear stresses shall be selected such that it is representative of the population of on-grade lumber used in normal production for the species and grade being evaluated. The required number of samples and the lower 5th percentile tolerance limit of shear strength shall be determined in accordance with Practice D 2915 and the analysis procedures given in Annex A5. The horizontal shear stress index is determined by multiplying the lower 5th percentile tolerance limit of shear strength by 1/2.1.

6.1.6 Determine a compression stress index perpendicular to grain as follows (Ref **1**):[6]

$$F_{c_{\perp}} = (2674\,SG - 551.3)\,(1.9/1.67) \quad (1)$$

where:

$F_{c_{\perp}}$ = compression stress index perpendicular to grain, and

SG = average species green specific gravity from Test Methods D 2555 or, for a species group, the standing timber volume weighted average green specific gravity; reduced as specified in 6.1.6.1 or 6.1.6.2.

6.1.6.1 For purposes of calculating compression perpendicular to grain values for visually graded material, the average green specific gravity of a species or species group which have an average green specific gravity of 0.36 or above shall be reduced by the following amounts for various rates of growth and density to account for variation in the specific gravities.

Dense grain—0.03
Close grain—0.05
Medium grain—0.06
Coarse grain—0.09

6.1.6.2 When the average green (specific gravity) of a species or species group is 0.35 or less, the reductions are as follows:

Close grain—0.03
Medium grain—0.04

6.1.6.3 As an alternative to the provisions for specific gravity selection of Practice D 245, lumber may be qualified as dense by weighing. The lumber specific gravity shall be adjusted to a green condition using Test Methods D 2395, Appendix XI conversion formula to meet the minimum specific gravity as specified in 6.1.6.1. The minimum shall be used in Eq 1 to determine compression perpendicular to grain clear wood stresses.

6.2 *E-rated lumber*—This practice is based on lumber that has been *E*-rated and visually graded in accordance with Annex A1. *E*-rated lumber is designated by the size of the edge characteristics permitted in the grade and the modulus of elasticity such as ⅙-1.9*E*, ¼-1.6*E*, etc. Edge characteristics include knots, knot holes, burls, distorted grain or decay partially or wholly at edges of wide faces.

[6] The boldface numbers in parentheses refer to the references at the end of this practice.

TABLE 2 Bending Stress Index Based on Large Beam Tests and Modulus of Elasticity Values for Visually Graded Lumber

NOTE 1—Appendix X1 provides one method of developing new data.

Species	Growth Classification[A]	Bending Stress Index[B]		Modulus of Elasticity	
		psi	MPa	million psi	MPa
Douglas Fir-Larch	medium grain	3000	20.7	1.9	13 100
	close grain	3250	22.4	2.0	13 800
	dense	3500	24.1	2.1	14 500
Southern Pine	coarse grain[C]	2000	13.8	1.5	10 300
	medium grain	3000	20.7	1.8	12 400
	dense	3500	24.1	2.0	13 800
Hem-Fir	medium grain	2560	17.7	1.7	11 700
	dense[D]	3000	20.7	1.8	12 400

[A] Classification for "dense" wood shall follow Practice D 245.
[B] Values shown are based on full-size beam tests. As a result, these values incorporate the effects of some features such as grain deviations in lumber along with influences of end and face bonding influences. Beams designed using these values and tested in accordance with Methods D 198 will yield strength values such that the lower fifth percentile will exceed the design bending stress by a factor of 2.1 with 75 % confidence. Analysis of test data assumed a log normal distribution. For unsymmetric combinations, tests have shown that values up to 40 % higher than those listed may be applied to the compression side of bending members.
[C] Also applicable to minor species of southern pine regardless of growth rate.
[D] Specific gravity, based on oven-dry weight and volume at 12 % moisture content, must equal or exceed 0.39.

6.2.1 Bending stress indexes for *E*-rated lumber shall be determined based on methods given in Ref **(2)**.

6.2.1.1 Bending stress indexes for some long span *E* values are given in Table 3.

6.2.2 Compression stress indexes parallel to grain are included in Table 3.

6.2.3 Determine a tension by using ⅝ of the bending stress index for 12-in. (0.3-m) deep members obtained in 6.2.1.

6.2.4 The modulus of elasticity for *E*-rated lumber shall be the long span *E* as defined as 3.1.7.1.

6.2.5 The horizontal shear stress index is determined in the same manner as for visually graded lumber in 6.1.5.

6.2.6 The stress indexes in compression perpendicular to grain for *E*-rated lumber are determined by comparing with the long span of grade listed in Table 2. When the modulus of elasticity equals or exceeds that of the dense classification for the species, the stress index for the dense visual grade of the species or species group is used. The same procedure is used for close grain, medium grain and coarse grain. When the long *E* of the *E*-rated grade of lumber is less than the average *E* of the species or species groups, but no less than 300 000 psi below the average, use the compression perpendicular to grain value determined for medium grain lumber. When the long span *E* is less than the average *E* minus 300 000 psi, determine the compression perpendicular to grain values by using a specific gravity of 0.8 times the average specific gravity of the species in solving Eq 1. (The value obtained is approximately the same as that used for coarse grain lumber.)

6.2.6.1 As an alternative to 6.2.6, the allowable property for compression perpendicular to grain may be determined in accordance with the applicable provisions of Refs (**1, 3** and **4**).

TABLE 3 Bending Stress Indexes and Compression Stress Index Parallel to Grain for *E*-Rated Lumber Used in Laminating[A]

Long Span, E, psi	Bending Stress Index,[A] psi	Compression Stress Index Parallel to Grain,[B,C] psi
1 600 000	2560	1900
1 900 000	3000	2400
2 100 000	3500	2800
2 300 000	4000	3100

[A] Values shall be not higher than obtained by interpolation for intermediate *E* values.
[B] Values are for 12-in. deep members at 12 % moisture content (dry).
[C] Values are for members at 12 % moisture content (dry) values.

6.2.7 Radial tension perpendicular to grain is the same as determined for visually graded lumber in 6.1.7.

7. Procedure for Determining Stress Modification Factor (SMF) for Glulam Made of Visually Graded Lumber

7.1 For some properties, knots, slope of grain, and other factors act to reduce strength values derived in Section 6 to values below the stress index values. Conversely, some properties are not affected by these characteristics and no reduction is necessary.

7.2 *Bending Stress Modification Factor*— The bending stress modification factor is the lower of the two stress modification factors determined on the basis of knots and on the basis of slope of grain.

7.2.1 The bending stress modification factor for members loaded perpendicularly to the wide faces of the laminations (horizontally laminated beams):

7.2.1.1 *Knots*—Knots will affect strength less if located in laminations near the neutral axis than in outer laminations. Thus, the influence of knots depends both on their size and position and is best measured by their moment of inertia. Tests of glulam beams have provided an empirical relationship between the ratio I_K/I_G and bending strength. I_K is defined as the moment of inertia of all knots within 6 in. (152 mm) of critical cross section and I_G is the gross moment of inertia. Procedures for calculating values of I_K/I_G ratios are given in Annex A2 and Refs (**2** and **5**). Determine the bending stress modification factor from the following empirical relationship:

$$SMF_b = (1 + 3R)(1 - R)^3(1 - R/2) \quad (2)$$

where:
SMF_b = bending stress modification factor, and
R = I_K/I_G ratio.

7.2.1.2 *Slope of Grain*—Stress modification factors associated with various slopes of grain are given in Table 4. Those given for tension apply to lumber in the tension side of bending members while those given for compression apply to that in the compression side.

7.2.1.3 The value of SMF_b shall be equal to or greater than the strength ratio in flatwise bending as determined by formula X1.2 in Practice D 245.

TABLE 4 Parallel to Grain Stress Modification Factors Associated with Slope of Grain for Designing Glulam Combinations

Slope of Grain	Stress Modification Factor	
	Tension	Compression
1:4	0.27	0.46
1:6	0.40	0.56
1:8	0.53	0.66
1:10	0.61	0.74
1:12	0.69	0.82
1:14	0.74	0.87
1:15	0.76	1.00
1:16	0.80	1.00
1:18	0.85	1.00
1:20	1.00	1.00

7.2.1.4 Special tension lamination grades of lumber as described in Section 11 are required to justify the stress modification factor calculations.

7.2.2 The bending stress modification factor for members loaded parallel to the wide faces of the laminations (vertically laminated beams):

7.2.2.1 *Knots*—Determine the effect of knots on vertically laminated beams of a single grade of lumber by calculating a stress modification factor, SMF, by the following empirical relationship (see Ref **(6)** for further details):

$$\text{SMF} = C_1 (SR_1{}^{\gamma})(N^{\alpha})(1 - 1.645\Omega_1/N^{1/2}) \tag{3}$$

where:
C_1 = empirical constant from Table 5,
SR_1 = strength ratio from Practice D 245 for an individual piece of lumber loaded on edge,
γ = empirical constant equal to 0.81,
α = $0.329(1 - 1.049\text{SR}_1)$,
N = number of laminations up to 5. Use $N = 5$ for members with five or more laminations, and
Ω_1 = coefficient of variation of bending strength for one lamination. The coefficient of variation for one lamination of visually graded lumber = 0.36.

7.2.2.2 *Slope of Grain*—Bending stress modification factors associated with various slopes of grain are equal to those for tension stress in Table 4 assuming the steepest slope of grain permitted in the grade.

7.3 *Stress Modification Factor in Compression Parallel to the Grain*:

7.3.1 The stress modification factor is the lower of the two stress modification factors determined separately from both knots and slope of grain.

7.3.2 *Knots*—Tests have shown that axial compressive strength of short glulam compression members is related to the percent of the cross section occupied by the largest knot for individual laminations. Procedures for estimating values of this percentage for glulam compression members are given in Annex A3. Derive the stress modification factor in compression from the following empirical relationship.

$$SMF_c = Y^3/4 - Y^2 - Y/4 + 1 \tag{4}$$

where:
SMF_c = compression stress modification factor, and
Y = knot size at the 99.5 percentile, expressed in a decimal fraction of the dressed width of lumber used for the lamination.

For members with grades of lumber placed unsymmetrically, an additional adjustment such as given in Annex A3 is necessary to compensate for additional bending stresses.

7.3.3 *Slope of Grain*—Stress modification factors in compression associated with various slopes of grain are given in Table 4. When compression members consist of different grades, determine a weighted average stress modification factor.

7.3.4 The stress modification factor in compression parallel to grain for members of two or three laminations of the same grade of lumber shall be that determined by the procedure in Practice D 245 for a single piece of lumber of the grade being used.

7.4 *Stress Modification Factor in Tension Parallel to the Grain*:

7.4.1 The stress modification factor to use in design is the lower of the two stress modification factors determined on the basis of knots and on the basis of slope of grain.

7.4.2 *Knots*—Determine the stress modification factor in tension as governed by knots as follows:

$$SMF_t = 1 - Y_2 \tag{5}$$

where:
SMF_t = tensile stress modification factor, and
Y_2 = maximum edge knot size permitted in the grade expressed in a decimal fraction of the dressed width of the wide face of the piece of lumber used for the lamination. (Centerline knot size shall be limited to that resulting in an equivalent edgewise bending strength ratio as determined by Practice D 245.)

7.4.3 *Slope of Grain*—Stress modification factors in tension are given in Table 4.

7.5 *Modulus of Elasticity (E)*:

7.5.1 The *E* of glulam members is directly dependent upon the *E* of laminations used in its manufacture. Standard conditions for laminations shall be a 100:1 span-depth ratio under center-point loading. Under these conditions, *E* is essentially unaffected by shear deformations and approaches the true modulus of elasticity. *E* values determined by other methods may be adjusted using Practice D 2915. Adjustment factors for *E* of different grade laminations are given in Table 6 and depend upon the bending strength ratio of the individual pieces determined in accordance with Practice D 245.

7.5.1.1 The *E* values given in Table 2 may be used as alternatives to those determined by the method in 7.5.1. These values were determined by surveys of laminating grades adjusted to standard values.

TABLE 5 Constant Used to Adjust Vertically Laminated Bending Strength Ratio

Strength Ratio (SR_1)	C_1
0.45 or greater	1.238
0.40	1.292
0.35	1.346
0.30	1.400
0.26 or less	1.444

TABLE 6 Grade Adjustment Factors for Modulus of Elasticity

Bending Strength Ratio[A]	Adjustment Factor
0.55 or greater	1.00
0.45 to 0.54	0.90
0.44 or less	0.80

[A] Determined in accordance with Practice D 245.

7.5.2 Member *E* values for axially loaded symmetric combinations of glulam members shall be assumed to be the weighted average of the component lumber used in the member.

7.5.3 Member *E* values applicable to vertically laminated bending combinations shall be 95 % of the average of the laminations.

7.5.4 Member *E* values applicable to horizontally laminated bending combinations shall be 95 % of the value calculated by a transformed section analysis (Annex A2).

7.6 *Horizontal Shear*:

7.6.1 By restricting shakes and splits as given in 4.5, the stress modification factor for horizontal shear in horizontally laminated members can be assumed to be 1.0.

7.6.1.1 For wet-use conditions, wane is limited to amounts that will clean off during surfacing and a stress modification factor of 1.0 is applicable. Wane up to one sixth of the width may be permitted along each edge of laminations for dry-use members only. In these members, the stress modification factor in horizontal shear shall be limited to the ratio of the wane-free width to total width based on actual lumber dimensions. For example, permitting wane along one sixth of the width on the face of the lamination at each edge results in a stress modification factor of two thirds.

7.6.2 For vertically laminated members consisting of four or more laminations, one out of four pieces is assumed to have a check or split that limits its strength ratio in shear to ½ resulting in a stress modification factor of the composite of ⅞. For two and three lamination beams, the stress modification factor is ¾ and ⅚, respectively. When species having different shear properties are combined in a glued laminated timber, use a weighted average to determine the clear wood stress in shear.

7.7 *Compression and Radial Tension Perpendicular to Grain*—A stress modification factor of 1.0 shall be applicable to glulam combinations.

8. Procedure for Determining Stress Modification Factor (SMF) for Glulam Made of *E*-Rated Lumber

8.1 The determination of the stress modification factor for glued laminated timbers made with *E*-rated lumber is similar to that for visually graded lumber except that the effect of slope of grain is accounted for in the *E* value and slope of grain stress modification factors are not used. However, the tension laminations prescribed for the outer 5 % of bending members have specific slope of grain restrictions. See 11.2.3.1.

8.2 *Bending Stress Modification Factor*:

8.2.1 *Horizontally Laminated Members*— Determine the bending stress modification factor by the I_K/I_G method used for members made of visually graded lumber as shown in Annex A2.

8.2.1.1 The minimum stress modification factor shall not be less than the stress modification factor given in Table 7 for members 15 in. or less in depth. The minimum value for SMF_b shall not be less than 0.50 for members of greater depths.

TABLE 7 Minimum Bending and Compression Parallel to Grain Stress Modification Factors for Members of *E*-Rated Lumber

	Minimum Stress Modification Factor (SMF) Bending		
E-Grade[A] Designation	Horizontally Laminated Members	Vertically Laminated Members	Compression[B] Parallel to Grain
⅙	0.70	0.70	0.70
¼	0.65	0.65	0.70
½	0.50	0.25	0.50

[A] The second part of the *E*-grade designation (for example, 2.0-⅙) indicates fraction of cross section that can be occupied by edge characteristics which include knots, knot holes, burls, distorted grain, or decay partially or wholly at edges of wide faces.

[B] Values are for members of two or more laminations.

8.2.2 Determine the stress modification factor for vertically laminated members by use of Eq 3. The coefficient of variation Ω_1 for *E*-rated lumber for use in Eq 3 is 0.24, except where the edge characteristics occupy *one half* of the cross section; in which case, the coefficient of variation is the same as for visually graded lumber (0.36).

8.3 *Stress Modification Factor in Compression Parallel to Grain*:

8.3.1 The stress modification factor is based on a knot frequency study as shown for visually graded lumber in 7.3.2 and Annex A3.

8.4 *Stress Modification Factor in Tension Parallel to Grain*:

8.4.1 Determine the strength ratio in tension that is governed by knots as follows:

$$SMF_t = 1 - Y_2 \qquad (6)$$

where:

SMF_t = tensile stress modification factor, and

Y_2 = maximum edge knot size permitted in the grade expressed in a decimal fraction of the dressed width of the wide face of the piece of lumber used for the lamination.

8.5 *Modulus of Elasticity (E)*:

8.5.1 For designations of various terminology used with measurement and classification of *E* values, see 3.1.5 and Annex A1.

8.5.2 Member *E* values for axially loaded symmetric combinations shall be assumed to be the weighted average of the component lumber used in the member.

8.5.3 Member *E* values applicable to vertically laminated bending combinations shall be 95 % of the average of the laminations.

8.5.4 Member *E* values applicable to horizontally laminated bending combinations shall be 95 % of the value calculated by a transformed section analysis (Annex A2).

8.6 *Horizontal Shear*—The stress modification factor for horizontal shear is determined in the same manner used for visually graded lumber in 7.6.

8.7 *Compression and Tension Perpendicular to Grain*—A stress modification factor of 1.0 shall be applicable to glulam combinations.

9. Qualification of Laminations by Test

9.1 If lumber is to be qualified by test as equivalent to visually graded or *E*-rated laminations, procedures in Section 9 shall be followed. Tests shall include tensile strength, long span *E*, specific gravity, compression perpendicular to the grain, and shear strength.

9.1.1 Qualification shall be carried out on the size and grade of product for which qualification is desired, except that qualification at a specific width will satisfy qualification requirements for the next smallest width.

9.1.1.1 If qualification of a width by test is used to qualify the next smaller width, selection criteria for the grade of both widths must be identical.

NOTE 1—As an example, qualification of a ⅙-2.0*E* grade in nominal 2 by 6 may qualify the same grade in 2 by 4 if the same edge knot and *E* selection criteria are used.

9.1.1.2 Principles of Practice D 2915 shall be followed in sampling. A minimum of sample size of 58 is required for tensile strength; a minimum sample of 50 is required for all other properties.

9.2 *Flatwise Bending Test*:

9.2.1 Qualification tests for *E* shall be carried out in accordance with Test Method D 4761 for long-span flatwise-bending *E* tests (see 3.1.6).

9.2.2 The average *E* ($\bar{E}$) of the sample shall meet the following criteria:

$$\bar{E}\,[1 + 0.237\,COV] \geq E_0$$

where:

COV = coefficient of variation of *E* in the candidate stock from the tests, and

E_0 = average long-span design *E* of the target grade for which replacement is sought.

NOTE 2—For example, if the target grade is L1 Douglas-fir with a design long-span *E* of 2.1 million psi and the candidate stock has a COV of *E* of 7 %, the average long-span *E* of the sample must equal or exceed 2.066 million psi.

9.3 *Full Size Tension*:

9.3.1 Tension testing procedures shall follow Test Method D 4761 with a minimum gage length between grips of 8 ft.

9.3.2 The lower tolerance limit of the fifth percentile with 75 % confidence shall be determined from the sample using the analysis procedure of Practice D 2915.

9.3.3 The 5 % tolerance limit from 9.3.2 shall equal or exceed the fifth percentile of the laminating grade for which replacement is sought.

9.4 *Specific Gravity*—The specific gravity shall be determined following procedures in Test Method D 2395. If the average specific gravity of the sample is less than the average specific gravity of the laminating grade for which replacement is sought, design properties depending upon specific gravity shall be adjusted following recognized practices.

9.5 *Compression Perpendicular to the Grain*—The design stress in compression perpendicular to the grain for products qualified by tests shall be established in accordance with this practice.

9.6 *Shear*—The design stress in shear for products qualified by tests shall be established in accordance with this practice.

10. Adjustment of Stresses for End-Use Conditions

10.1 Stresses discussed in Sections 6-8 are based on normal load duration (9.3), 12 % average moisture content conditions, and approximately 70°F (21°C) temperatures. Bending stress is for a 12-in. (0.3-m) deep straight beam uniformly loaded with a 21:1 span-to-depth ratio. Design at other conditions requires modifications.

10.2 *Moisture Content*—Two different moisture conditions are recognized for glulam members, dry-use and wet-use. Dry-use is the service condition where wood remains at a moisture content below 16 %. Wet-use is the service condition where wood attains moisture contents of 16 % or more. For wet-use conditions, stresses developed in Sections 6-8 should be multiplied by factors given in Table 8.

10.3 *Duration of Load*—Normal load duration contemplates fully stressing a member to its allowable value either continuously or cumulatively for ten years. For other durations of load, all properties except *E* and compression perpendicular to grain may be modified in accordance with Practice D 245.

10.4 *Size Effect*—For bending members, the bending stress must be adjusted for depths other than 12 in. (0.3 m) by multiplying by $(12/d)^{1/9}$ where *d* is the beam depth, in inches, or $(0.3/\,d)^{1/9}$ where *d* is the beam depth in metres. Under some conditions, adjustments for method of loading (Table 9) and span-to-depth ratio (Table 10) may also be necessary. For span-to-depth ratios other than those given, straight-line interpolations may be used.

10.5 *Curvature*—For the curved portion of members, the bending stress shall be modified by the following factor, $1 - 2000\,(t/R)^2$, where *t* is the lamination thickness and *R* is the radius of curvature, both in similar units of measurement. Experience has shown that, in order to minimize breakage problems, the *t/R* ratio should not exceed 1/100 for hardwoods and Southern Pine and 1/125 for softwood species.

10.6 *Treated Wood*:

10.6.1 Stress values associated with preservative or fire-retardant treated glulam members, whether the lumber is treated prior to gluing or the entire member is treated following gluing, must take into account possible reductions in strength due to high temperatures, pressure, or chemical effects. Such reductions must be based on tests or material subjected to the specific treatment conditions.

10.6.2 Glulam members incised prior to preservative treatment may be subjected to a strength reduction depending on member size and the incision pattern and configuration. Such reductions must be based on test of the material.

10.7 *Temperature*—Special design allowances should be made for glulam members subjected to abnormally high temperatures, especially for extended periods of time or for

TABLE 8 Wet-Use Adjustment Factors

Type of Stress	Wet-Use Factor
Bending	0.800
Compression parallel to the grain	0.730
Tension parallel to the grain	0.800
Modulus of elasticity	0.833
Horizontal shear	0.875
Compression perpendicular to the grain	0.530
Tension perpendicular to the grain	0.875

TABLE 9 Bending Stress Adjustment Factors for Loading Conditions

Loading Conditions for Simply Supported Beams	Adjustment Factor
Single concentrated load	1.08
Uniform load	1.00
Third-point load	0.97

TABLE 10 Adjustment Factors for Span-to-Depth Ratios

Span-to-Depth Ratio	Adjustment Factor
7	1.06
14	1.02
21	1.00
28	0.98
35	0.97

exposure combining high temperatures and high-moisture content. Also, an increase in stresses can be taken for glulam used in continuous cold climatic conditions. Design guidelines are given in Ref **(7)**.

10.8 *Shear Deflection*—Member *E* values for glulam bending combinations, calculated in accordance with 7.5.3, 7.5.4, 8.5.3, and 8.5.4 are applicable for 21:1 span-to-depth ratio and assume that up to 5 % of the deflection will be due to shear and about 95 % due to bending when loaded uniformly. Such values may be applied to all loading conditions with span-to-depth ratios greater than 14:1 and the maximum deflection error due to shear will be of the order of 5 % or less. For more precise deflection calculations or for span-to-depth ratios less than 14:1, the effect of shear deflections should be considered separately.

11. Design Values for Glulam Members

11.1 Allowable design stress values for specific glulam members can be obtained by multiplying the clear wood design stress from Section 6 by the strength ratio from Section 7 or 8 and modifying for specific conditions from Section 10. The one exception to that statement is described in 11.1.1.

11.1.1 When vertically laminated bending members are made up of two or more grades of lumber, use the following equation to calculate the allowable design value:

$$f_{byy} = \bar{E}(f/E) \qquad (7)$$

where:

f_{byy} = allowable design stress of the vertically laminated beam combination made up of two or more grades of lumber,

$\bar{E}$ = weighted average of the component lamination E values,

f/E = ratio of allowable design stress to modulus of elasticity for each grade of lumber in the beam combination. The lowest ratio is used in Eq 8,

f = allowable design stress for a grade in the combination which is obtained by multiplying the clear wood design stress from Section 6 by the strength ratio calculated using Eq 3 and modifying for specific conditions from Section 10. The number of laminations, N, to be used in Eq 3 depends on the number of laminations in the member of the same grade or higher. Use $N = 5$ if the number of the laminations of the same grade or higher is five or more, and

E = corresponding E for a grade in the combination (see 7.5.1 and 7.5.1.1).

11.2 Allowable property values shall be rounded to at least as few significant digits as shown as follows after all adjustments have been made.

Bending Tension parallel to grain Compression parallel to grain	0 to 1000 psi to nearest 25 psi (0.3 MPa) 1000 to 2000 psi; to nearest 50 psi (0.5 MPa) 2000 to 3000 psi; to nearest 100 psi (1 MPa)
Horizontal shear	nearest 5 psi (0.05 MPa)
Compression perpendicular to grain	nearest 5 psi (0.05 MPa)
Modulus of elasticity	nearest 100 000 psi (500 MPa)

11.3 The modulus of rigidity of glulam members can be considered to have a constant relationship to the modulus of elasticity. For design purposes, the relationship $G = E/16$ is satisfactory for members consisting of a single grade. A conservative approximation for members consisting of multiple grades of lumber can be obtained by assuming the E of the lowest grade applies to the entire member.

11.4 *Radial Stresses in Curved Members*:

11.4.1 *Radial Tension*—Allowable design values for radial tension in curved members shall be limited to one third of the value for horizontal shear. An exception is for Douglas fir-larch and Hem-fir that are limited to 15 psi (0.10 MPa) for loads of normal duration. For wind and earthquake loading of all species, adjustments shall be based on one third of the value for horizontal shear.

11.4.2 *Radial Compression*—Allowable design values for radial compression in curved members shall be limited to the allowable design value for compression perpendicular to the grain.

12. Tension Laminations for Bending Members

12.1 The results of full-size beam tests reported in Refs (**2, 8,** and **9**) have yielded an empirical relationship between the size of knots in the tension zone and bending strength. This relationship dictates special grading consideration in the outer 10 % of beam depth on the tension side. This tension side may exist on the top or bottom of the beam, or both, depending upon the design considerations and conditions. If beams are fabricated without these special considerations, the design bending strength is obtained by multiplying the design value predicted by the I_K/I_G theory by 0.85 if the depth is 15 in. or less or by 0.75 if the depth exceeds 15 in.

12.1.1 The outer 10 % is further divided into two zones, the outer 5 % and the next inner 5 %.

12.1.2 The use of the equations in 12.2 for the outer 5 % zone is limited to laminations with SR_{t1} values of 0.5 to 0.8 because bending tests cited used tension laminations within that range.

12.2 *Visually Graded Lumber*:

12.2.1 For definitions of terms required for calculation of knot and grain deviation restrictions, see 3.2.

12.2.2 Knots and local grain deviations are expressed as a ratio of the cross-sectional area they occupy to the cross-sectional area of the lumber based on the dressed width of the lumber. They are measured using the displacement technique. Knots are measured to the lateral extremes of the knot; grain deviations (with or without knots) are measured to the lateral extremes of the zone within which the local slope of grain exceeds the allowable slope of grain for the grade. Eq 9-12 which follow yield the maximum allowable knot and grain deviation ratios in the outer 10 % of depth. It is suggested these ratios be adjusted downward to the nearest 0.05 or to the next nearest convenient fraction (such as ⅓). Examples of knot and grain deviation restrictions for tension lamination grades are given in Table 11.

12.2.3 *Beams Greater Than 15 in. in Depth*:

12.2.3.1 *Outer 5 %*—Grain deviation shall be limited in accordance with Eq 9 and Eq 10.

$$GDS \leq 1.55(1 - SR_{t1}) \quad (8)$$

$$GDS \leq 1.82(1 - SR_{t1}) \quad (9)$$

Use Eq 8 when *GDE*, with or without *GDC*, is used to determine *GDS* (see Fig. 1). Use Eq 9 when *GDE* is not used to determine *GDS*. In addition, general slope of grain shall not exceed 1:16 if the required tensile strength ratio is 0.60 or greater. If it is less than 0.60, the general slope of grain shall not exceed 1:12.

12.2.3.2 *Next Inner 5 %*—Knots are restricted in accordance with Eq 11 and 12.

$$KE = 0.66 - 0.45\, SR_{t1} \quad (10)$$

$$KC = 1.20 - 0.93\, SR_{t1} \quad (11)$$

General slope of grain shall be limited in accordance with the strength requirements of the individual laminations.

12.2.4 *Beams 12 to 15 in. in Depth*:

12.2.4.1 *Outer 5 %*—The requirements of 12.2.3.1 apply except that $SR_{t\,1}$ shall be multiplied by 0.90 in Eq 9 and 10. The value of 0.9 $SR_{t\,1}$ shall not be less than 0.50.

12.2.4.2 *Next Inner 5 %*—General slope of grain shall be limited in accordance with the strength requirements of the individual laminations.

TABLE 11 Examples of Knot and Knot Plus Grain Deviation Restrictions for Tension Lamination Grades

Strength Ratio[A] (SR_{t1})	Outer 5 %		Next Inner 5 %	
	GDE[B]	GDC[B]	KE[B]	KC[B]
0.80	0.310	0.364	0.300	0.456
0.75	0.388	0.455	0.323	0.503
0.70	0.465	0.546	0.345	0.549
0.65	0.543	0.637	0.368	0.596
0.60	0.620	0.728	0.390	0.642
0.55	0.698	0.819	0.413	0.689
0.50	0.775	0.910	0.435	0.735

[A] Tension lamination strength ratio at the outermost fiber.
[B] See 3.2 for definitions of terms.

12.2.5 *Beams of Four or More Laminations and Less Than 12 in. in Depth*:

12.2.5.1 *Outer 5 %*—The requirements of 12.2.3.1 apply except that $SR_{t\,1}$ shall be multiplied by 0.80 in Eq 9 and 10. The value of 0.80 SR_{t1} shall not be less than 0.50.

12.2.5.2 *Next Inner 5 %*—General slope of grain shall be limited in accordance with the strength requirements of the individual laminations.

12.2.6 *Density Requirements*:

12.2.6.1 *Outer 5 %*—Density requirements shall apply to the full length of the piece of lumber. In order to assure that lumber is near-average or above specific gravity for the species, visually graded tension laminations shall have a mini-mum specific gravity of at least 94 % of the recognized species average from Test Methods D 2555 based on dry weight and volume at 12 % moisture content. The minimum specific gravity of the piece of lumber shall be the average specific gravity of the entire piece. Rate of growth and percentage of latewood requirements for tension laminations shall apply to the full length of lumber. Visual inspection alone is not an acceptable method of determining specific gravity.

12.2.7 *Other Requirements*:

12.2.7.1 *Outer 5 %*—Wide-ringed or lightweight pith associated wood has a pronounced effect on finger joint strength. The amount of material not meeting rate of growth and density requirements, in combination with compression wood, shall be limited to ⅛ of the cross section of the piece of lumber throughout the length. In addition, for wet conditions of use or pressure-treated members, compression wood by itself is limited to 5 % of the cross section.

12.2.7.2 *Next Inner 5 %*—There are no special requirements.

12.3 *E-rated Lumber*:

12.3.1 *Grading Requirements*:

12.3.1.1 *Outer 5 %*—In addition to having the required modulus of elasticity, *E*-rated lumber must meet the requirements for visually graded lumber given in 12.2.2, 12.2.3.1, and 12.2.4.1, with the exception that knot and slope of grain requirements are given in 12.3.3.

12.3.1.2 *Next Inner 5 %*—There are no special requirements.

12.3.2 *Other Requirements*:

12.3.2.1 *Outer 5 %*—Wide-ringed or lightweight pith associated wood and compression wood are limited in the same manner as for visually graded lumber, except that there are no density requirements. Material not meeting medium grain rate of growth, in combination with compression wood, shall be limited to ⅛ of the cross section of the piece of lumber throughout the length. In addition, for wet conditions of use or pressure-treated members, compression wood by itself is limited to 5 % of the cross section.

12.3.2.2 *Next Inner 5 %*—There are no special requirements.

12.3.3 The ends of the piece not subjected to mechanical *E* measurements shall have visual criteria applied to assure piece quality. Edge knots up to the size permitted in the grade are acceptable. Other knots are limited to visual laminating grade cross-section requirements of the strength level for which the *E*-rated lumber is qualified. For tension laminations, the slope of grain shall not exceed 1:12 and wide-ringed or pith-associated wood and compression wood is limited as in 12.3.2. Medium-grain growth requirements shall be met for Douglas Fir-Larch and Southern Pine material.

12.4 Tension laminations of solid lumber for bending members to meet the needs identified in 12.1 may be qualified by test as an alternative to the grading criteria of 12.2 and 12.3.

12.4.1 Qualification shall be carried out on the size and grade of product for which qualification is desired, except that qualification at a specified width will satisfy qualification requirements for the next smallest width.

12.4.1.1 If qualification of a width by test is used to qualify the next smaller width, selection criteria for the grade of both widths must be identical.

NOTE 3—As an example, qualification of a ⅙ –2.0*E* grade in nominal 2 by 6 for a tension lamination target may qualify the same grade in 2 by 4 if the same *E* selection levels and edge knot selection criteria are used.

12.4.1.2 Principles of Practice D 2915 shall be followed in sampling. A sample of 50 or more is required for *E* measurements; a minimum of 58 is required for tensile strength.

12.4.2 Qualification by test shall include a flatwise bending modulus of elasticity on a 100:1 span-to-depth ratio (see section 3.1.7.2).

12.4.2.1 Qualification tests for *E* shall be carried out in accordance with Methods D 198 or Test Method D 4761.

12.4.2.2 To qualify by *E* criterion, the average *E* ($\bar{E}$) of the sample shall meet the following criteria:

$$(\bar{E})\,[1 + (0.237)\,(COV)] \geq E_D \qquad (12)$$

where:

COV = coefficient of variation of *E* in the candidate stock, and

E_D = average long-span design *E* of the target grade for which replacement is sought.

Example 1: Target grade is 302-24 from *D*.Fir L1 with a design long span *E* of 2.1 × 10^6 psi. The candidate stock is *E*-rated. The NDS COV for *E* of MSR is used (0.11). The product of $\bar{E}$ of the candidate sample and 1.026 must equal or exceed 2.1.

Example 2: Target grade is 302-24 from Hem-Fir SSS with a design long span *E* of 1.8 × 10^6 psi. The candidate stock is visually graded; the National Design Specification (NDS) COV for visually graded lumber is 0.25. The product of $\bar{E}$ and 1.059 must equal or exceed 1.8.

12.4.3 Qualification shall include a strength test of full-size laminations in tension.

12.4.3.1 Tensile testing procedures shall follow the principles of Methods D 198 or Test Method D 4761. The minimum gage length shall be 8 ft, with a range from 8 to 12 ft preferred.

12.4.3.2 To qualify by tensile strength criteria, the lower tolerance limit of the fifth percentile with 75 % confidence shall be determined from the qualification sample. The analysis procedure of Practice D 2915 shall be followed. The fifth percentile so determined must equal or exceed the following multiple of the design bending stress of the target grade for which qualification is desired:

For beams over 15 in. deep—1.67
For beams 12 to 15 in. deep—1.50
For beams less than 12 in. deep—1.34.

12.4.4 Design stress in compression perpendicular to grain for products qualified by test shall be established in accordance with this test method.

13. Keywords

13.1 clear wood; glulam; lumber; structural glued laminated timber; timber

ANNEXES

(Mandatory Information)

A1. GLUED LAMINATED TIMBERS MANUFACTURED WITH *E*-RATED LUMBER

A1.1 General

A1.1.1 Glued laminated timbers may be made with *E*-rated lumber or a combination of *E*-rated lumber and visually graded lumber: for the latter case, the visually graded lumber is commonly used in the inner zones or core, but it may be used in any location. *E* rating of lumber is accomplished by several different methods in commercial practice. For laminating, the specific requirements are included in A1.2 and A1.3.

A1.2 *E*-rated Requirements

A1.2.1 Any method may be used for *E* rating, provided that the long span *E* of the lumber meets or exceeds the requirements for the specified grade mean *E* and a lower fifth percentile calculated as follows:

$$E_{5th} = 0.955\,E_{mean} - 0.233$$

A1.3 Visual Grading Requirements

A1.3.1 In addition to the requirements of Section 4, edge characteristics defined as knots, knot holes, burls, or distorted grain, located partially or wholly at edges of wide faces must not occupy more of the cross section than that indicated by the grade designation. For example, in a 1/6–2.1*E* grade, the edge characteristics described above must not exceed ⅙ of the cross section.

A1.4 Designation

A1.4.1 *E*-rated lumber for laminating shall be designated by the long-span *E* and the fraction of the cross section at the edge which may contain the growth characteristics given in A1.3.

A2. ANALYSIS OF A GLULAM BEAM WITH THREE STIFFNESS ZONES

A2.1 Symmetric Combinations

A2.1.1 For a three-zone beam **(10)**, the transformed section moment of inertia factor, T_i, can be expressed as:

$$T_i = \frac{(E_1 d_1^3 - d_2^3(E_1 - E_2) - d_3^3(E_2 - E_3)}{E_1 d_1^3} \quad \text{(A2.1)}$$

where:

E_1, E_2, and E_3 = moduli of elasticity for the zones shown in Fig. A2.1 and

d_1, d_2, and d_3 = depths shown in Fig. A2.1.

A2.1.2 The calculation for the I_K/I_G ratio becomes:

$$R = \frac{1}{\sum_0^{n_1} Z} \left\{ x_1 \sum_{n_2}^{n_1} Z + \left(\frac{E_2}{E_1}\right) x_2 \sum_{n_3}^{n_2} Z + \left(\frac{E_3}{E_1}\right) x_3 \sum_0^{n_3} Z + \left[h_1^2 \sum_{n_2}^{n_1} Z^2 + \left(\frac{E_2}{E_1} h_2\right)^2 \sum_{n_3}^{n_2} Z^2 + \left(\frac{E_3}{E_1} h_3\right)^2 \sum_0^{n_3} Z^2 \right]^{1/2} \right\} \quad \text{(A2.2)}$$

where:

R = I_K/I_G,

x_1, x_2, and x_3 = average knot sizes expressed in decimal fraction of the width for grades of lumber with average stiffness values of E_1, E_2, E_3, respectively,

h_1, h_2, h_3 = differences between the 99.5 percentile and average knot size in decimal fraction of the width for the respective grades,

Z, Z^2 = weighting factors from Table A2.1 and

n_1, n_2, n_3 = number of laminations in d_1, d_2, and d_3, respectively.

A2.1.3 A corresponding bending stress modification factor (SMF_b) can be determined by:

$$SMF_b = (1 + 3R)(1 - R)^3(1 - R/2) \quad \text{(A2.3)}$$

A2.1.4 Multiplication of SMF_b by the stress index results in an allowable bending stress for outer laminations, f_1.

A2.1.5 The intermediate beam of depth d_2 must be checked to assure that the laminations are not overstressed.

$$R = \frac{1}{\sum_0^{n_2} Z} \left\{ x_2 \sum_{n_3}^{n_2} Z + \left(\frac{E_3}{E_2}\right) x_3 \sum_0^{n_3} Z + \left[h_2^2 \sum_{n_3}^{n_2} Z^2 + \left(\frac{E_3}{E_2} h_3\right)^2 \sum_0^{n_3} Z^2 \right]^{1/2} \right\} \quad \text{(A2.4)}$$

A2.1.6 An allowable stress f_2 (subject to a minimum strength ratio of the grade) can then be calculated. In order to avoid inner lamination overstresses in the depth d_2,

$$f_2 \geq \left(\frac{d_2}{d_1}\right)\left(\frac{E_2}{E_1}\right) f_1 \quad \text{(A2.5)}$$

A2.1.7 Finally, the inner beam of depth d_3 must be checked for overstress.

$$R = \frac{1}{\sum_0^{n_3} Z} [x_3 \sum_0^{n_3} Z + h_3 (\sum_0^{n_3} Z^2)^{1/2}] \quad \text{(A2.6)}$$

$$= x_3 + h_3 \frac{[\sum_0^{n_3} Z^2]^{1/2}}{\sum_0^{n_3} Z}$$

A2.1.8 An allowable stress f_3 is calculated next in order to avoid inner lamination overstresses in depth d_3.

$$f_3 \geq \left(\frac{d_3}{d_1}\right)\left(\frac{E_3}{E_1}\right) f_1 \quad \text{(A2.7)}$$

A2.1.9 If f_2 and f_3 are less than the quantity calculated for the right side of the equation, f_1 is limited to a value that will satisfy an equality. For use with properties of the actual physical section, f_1 can be multiplied by T_i to yield a value of f. Also, for use with the original moment of inertia, I, the value of E_1 must be multiplied by T_i to yield a design value, E.

$$f = f_1 T_i \quad \text{(A2.8)}$$

$$E = E_1 T_i$$

A2.2 Unsymmetric Combinations

A2.2.1 For unsymmetric combinations, the neutral axis must first be located. The procedure is to then analyze the

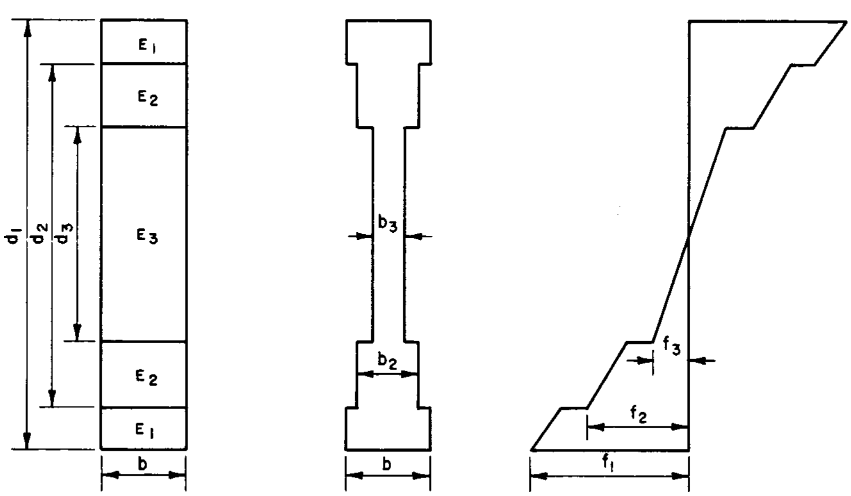


FIG. A2.1 Beam with Three Stiffness Zones

TABLE A2.1 Factors for Use in Computing Values of I_K/I_G from Characteristics of Knot Distributions[A]

Number of Lamination = 2*N*	Weighting Factor for *N*th Lamination from Neutral Axis $Z = 3N^2 - 3N + 1 = N^3 - (N-1)^3$	For 2*N* Laminations $\Sigma Z = 2N^3$	$\Sigma Z^2 = 2/5[N(9N^4 - 5N^2 + 1)]$	Z^2/Z
1	¼	¼	1⁄16	1.000
2	1	2	2	0.707
3	3¼	6¾	21 3⁄16	0.682
4	7	16	100	0.625
5	12¼	31¼	321 5⁄16	0.573
6	19	54	822	0.531
8	37	128	3 560	0.466
10	61	250	11 002	0.420
12	91	432	27 564	0.384
14	127	686	59 822	0.357
16	169	1 024	116 944	0.334
18	217	1 458	211 122	0.315
20	271	2 000	358 004	0.299
22	331	2 662	577 126	0.285
24	397	3 456	892 344	0.273
26	469	4 394	1 332 266	0.263
28	547	5 488	1 930 684	0.253
30	631	6 750	2 727 006	0.245
40	1 141	16 000	11 504 008	0.212
50	1 801	31 250	35 125 010	0.190

[A] From Ref **(2)**.

compression and tension sides independently as half of symmetric beams. For the compression side, stresses 40 % higher than the tension side may be permitted without changing the near minimum strength.

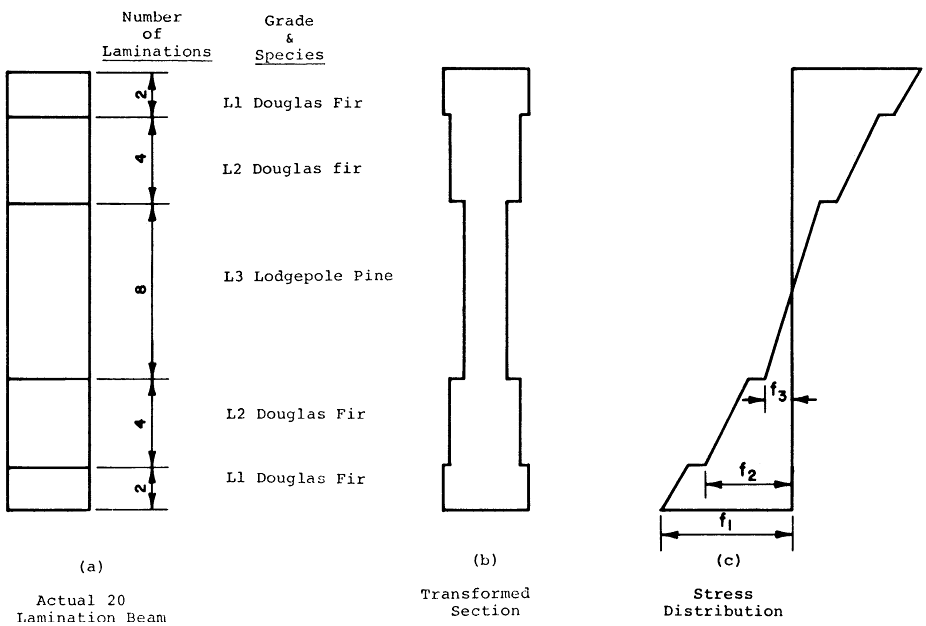


FIG. A2.2 Analysis of 20-Lamination Beam

A2.3 Example: Analysis of a 20-Lamination Glulam Beam

A2.3.1 *Given*, a 20-lamination symmetric beam shown in Fig. A2.2(*a*) consisting of two L1 and four L2 Douglas fir outer laminations, and eight L3 grade lodgepole pine inner laminations.

A2.3.2 *Determine* the allowable bending stress.

A2.3.3 *Required Data:* Modulus of elasticity, bending stress index, and knot data for the three grades of lumber. These values along with the source of information are given in Table A2.2.

A2.3.4 *Procedure*:

A2.3.4.1 Calculate the transformed section moment of inertia factor, T_i, for the simulated I-beam shown in Fig. A2.2(*b*) as follows:

$$T_i = \frac{2.1(20^3) - \{(2.1 - 1.8)(16^3)\} - \{(1.8 - 1.1)(8)^3\}}{2.1 \times 20^3} = 0.906 \quad \text{(A2.9)}$$

A2.3.4.2 Determine I_K/I_G ratio (R) and bending stress modification factor (SMF_b) of whole beam as follows:

$$R = \frac{1}{\sum Z_{20}}\left\{(0.069)(Z_{20} - Z_{16}) + (0.109)\left(\frac{1.8}{2.1}\right) \cdot (Z_{16} - Z_8) + (0.230)\left(\frac{1.1}{2.1}\right)(Z_8) + \left[(0.353)^2(Z_{20}^2 - Z_{16}^2) + \left(0.440 \times \frac{1.8}{2.1}\right)^2 \cdot (Z_{16}^2 - Z_8^2) + \left(0.558 \times \frac{1.1}{2.1}\right)^2 Z_8^2\right]^{1/2}\right\} \quad \text{(A2.10)}$$

$$= \frac{1}{2000}\left\{(0.069)(2000 - 1024) + (0.109)\left(\frac{1.8}{2.1}\right) \cdot (1024 - 128) + (0.230)\left(\frac{1.1}{2.1}\right)(128) + \left[(0.353)^2(358\ 004 - 116\ 944) + \left(0.440 \times \frac{1.8}{2.1}\right)(116\ 944 - 3560) + \left(0.558 \times \frac{1.1}{2.1}\right)^2(3560)\right]^{1/2}\right\} = 0.191$$

$$SR_b = (1 + 3 \times 0.191)(1 - 0.191)^3\left(1 - \frac{0.191}{2}\right) = 0.753 \quad \text{(A2.11)}$$

A2.3.4.3 Calculate allowable outer fiber stress as follows (see Fig. A2.2(*c*)):

$$\text{Allowable } f_1 = 0.753 \times 3500 = 2640 \text{ psi} \quad \text{(A2.12)}$$

A2.3.4.4 Determine I_K/I_G ratio (R) and bending stress modification factor (SMF_b) of 16-lamination intermediate beam as follows:

$$R = \frac{1}{\sum Z_{16}} \cdot \left\{(0.109) \times (Z_{16} - Z_8) + (0.230)\left(\frac{1.1}{1.8}\right)(Z_8) + \left[(0.440)^2(Z_{16}^2 - Z_8^2) + \left(0.558 \times \frac{1.1}{1.8}\right)^2 Z_8^2\right]^{1/2}\right\} = 0.259 \quad \text{(A2.13)}$$

$$SMF_b = (1 + 3 \times 0.259)(1 - 0.259)^3\left(1 - \frac{0.259}{2}\right) = 0.629$$

A2.3.4.5 Calculate allowable fiber stress at interface between L1 and L2 material as follows:

$$\text{Allowable } f_2 = 0.629 \times 3000 = 1890 \text{ psi}$$

A2.3.4.6 Determine I_K/I_G ratio (R) and bending stress modification factor (SMF_b) for 8-lamination inner beam as follows:

$$R = \frac{1}{\sum Z_8}\{(0.230)(Z_8) + [(0.558)^2(Z_8)^2]^{1/2}\} = 0.490 \quad \text{(A2.14)}$$

$$SMF_b = (1 + 3 \times 0.490)(1 - 0.490)^3\left(1 - \frac{0.490}{2}\right) = 0.2472 < 0.50$$

Assume $SR_b = 0.50$ because largest knots permitted in L3 grade are 50 % of cross section.

A2.3.4.7 Calculate allowable fiber stress at interface between L2 and L3 material as follows:

$$\text{Allowable } f_3 = 0.500 \times 1933 = 970 \text{ psi} \quad \text{(A2.15)}$$

A2.3.4.8 Determine which of calculated stresses control as follows:

$$f_2 > \frac{1.8}{2.1} \times \frac{8}{10} \times f_1 = 24/35 f_1 = 1810 \text{ psi} \quad \text{(A2.16)}$$

$$\text{Allowable } f_2 = 1890, f_1 \text{ controls.}$$

$$\text{Actual } f_3 > \frac{1.1}{2.1} \times \frac{4}{10} \times f_1 = 550 \text{ psi}$$

but

TABLE A2.2 Lumbar Data for Analysis of Glulam Beam Bending Stress

Grade and Species[A]	Modulus of Elasticity[B]		Bending Stress Index[C]		Knot Data[D]		
					x	99.5 Percentile	h
	psi	MPa	psi	MPa	%	%	%
L1 Douglas fir	2 100 000	14 500	3500	24.1	6.9	42.2	35.3
L2 Douglas fir	1 800 000	12 400	3000	20.7	10.9	54.9	44.0
L3 Lodgepole pine	1 100 000	7 600	1933	13.3	23.0	78.8	55.8

[A] Graded in accordance with WWPA and WCLIB rules under the American Lumber Standard. (Refs **3** and **4**) L3 lodgepole pine graded under rules for L3 Douglas fir.
[B] Based on 7.5.1.1 for Douglas fir and 6.1.4 and 7.5.1 for lodgepole pine.
[C] Based on 6.1.1.1 for Douglas fir and 6.1.1 for lodgepole pine.
[D] Based on 5.1.2 for Douglas fir and 5.1.1 for lodgepole pine.

$$\text{Allowable } f_3 = 970, f_1 \text{ controls.}$$

Therefore,

$$\text{Allowable } f_1 = 2640-\text{psi controls.}$$

A2.3.4.9 Determine allowable combination bending stress and modulus of elasticity as follows:

$$f = 2640 \times 0.906 = 2390 \text{ psi} \simeq 2400 \text{ psi.} \quad \text{(A2.17)}$$

$$E = 2.1 \times 0.906 \times 0.95 = 1.81 \times 10^6 \text{ psi} \simeq 1.8 \times 10^6 \text{ psi.}$$

A2.3.4.10 Determine outer 5 % tension lamination requirement (see 12.2.3.1.)
Required strength ratio:

$$SR_{t1} = 2400/0.906/3500 = 2650/3500 = 0.757 \quad \text{(A2.18)}$$

Edge knot plus grain deviation:

$$GDS \leq 1.55(1 - SR_{t1}) \quad \text{(A2.19)}$$

$$GDS = 1.55(1 - 0.757) = 0.38$$

Therefore edge knot plus grain deviation limited to 0.35 (rounded to next lower 0.05) for outer tension lamination.
Centerline knot plus grain deviation:

$$GDS \leq 1.82(1 - SR_{t1}) \quad \text{(A2.20)}$$

$$GDS = 1.82(1 - 0.757) = 0.44$$

Therefore centerline knot plus grain deviation limited to 0.40 for outer tension lamination.

A2.3.4.11 Determine next 5 % tension lamination requirement (see 12.2.3.2).
Edge knot:

$$KE = 0.66 - 0.45(0.757) = 0.32 \quad \text{(A2.21)}$$

Therefore, edge knot limited to 0.30 (L1 permits up to 0.25 knot) for next inner tension lamination.
Centerline knot:

$$KC = 1.20 - 0.93(0.757) = 0.50 \quad \text{(A2.22)}$$

Therefore centerline knot limited to 0.50 for next inner tension lamination.

A2.3.4.12 Determine slope of grain requirements for all laminations. The bending stress modification factor is determined as follows:

$$SMF = \textit{maximum actual stress/bending stress index} \quad \text{(A2.23)}$$

$$SMF = (2400/0.906)/3500 = 0.757$$

From Table 4, outer tension lamination requires a slope of grain of 1:16. Outer compression lamination requires a slope of grain of 1:12. Suitable for top two laminations as L1 has a slope of grain of 1:14. The outer surface of the second lamination is 0.9 of the distance from the neutral axis to outer face of the member. Second tension lamination stress modification factor:

$$SMF = 0.9 \times 0.757 = 0.681 \quad \text{(A2.24)}$$

1:12 slope of grain required, 1:14 per grade is suitable.

L2 zone stress modification factor

$$= 2400/0.906 \times 1.8/2.1 \times 0.8 \div 3000$$
$$= 0.605$$

Tension side needs a slope of grain of 1:10, 1:12 per grade; all L2 suitable.

L3 zone stress modification factor

$$= 2400/0.906 \times 1.1/2.1 \times 0.4 \div 1933$$
$$= 0.287$$

Tension side needs a slope of grain of 1:6, 1:8 per grade; all L3 suitable. Slope of grain requirement of all lamination grades are adequate except outer tension lamination which needs a slope of grain of 1:16.

A3. PROCEDURE FOR DETERMINING DESIGN STRESSES IN COMPRESSION PARALLEL TO GRAIN

A3.1 Procedural Steps

A3.1.1 Determine the transformed area factor, T_a, as follows:

$$T_a = \frac{\sum_{k=1}^{n} E_k A_k}{E_1 \sum_{k=1}^{n} A_k} \quad \text{(A3.1)}$$

where:

n = total number of laminations,
E_k = long-span modulus of elasticity of k-th lamination,
A_k = actual (untransformed) cross-sectional area occupied by k-th lamination, and
E_1 = long-span modulus of elasticity of outermost lamination on the bottom face.

A3.1.2 Using values of the average (m_k) and the standard deviation (σ_k) knot size determined in accordance with 5.3 for the respective laminations, calculate values for composite average knot size (m_c) and composite standard deviation knot size (σ_c) for the combination as follows:

$$m_c = \frac{\sum_{k=1}^{n} (E_k A_k m_k)}{E_1 \sum_{k=1}^{n} A_k} \quad \text{(A3.2)}$$

$$\sigma_c = \frac{\{\sum_{k=1}^{n} (E_k^2 A_k^2 \sigma_k^2)\}^{1/2}}{E_1 \sum_{k=1}^{n} A_k} \quad \text{(A3.3)}$$

For glulam members made with single-grade laminations, Eq A3.3 can be reduced to:

$$\sigma_c = \frac{s}{n^{1/2}} \quad \text{(A3.4)}$$

where:

n = total number of laminations, and
s = standard deviation knot size for the laminations in accordance with 5.3 ($s = \sigma_1 = \sigma_2 = ... = \sigma_k$).

A3.1.3 Compute the composite knot size at the 99.5 percentile, Y_1, as follows:

$$Y_1 = m + 2.576\,\sigma \quad \text{(A3.5)}$$

where m, σ, and Y_1 are expressed in decimal fractions of the width of the dressed size of lumber used for a lamination.

A3.1.4 Compute the stress modification factor from Eq 4 (see 7.3.2) and compare with that determined by the slope of grain for each grade.

A3.1.5 Calculate the allowable compressive stress on the actual combination for each grade at the interface between grades as follows:

$$f_c = Sl_c \times SMF_c \quad \text{(A3.6)}$$

where:

f_c = allowable compressive stress,
Sl_c = stress index in compression, and
SMF_c = stress modification factor in compression (Eq 4 in 7.3.2).

A3.1.6 For unsymmetric combinations, calculate relative stress factors for each interface as follows:

$$S_i = \left(\frac{E_j}{E_1}\right)\left[\left(\frac{1}{T_a}\right) \pm \left(\frac{12a}{T_i d_1{}^2}\right) x_i\right] \quad \text{(A3.7)}$$

where:

S_i = relative stress factor at the i-th interface,
E_j, = long-span modulus of elasticity of laminations in j-th zone ($j = i - 1$),
E_1, and T_a = as defined in Eq A3.1,
T_i = transformed moment of inertia factor (see Eq A2.1),
a = shift in the neutral axis from midheight,
d_1 = beam depth, and
x_i = distance from neutral axis to the i-th interface.

The sign plus (+) or minus (−) depends upon whether the induced bending stress is compressive or tensile, respectively. For symmetric combinations, $S_i = E_j/(E_1 T_a)$.

A3.1.7 Combination for f_c is lowest of all f_{ci}/S_i.

A3.2 Example—Analysis of an Eight-Lamination Member

A3.2.1 *Given*—An eight-lamination compression member as shown in Fig. A3.1, lumber properties as shown in Table A3.1 and the following data:

$$T_i = 0.845$$

$$a = 0.120$$

$$d_1 = 8$$

A3.2.1.1

$$T_a = \frac{2.1(1) + 1.9(1) + 0.8(4) + 1.8(2)}{2.1(8)} = 0.643$$

A3.2.1.2

$$m_c = \frac{2.1(1)(0.2) + 1.9(1)(0.35) + 0.8(4)(0.45) + 1.8(2)(0.35)}{2.1(8)} = 0.225$$

$$\sigma_c = \left\{\frac{(2.1)^2(1)^2(0.10)^2 + (1.9)^2(1)^2(0.15)^2 + (0.8)^2(1)^2(0.20)^2 + (0.8)^2(1)^2(0.20)^2 + (0.8)^2(1)^2(0.20)^2 + (0.8)^2(1)^2(0.20)^2 + (1.8)^2(1)^2(0.15)^2 + (1.8)^2(1)^2(0.15)^2}{(2.1)(8)}\right\}^{1/2}$$

$$= \left\{\frac{(2.1)^2(1)^2(0.10)^2 + (1.9)^2(1)^2(0.15)^2 + (4)\,(0.8)^2(1)^2(0.20)^2 + (2)(1.8)^2(1)^2(0.15)^2}{(2.1)(8)}\right\}^{1/2}$$

$$= 0.0364$$

A3.2.1.3

$$Y_1 = 0.225 + 2.576 \times 0.0364 = 0.319$$

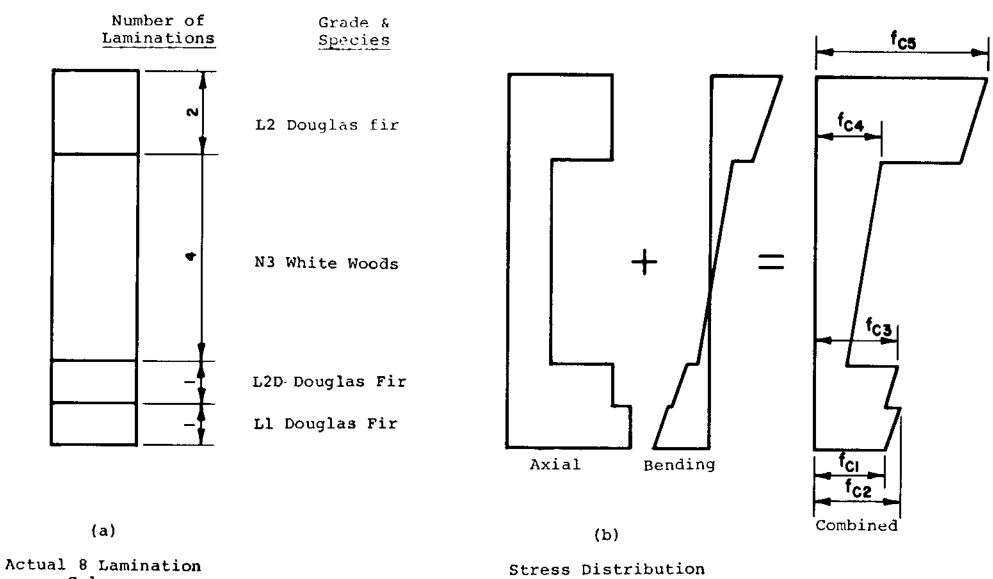


FIG. A3.1 Axially Loaded Member with Unsymmetric Grades

TABLE A3.1 Number Data for Analysis of Compression Parallel to Grain Stress

Grade and Species	Modulus of Elasticity	Compression Stress Index		Knot Data[A]	
				m	σ
	million-psi	psi	MPa		
L1 Douglas fir	2.1	2 780	19.2	0.20	0.10
L2D Douglas fir	1.9	2 780	19.2	0.35	0.15
L2 Douglas fir	1.8	2 380	16.4	0.35	0.15
N3 white wood	0.8	1 330	9.2	0.45	0.20

[A] Estimated parameters.

A3.2.1.4 Determine SMF_c for knots and slope of grain as follows:

$$SMF_c = \frac{(0.319)^3}{4} - (0.319)^2 - \frac{0.319}{4} + 1$$

$$= 0.827$$

According to Table 4:

1:14 Slope of grain of L1 limits SMF_c to 0.87.

1:12 Slope of grain of L2 limits SMF_c to 0.82.

1:4 Slope of grain of N3 limits SMF_c to 0.46.

A3.2.1.5 Calculate allowable stresses using stress indexes shown in Table A3.1 as follows:

$$f_{c1} < f_{c2}$$

$$f_{c2} = 0.827 \times 2780 = 2300 \text{ psi}$$

$$f_{c3} = 0.82 \times 2780 = 2280 \text{ psi}$$

$$f_{c4} = 0.46 \times 1330 = 610 \text{ psi}$$

$$f_{c5} = 0.82 \times 2380 = 1950 \text{ psi}$$

A3.2.1.6 Calculate relative stress factors as follows:

$$S_2 = \frac{2.1}{2.1}\left[\frac{1}{0.643} - \frac{12(0.120)}{0.845(64)}(2.88)\right]$$

$$= 1.555 - 0.0266\,(2.88)$$
$$= 1.478$$

$$S_3 = \frac{1.9}{2.1}[1.555 - 0.0266(1.88)] = 1.362$$

$$S_4 = \frac{0.8}{2.1}[1.555 + 0.0266(2.12)] = 0.614$$

$$S_5 = \frac{1.8}{2.1}[1.555 + 0.0266(4.12)] = 1.427$$

A3.2.1.7 Determine which f_c is the lowest of $f_{c\ ix} / S_{ix}$. Lowest is $f_{c\ 4}/S_4$ = 990 psi. Therefore, f_c = 990 psi, or 1000 psi (rounded to nearest 50 psi).

A4. GUIDELINES FOR DETERMINING ACCEPTANCE OF NEW KNOT DATA

A4.1 In order to establish a knot survey data base for a laminating lumber grade, all knots in individual pieces of lumber selected from a representative sample of the material (see Annex C) shall be physically measured (mapped) to determine the % of the cross-section of the piece occupied by each knot based on a displacement technique. Knots shall be identified in accordance with the accompanying sketches. Knots shall be identified as Types 1–9 with various subcategories further defined within the basic knot type. It is noted that there is no knot Type 8. All knots greater than ⅜ in. (6 mm) (equivalent cylindrical cross-section) shall be measured.

A4.2 Each knot shall be initially recorded using a longitudinal measurement, the "x" distance, from a reference position (one end of the piece being measured) and the physical size of the knot. The "x" distance is the length from the end of the piece to the position of the cross section through the center of the knot. The physical size of the knot is recorded by measurements from a reference edge of the piece. Dimensions to each edge (intersection point) of the knot on each surface (face) where the knot occurs are recorded to accurately determine the size of the knot. When a knot radiates out from the pith center, the location of the pith center is recorded (see knot Type 7 for a diagram indicating pith centers). The faces of the piece shall be identified as follows for recording purposes:

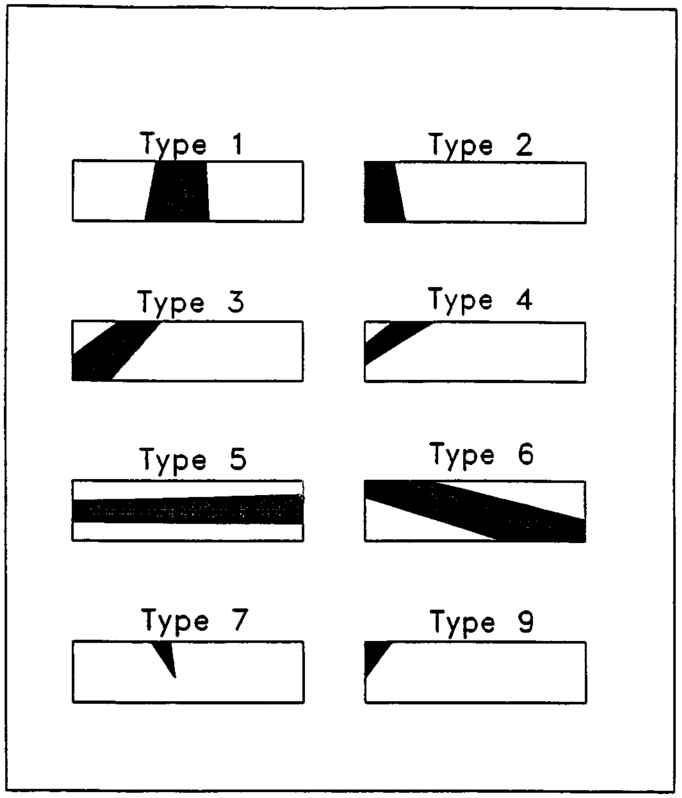
T	Top (wide face) T1 and T2
B	Bottom (wide face) B1 and B2
Z	Near face (narrow edge that is the reference edge) Z1 and Z2
F	Far face (narrow edge) F1 and F2
P1	Pith Center (dimension through the thickness of the piece)
P2	Pith Center (dimension along the wide face)

A4.2.1 See Figs. A4.1-A4.10 for each type of knot and associated measurements. Note that there purposely is no knot Type 8.

A4.2.2 Knots are recorded systematically with the knot closest to the reference end recorded first. Two measurements are recorded for each face or edge. When the knot is not visible on a face or edge, zero is recorded for the measurements for that surface. For example, a Type 1 (cylindrical knot) will have measurements for T1, T2, B1, and B2. Zeros are recorded for all other measurements. A Type 7 (pith center knot) may have measurements for any of the faces in addition to the P1 and P2 measurements that locate the pith center. When more than one knot occurs at the same "x" distance, each knot will have the same "x" measurement recorded together with the other corresponding measurements for the knot. Multiple knots at the same cross section will require separate entries on the data form.

A4.3 Calculation

A4.3.1 Knot X-bar and h values computed by these methods are based on the principles presented in USDA Technical Bulletin 1069 **(2)**. The value, X-bar, is defined as the average of the sum of all knot sizes within any 1-ft length along the



NOTE 1—Minimum knot size = 3/8 in.

FIG. A4.1 Knot Types

piece of lumber, whereas, the value, *h*, is defined as the 99.5 percentile knot size. Computer programs may be employed to determine these knot properties from a knot survey data base. The following general procedures shall be incorporated in such a program to determine the values of X-bar and *h*.

A4.3.2 Any linear regression routine that determines the parameters of the regression line and the value of the 99.5 percentile shall emulate the procedure of plotting the sum of knots cumulative frequency data on arithmetical probability paper and drawing a straight line through the data which was the method used in USDA Bulletin 1069. The underlying assumption for using this procedure is that an analysis, which handles the knot data as normally distributed is satisfactory. USDA Bulletin 1069 determines cumulative frequency by dividing cumulative number of knots up through the knot size of interest by the total number of knots. This results in the maximum knot size having a cumulative frequency on the probability scale is at infinity and cannot be shown on the graph. An alternative is to calculate cumulative frequency in the same manner except 0.5 is subtracted from the cumulative total for each knot size before dividing by the total number of knots to avoid having infinity as the value for plotting the cumulative frequency of the largest knot.

A4.3.3 Two possible options for the selection of the knot size range over which to calculate the linear regression are as follows:

A4.3.3.1 One option is to calculate regressions for all knot ranges possible using as the lowest point the first point above the average real knot size (“real” knots are all those knots that have a size greater than zero), and each of the points above the 99.5 percentile as the highest point. The regression having the least standard error of estimate is selected for the calculation X-bar and h for the data set.

A4.3.3.2 Another option is to use the first and last knot data points over which to calculate a linear regression for purposes of determining the 99.5 percentile sum of knots size. Knot sizes are presented as number of 1⁄8 ths of inches equivalent diameter. These regression curves typically are plotted with the Y-axis (vertical) of the graph as knot diameter (size) in number of 1⁄8 ths of inches and the X-axis (horizontal) as cumulative frequency as percent using an arithmetical probability scale. All the data points are shown on the graph. The left most point is for the sum of knots of 0⁄8 ths size and the right most point is for sum of knots of the largest size in the data. A vertical line for the 99.5 percentile is plotted on the graph so the intersection of this line with the regression line can be observed.

A4.3.3.3 The selection of the regression line by using the minimum standard error of estimate gives the line with the closest fit of the data, and thus, the best estimate of the 99.5 % value.

A4.4 Acceptance

A4.4.1 *General*—A proposal for replacement of existing knot data shall include adequate statistical analyses and information to determine if the new data substantiates retaining existing date, augments existing data, or replaces existing data.

A4.4.2 *Statistical Comparison*—Statistical comparison of the new and existing data consists of a three-step process:

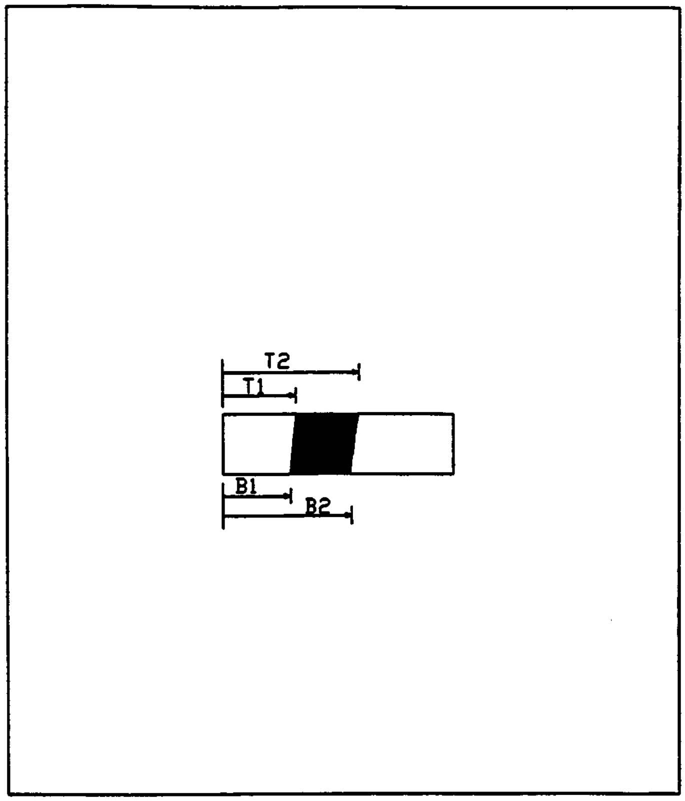


FIG. A4.2 Type 1

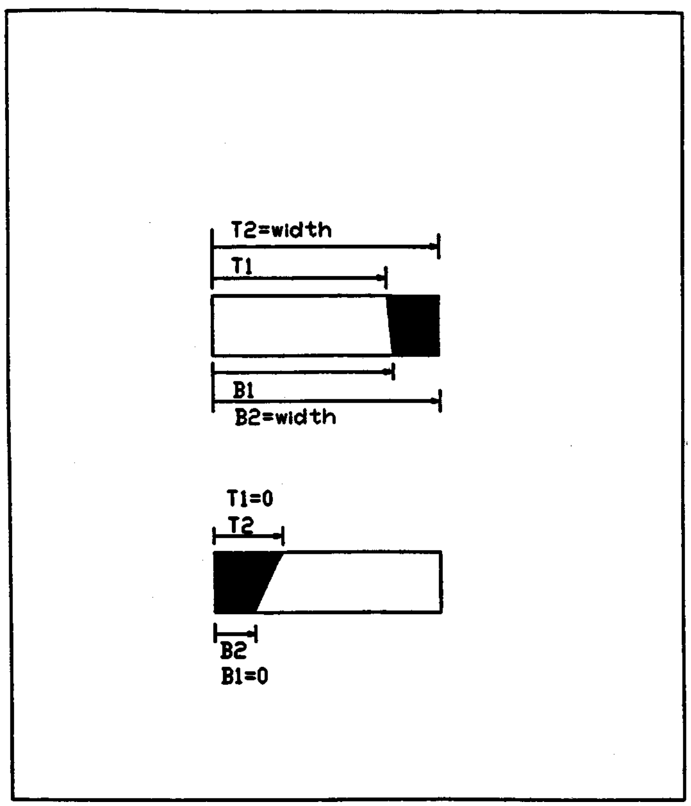


FIG. A4.3 Type 2

A4.4.2.1 Conduct a joint probability test for means and variances.

A4.4.2.2 Conduct an equivalency test for the quantities (usually 99.5 percentile).

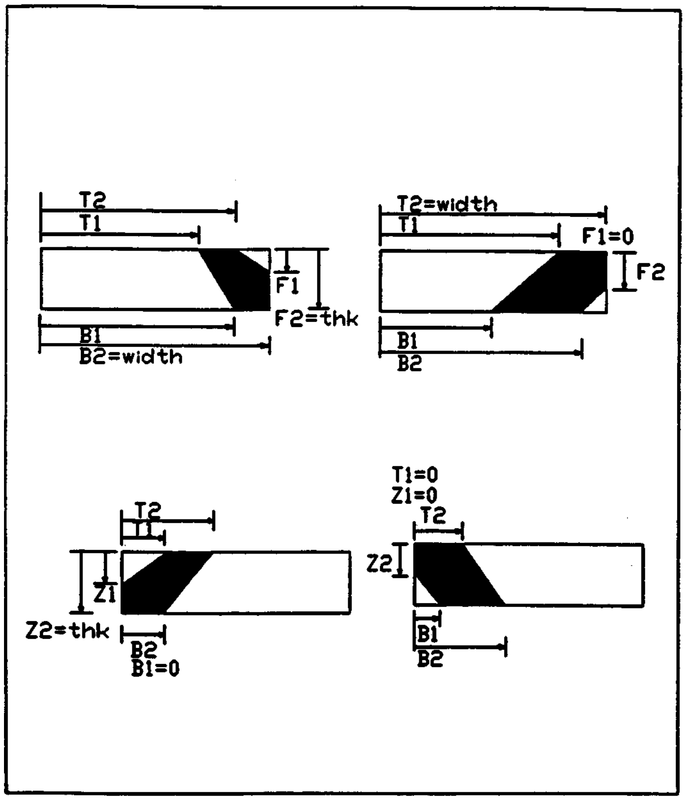


FIG. A4.4 Type 3

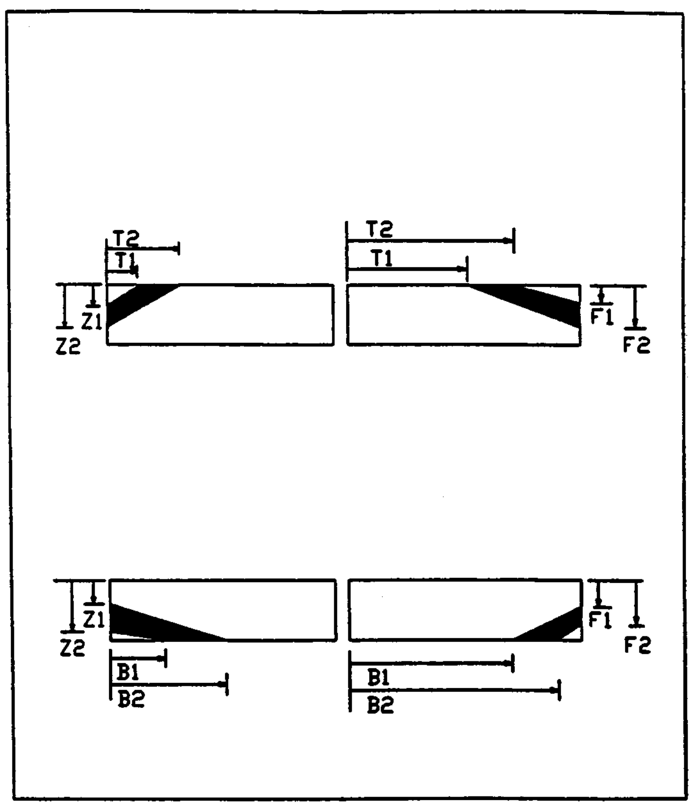


FIG. A4.5 Type 4

A4.4.2.3 If necessary, conduct tests of distribution fit.

A4.4.2.4 *Decision Procedure*—Based on the results of A4.4.2, take action based on a sequence of analysis and decision such as the one in Table A4.1.

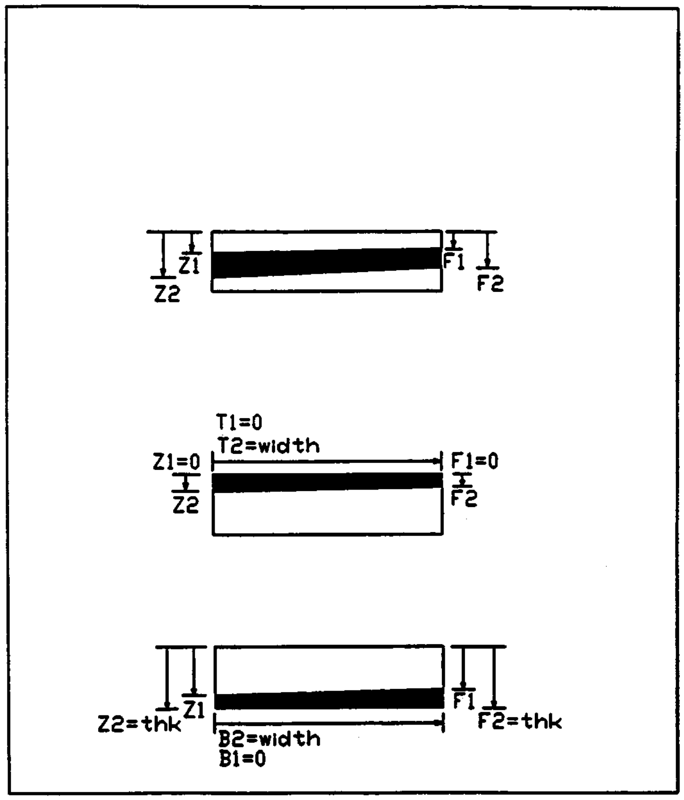


FIG. A4.6 Type 5

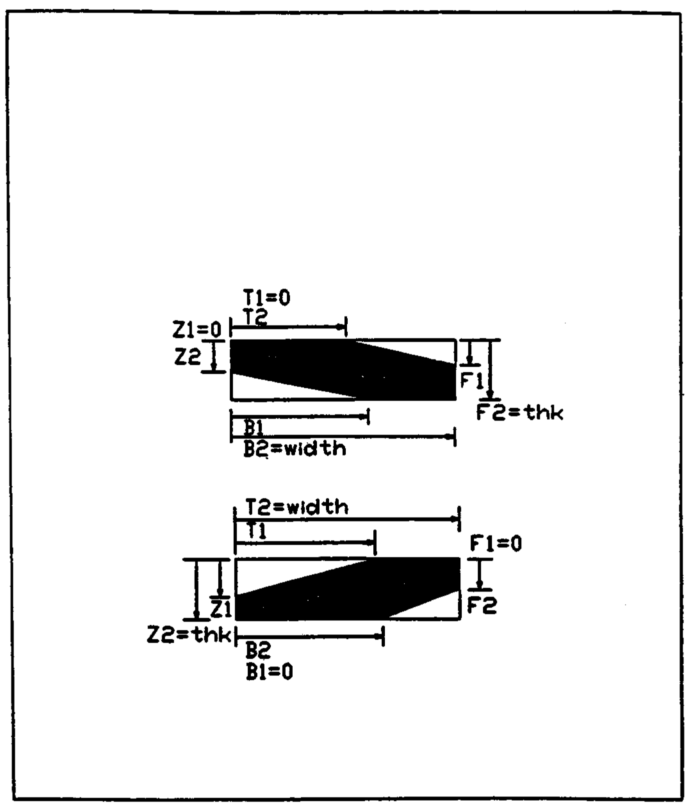


FIG. A4.7 Type 6

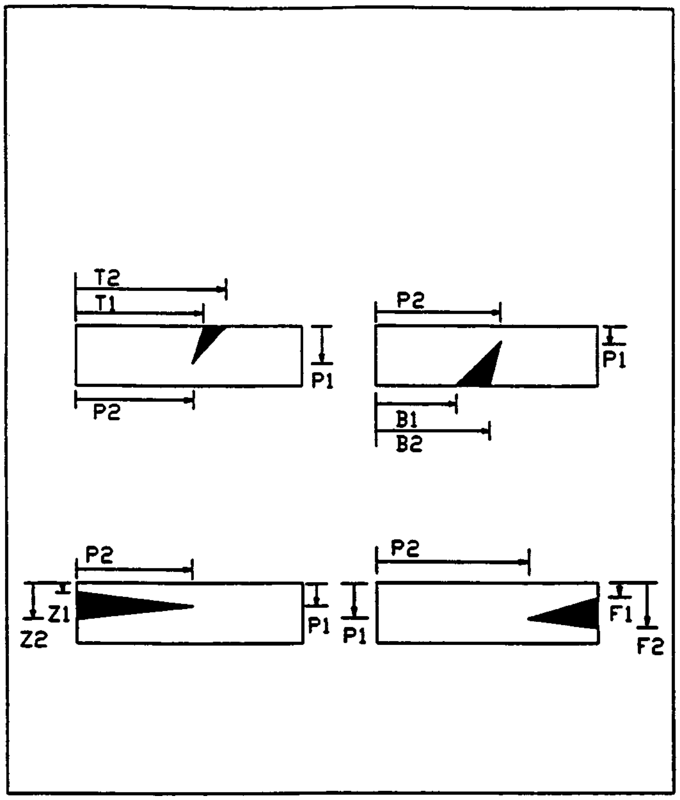


FIG. A4.8 Type 7

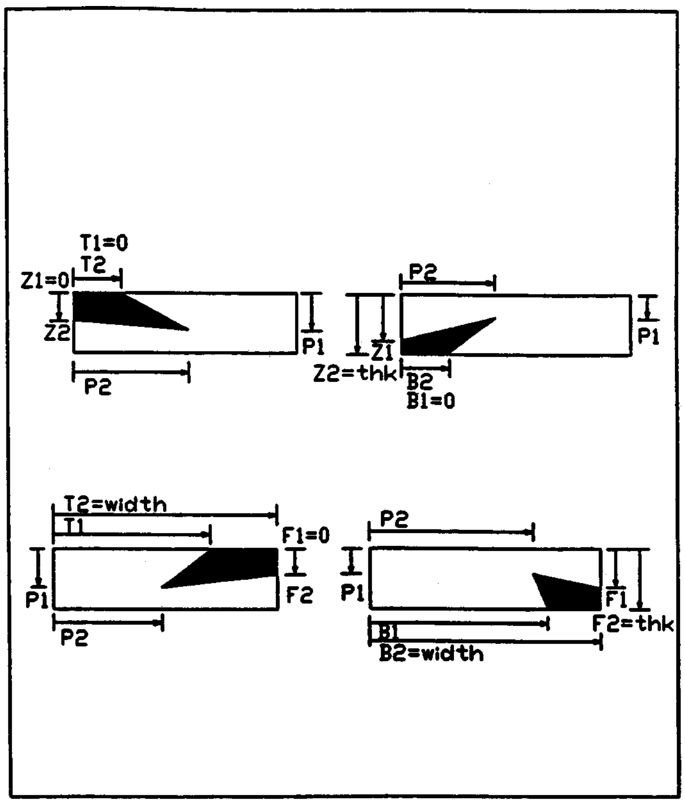


FIG. A4.9 Type 8

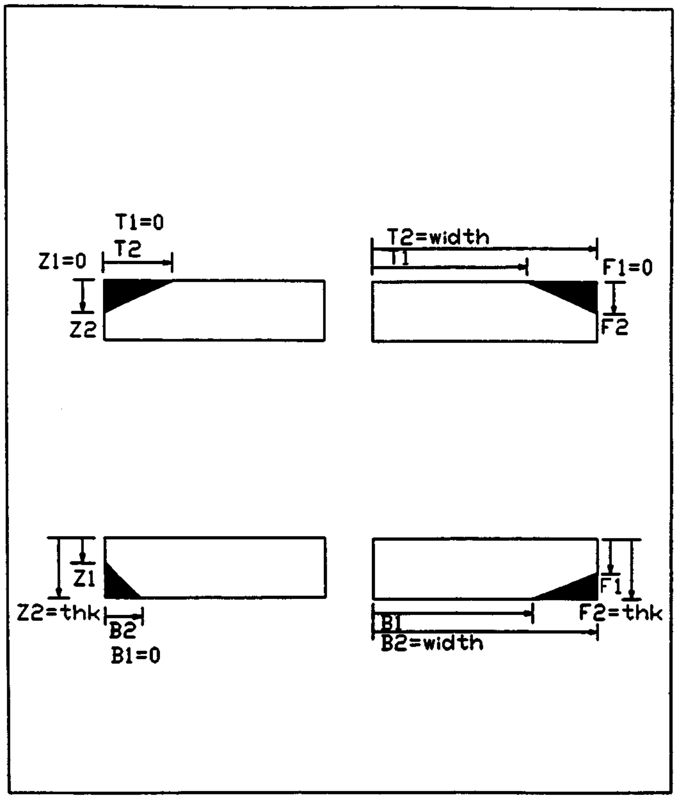


FIG. A4.10 Type 9

TABLE A4.1 Example Decision Sequence Composed of Analysis and Subsequent Decisions

Mean and Variances	Quantile	Action
1. Unequal	Unequal	Accept new data as different from existing data; apply "practical significance" tests.
2. Unequal	Equal	Examine distribution fit.
		(a) If normal, consult power table to make sure sample is large enough. If it is large enough, accept new data and apply "practical significance" tests. I not large enough, take additional samples.
		(b) If not normal, go to 4b.
3. Equal	Equal	No change in knot data.
4. Equal	Unequal	Examine distribution fit.
		(a) In normal, accept new data, apply "practical significance" test.
		(b) If not normal, seek help of statistician.

A5. TEST SETUP AND DATA ANALYSIS PROCEDURE FOR DETERMINING HORIZONTAL SHEAR STRESS BY FULL SCALE BEAM TESTS

A5.1 *Test Method*—A two-point load method, as shown in Fig. A5.1, shall be used to test all specimens. The test apparatus, including rocker-type reaction supports, reaction bearing plates and rollers, load bearing blocks, load bearing rollers, and chord length and radius of curvature of the curved load bearing blocks shall follow Test Methods D 198.

A5.1.1 The clear distance between the edge of the bearing plate to the edge of the nearest load bearing block must be at least two times the specimen depth. The minimum width of the specimen shall be 6 in. (nominal) and the minimum depth shall be approximately 18 in. (net). The clear distance indicated is regarded as critical to prevent the shear stress distribution from being influenced by the compression perpendicular to grain stress. All specimens are to be cut to the exact length with no overhangs allowed. Load is to be applied at a constant rate so as to reach the ultimate load in about 10 min. Ref **(11)** provides a detailed example of a typical test setup. All failure modes shall be recorded to permit the use of either a censored or

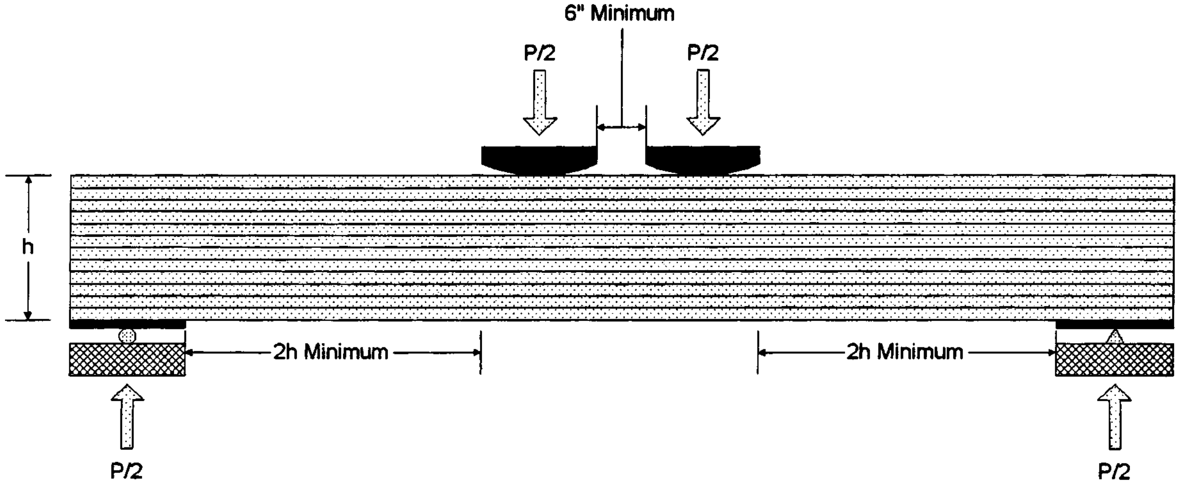


FIG. A5.1 Test Setup Based on Test Methods D 198 (not drawn to scale)

uncensored data set analysis as discussed in A5.2. A shear failure is one that fails along the length of the member in the approximate mid-depth area of the beam and is not precipitated by a typical bending failure mode which usually starts in the bottom tension lamination.

A5.2 *Beam Manufacture*—All test beams shall be manufactured with on-grade laminating lumber representative of the grade and species being evaluated used in the critical core area of the beam where maximum shear stresses will be observed during testing. It is permissible to use a higher grade of laminating lumber than may be required in the critical tension zone of the beam to minimize typical bending mode failures and maximize the number of shear failures.

A5.3 *Analysis Methods*—The shear (f_v) stresses at the time of specimen failure shall be calculated using the following equation:

$$f_v = \frac{3\,P_{ult}}{4\,b\,h} \quad \text{(A5.1)}$$

where:

f_v = shear stress, psi
P_{ult} = ultimate total load, lbf,
b = measured beam width, in., and
h = measured beam depth, in.

A5.3.1 If the specimens are not pre-conditioned to a standard moisture content level of 12 % prior to testing, which may not be feasible depending on the size of the test specimens, the calculated shear stress shall be adjusted to the 12 % moisture content condition using the procedures given in Practice D 2915.

A5.3.2 The test data may be analyzed based on those data due to shear failures only (uncensored data) and those data obtained from all failure modes combined (censored data) for each species and tested widths. The data set shall have a minimum of 28 shear failures as defined in A5.1. As an example, a detailed analysis on the shear strengths of Douglas fir, southern pine, and spruce-pine-fir glulam using both censored and uncensored data sets can be found in Ref **(12)**. In either case, a lower 5th percentile tolerance limit with 75 % confidence shall be determined.

A5.3.3 For the censored data analysis, the uncensored mean and standard deviation can be estimated by using the methodology for the maximum likelihood estimators (MLEs), as described in Lawless (Ref **(12))**. The estimates of the uncensored statistics from the censored data are critical due to the fact that although the uncensored mean is expected to be higher than the mean based on the censored data, the standard deviation might be also higher. As a result, the lower 5th percentile tolerance limit based on the uncensored data may or may not be actually higher than the value determined from the censored statistics.

A5.4 *Test Adjustment Factor*—Allowable shear stresses for structural glued laminated timber determined in accordance with 6.1.5 are based on block shear values of small-clear wood specimens. The shear reduction factor traditionally applied to test results of these small scale block shear specimens is 1/4.1, which is composed of the effects of load duration (10/16), stress concentration (4/9), and a factor of safety (8/9).

A5.4.1 Since the stress concentration factor of 4/9 is only applicable to small scale specimens, it is not included in the reduction factor to be applied to results of full-size beam tests. In addition, the factor of safety to be used in conjunction with full scale beam tests is revised to the same level that is applicable to the allowable flexural stress or 10/13. Combining this with the duration of load factor of 10/16 results in a net reduction factor of 1/2.1 that can then be applied to the shear test results of full-size glulam beams to establish design values.

A5.5 *Published Values*—The calculated shear stress may be reduced by 10 % to allow for occasional seasoning checking in accordance with industry recommended practice.

APPENDIX

(Nonmandatory Information)

X1. PROCEDURES FOR JUDGING ACCEPTANCE OF NEW MECHANICAL PROPERTY DATA

X1.1 *General*—A proposal for replacement of existing data shall include adequate statistical analyses and information to determine if the new data (*1*) substantiates retaining existing data; (*2*) augments existing data; or (*3*) replaces existing data.

X1.1.1 The new data set must have been sampled so as to be representative of the population in question. If the data set does not meet this criterion, additional data must be collected.

X1.2 *Parametric Comparison*—If, one of the competing data sets (current standard versus proposed alternative) belongs to one of the usual parametric families (for example, normal, log normal, Weibull, gamma) and the other does not (Note X1.1), then proceed to Table X1.1.

NOTE X1.1—As determined by statistical tests of goodness of fit. In general correlation-type and Cramer-Von Mises tests are to be preferred over χ^2 and Kolmogorov-Smirnov tests.

X1.3 *Nonparametric Tests*—If neither of the two data sets lies within one of the standard parametric families, perform the following nonparametric tests:

X1.3.1 The overall equality of the two distributions (for example, the two sample Kolmogorov-Smirnov tests),

X1.3.2 The equality of the "locations" of the two distributions (for example, the Wilcoxon rank sum test),

X1.3.3 The equality of the "scales" of the two distributions (for example, the Capon-Klotz test), and

X1.3.4 The equality of the fifth percentiles of the two distributions (for example, the modified Conover chi-squared test).

TABLE X1.1 Example Decision Sequence Based on Practical Application of Data

The following may be used when mechanical properties are determined to be different following a sequence such as X1.2-X1.4.

Step	
1	Apply the rounding rule of Practice D 245. If the new data remains different from the old, proceed.
2	Apply the rounded new data to a Practice D 3737-based beam analysis for one "classic" balanced and unbalanced lay up. If the lay-up of more than one depth between 4 and 20 laminations changes, the new data is considered different.
2a	If new knot data or other mechanical property data, or both, from this same lumber are also being examined for acceptance, this test shall be run with this new knot data and all new mechanical property, regardless of the outcome procedures for the other new data.

X1.3.5 If any of these tests is statistically significant, then proceed to Table X1.1. Otherwise, the two data sets can be treated as statistically equivalent.

X1.4 *Parametric Tests*—If a single parametric family contains both data sets (as judged by tests of goodness of fit), obtain maximum likelihood fits of the data sets to this parametric family. If these fits yield statistically different parameter estimates (for example, mean and variance estimates for normal fits; location, scale, and shape estimates for fits to a three-parameter Weibull), then proceed to Table X1.1. Otherwise, the two data sets can be treated as statistically equivalent.

X1.5 *Visual Inspection*—It is always wise to supplement formal statistical tests with visual inspection of data plots (Note X1.2). In general, these plots should not be used to overrule a finding that the two data sets are statistically different. They may be used, however, to overrule a finding that the two data sets are statistically equivalent. In this case, the investigator should then proceed to Table X1.1.

NOTE X1.2—For the purposes of this practice, three of the appropriate plots are (*1*) theoretical density superimposed on a data histogram, (*2*) theoretical cumulative distribution function superimposed on the empirical cumulative distribution function, and (*3*) probability plots (ordered data versus expected values of the ordered data).

X1.6 *Appropriate Statistical Methods*—The appropriate steps to take in analysis of data set are not easy to codify in advance. It may be appropriate to transform the data (for example, by taking logs) or to delete outliers before the main analysis begins. It might happen that the tests of goodness-of-fit do not reject either the normal or the Weibull families (say) so that fits to both might be made. If the sample sizes are" small," one might not want to rely on asymptotic maximum likelihood methods. Instead, one might want to rely on less powerful, but more robust nonparametric techniques. If it is desired that tests "emphasize regions of interest," censored data statistical methods will need to be used in place of more standard methods. In short, the exact course of an appropriate statistical analysis cannot be entirely specified in advance. Considerable judgment must be exercised. For this reason it is recommended that a professional statistician be involved at all stages of the statistical analysis.

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