Designation: D3737 – 12

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

This standard is issued under the fixed designation D3737; 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 properties for structural glued laminated timber. Included are the allowable stresses for bending, tension and compression parallel to the grain, horizontal shear, compression perpendicular to the grain, and radial tension and compression in curved members. Also included are modulus of elasticity and modulus of rigidity.

1.2 This practice is limited to the calculation of allowable properties 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 allowable properties developed using procedures in this practice, manufacturers must conform to recognized manufacturing standards. Refer to ANSI/AITC A190.1 and CSA O122.

1.4 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.5 *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:*[2]

D9 Terminology Relating to Wood and Wood-Based Products
D143 Test Methods for Small Clear Specimens of Timber
D198 Test Methods of Static Tests of Lumber in Structural Sizes
D245 Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber
D2395 Test Methods for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials
D2555 Practice for Establishing Clear Wood Strength Values
D2915 Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products
D4761 Test Methods for Mechanical Properties of Lumber and Wood-Base Structural Material
D5456 Specification for Evaluation of Structural Composite Lumber Products
D6570 Practice for Assigning Allowable Properties for Mechanically Graded Lumber
E105 Practice for Probability Sampling of Materials

2.2 *AITC Standards:*[3]

ANSI/AITC A190.1 Structural Glued Laminated Timber, 2007

2.3 *Other Standards:*

ANSI/AF&PA National Design Specification for Wood Construction[4]
CSA O122 Structural Glued Laminated Timber[5]

3. Terminology

3.1 *Definitions:*

3.1.1 *alternative lumber*—laminated veneer lumber (LVL), laminated strand lumber (LSL), oriented strand lumber (OSL), or parallel strand lumber (PSL) meeting the requirements of Specification D5456; or solid-sawn lumber that is produced according to Practice D6570 and the grading rules of the applicable grading or inspection agency.

3.1.2 *E-rated lumber*—lumber graded for use in manufacturing structural glued laminated timber by nondestructive measurement of a modulus of elasticity (E) and by visual

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

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from the American Institute of Timber Construction, 7012 S. Revere Parkway, Suite 140, Centennial, CO 80112, https://www.aitc-glulam.org.

[4] Available from American Forest and Paper Association (AF&PA), 1111 19th St., NW, Suite 800, Washington, DC 20036, http://www.afandpa.org.

[5] Available from Canadian Standards Association (CSA), 5060 Spectrum Way, Mississauga, ON L4W 5N6, Canada, http://www.csa.ca.

inspection in accordance with the grading rules of the applicable grading or inspection agency.

3.1.3 *glulam*—a term used to denote structural glued laminated timber, which is a product made from suitably selected and prepared pieces of wood bonded together with an adhesive either in a straight or curved form with the grain of all pieces essentially parallel to the longitudinal axis of the member.

3.1.4 *horizontally laminated timber*—a member designed to resist bending loads applied perpendicularly to the wide faces of the laminations (referred to as bending about the x-x axis).

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

3.1.6 *modulus of elasticity (E)*—for laminating, E is designated in two categories to distinguish mode of measurement and application.

3.1.6.1 *Long-Span E (LSE)*—the *modulus of elasticity* calculated from deflection measured in a flat-wise static bending test of lumber with a center point loading and a span-to-depth ratio (l/d) of approximately 100 or the E obtained from Test Methods D2555 and multiplying by the appropriate factors from Table 1 and Table 6.

3.1.6.2 *Member E* (E_{axial} , E_x, E_y)—the allowable *modulus of elasticity* values of the structural glued laminated member as defined in this practice.

3.1.7 *vertically laminated timber*—a member designed to resist bending loads applied parallel to the wide faces of the laminations (referred to as bending about the y-y axis).

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

3.1.9 *GDC*—the 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).

3.1.10 *GDE*—the 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).

3.1.11 *GDS*—the projected sum of all *GDE* and *GDC* values within a one-foot length of lumber as defined in Fig. 1.

3.1.12 *KC*—the ratio of the cross-sectional area of a knot located away from the edge of the lumber to the cross-sectional area of 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).

TABLE 1 Adjustment Factors for Clear Wood Stresses (Test Methods D2555)

Property	Multipliers for Average or 5th Percentile		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

3.1.13 *KE*—the ratio of cross-sectional area of a knot at the edge of wide face of lumber to the cross-sectional area of the lumber (see Fig. 2).

3.1.14 SR_{tl}—the required strength ratio of the tension lamination at the outermost fiber.

4. Materials Requirements

4.1 *Requirements for Laminations:*

4.1.1 Laminations of structural glued laminated timber shall be of lumber with net thickness of 2 in. (0.05 m) or less.

4.1.2 Lumber is permitted to be joined end to end with structural end joints to form long length laminations. End joints shall be qualified and quality controlled with a recognized manufacturing standard.

4.1.3 Lumber is permitted to be placed or joined side to side to form wide laminations.

4.1.4 Dimension lumber used to form laminations shall be visually graded or E-rated according to established grading rules.

4.1.5 Alternate lumber material is permitted by demonstrating equivalence to a dimension lumber grade in accordance with Annex A1.

4.1.6 For the analysis of a structural glued laminated timber layup, all laminations in a single cross section shall be of equal thickness.

4.1.7 The analytical procedures of this standard practice are based on specific lamination characteristics.

4.1.7.1 Lumber properties including knot size and frequency, physical properties such as specific gravity, and mechanical properties such as modulus of elasticity shall be based on measurements of 2 × 6 lumber for definition of grade characteristics.

4.1.7.2 The effect of decay or compression failures 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.

4.1.7.3 Compression wood (as defined in Terminology D9) in readily identifiable and damaging form shall be limited in accordance with 4.1.7.3 *(1)* and 4.1.7.3 *(2)*.

(1) For dry service conditions, 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.

(2) For wet service conditions, or for pressure-treated members, the conditions of 4.1.7.3 *(1)* apply except that compression wood is limited to 5 % of the cross section of the

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 D245.
[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 Test Methods D198 will yield strength values such that the lower 5th 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.

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]		Compression Stress Index Parallel to Grain[B,C]	
	psi	MPa	psi	MPa
1 600 000	2560	17.7	1900	13.1
1 900 000	3000	20.7	2400	16.5
2 100 000	3500	24.1	2800	19.3
2 300 000	4000	27.6	3100	21.4

[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.

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

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 D245.

laminations in tension members and in the outer 10 % of the total depth on the tension side of bending members.

4.1.7.4 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.

4.2 *Requirements for Adhesives:*

4.2.1 Adhesives for use in structural glued laminated timber shall be rigid (non-elastomeric) to ensure composite action of the laminations and shall be sufficiently strong to transfer stresses required by the intended use of the member.

4.2.2 Adhesives shall be sufficiently durable to provide bond for the life of the glued laminated member in its expected service environment.

4.3 *Tension Laminations*—for horizontally laminated bending members shall meet the requirements herein.

4.3.1 The results of full-size beam tests reported in Refs (**1-3**)[6] have yielded an empirical relationship between the size of knots in the tension zone and bending strength. This relationship dictates that special grading considerations be applied to the laminations used in the outer 10 % of the beam depth on the tension side. This tension side may exist on the top or bottom of the beam, or both, depending upon loading and support conditions. If horizontally laminated timbers are manufactured without applying these special tension lamination grading considerations, the allowable bending stress shall be reduced by multiplying the allowable stress calculated in 7.2.1.1 by 0.85 if the depth is 15 in. (0.38 m) or less or by 0.75 if the depth exceeds 15 in. (0.38 m).

4.3.2 *Visually Graded Lumber:*

4.3.2.1 Definitions of terms required for calculation of knot and grain deviation restrictions are listed in 3.1.9 – 3.1.14.

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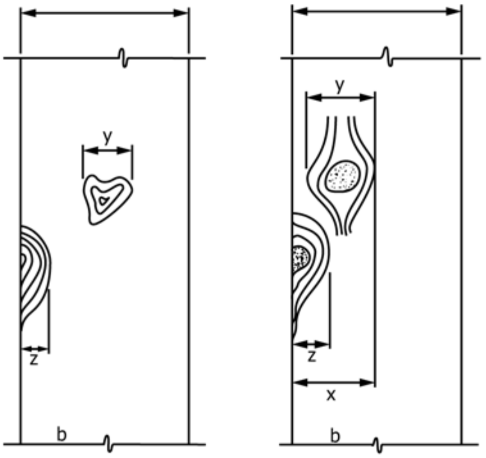
[6] The boldface numbers in parentheses refer to a list of references at the end of this practice.



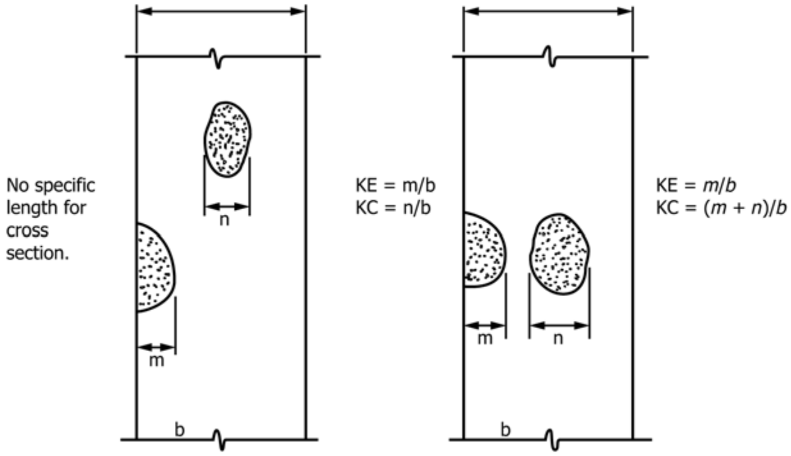
(*a*)

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.

(*b*)

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

4.3.2.2 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 8-11 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).

4.3.2.3 *Beams Greater than 15 in. (0.38 m) in Depth:*

(1) Outer 5 %—Grain deviation shall be limited in accordance with Eq 1 and 2.

$$GDS \leq 1.55(1 - SR_{tl}) \tag{1}$$

$$GDS \leq 1.82(1 - SR_{tl}) \tag{2}$$

(a) Eq 1 shall be used when *GDE*, with or without *GDC*, is used to determine *GDS* (Fig. 1). Eq 2 shall apply when *GDE* is not used to determine *GDS*. In addition, general slope of grain shall not exceed 1:16 if the required strength ratio of the tension lamination is 0.60 or greater. If SR_{tl} is less than 0.60, the general slope of grain shall not exceed 1:12.

(2) Next Inner 5 %—Knots are restricted in accordance with Eq 3 and 4.

$$KE = 0.66 - 0.45\, SR_{tl} \tag{3}$$

$$KC = 1.20 - 0.93\, SR_{tl} \tag{4}$$

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

4.3.2.4 *Beams 12 in. (0.30 m) to 15 in. (0.38 m) in Depth:*

(1) Outer 5 %—The requirements of 4.3.2.3 *(1)* apply except that SR_{tl} shall be multiplied by 0.90 in Eq 1 and 2. The value of 0.9 SR_{tl} shall not be taken as less than 0.50.

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

4.3.2.5 *Beams of Four or More Laminations and Less than 12 in. (0.30 m) in Depth:*

(1) Outer 5 %—The requirements of 4.3.2.3 *(1)* apply except that SR_{t1} shall be multiplied by 0.80 in Eq 1 and 2. The value of 0.80 SR_{t1} shall not be taken as less than 0.50.

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

4.3.2.6 *Density Requirements:*

(1) Outer 5 %—Density requirements shall apply to the full length of the piece of lumber. In order to ensure that lumber is near-average or above specific gravity for the species, visually graded tension laminations shall have a minimum specific gravity of at least 94 % of the recognized species average from Test Methods D2555 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.

4.3.2.7 *Other Requirements:*

(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. In addition, for wet service conditions or pressure-treated members, compression wood is limited to a maximum of 5 % of the cross section.

4.3.3 *E-Rated Lumber:*

4.3.3.1 *Grading Requirements:*

(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 4.3.2.2, 4.3.2.3 *(1)*, and 4.3.2.4 *(1)*, with the exception of the knot and slope of grain requirements as given in 4.3.3.3.

4.3.3.2 *Other Requirements:*

(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. In addition, for wet conditions of use or pressure-treated members, compression wood is limited to a maximum of 5 % of the cross section.

4.3.3.3 The portions of the piece not subjected to mechanical *E* measurements shall have visual criteria applied to ensure piece quality. Edge knots up to the size permitted in the grade are acceptable. Other knots are limited to the visual requirements of the bending stress index 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 4.3.3.2. Medium grain growth requirements shall be met for Douglas Fir-Larch and Southern Pine.

4.3.4 Tension laminations to meet the requirements identified in 4.3.1 may be qualified by test as an alternative to the grading criteria of 4.3.2 and 4.3.3. The procedure given in Annex A1 shall be used.

5. Allowable Properties for Glued Laminated Timber Members

5.1 Allowable properties for individual laminations shall be obtained by multiplying the stress index values from Section 6 by the stress modification factors from Section 7 and modifying for specific conditions from Section 8. Allowable properties for glulam members shall be calculated as described in 5.3 – 5.11.

5.2 Allowable properties shall be rounded to the significant digits as shown in the following table:

Bending, tension parallel to grain, and 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 and radial stresses in curved members	Nearest 5 psi (0.05 MPa)
Modulus of elasticity	Nearest 100 000 psi (500 MPa)

5.3 The allowable bending stress for horizontally laminated timbers shall be calculated as shown by example in Annex A4.

5.4 The allowable bending stress of vertically laminated timbers shall be determined by the following equation:

$$F_{by} = Min\left\{\frac{F_{by\ i}}{E_i}\right\}(E_{avg}) \geq Min\left\{F_{by\ i}\right\} \tag{5}$$

where:

F_{by} = allowable bending stress of the vertically laminated beam,

E_{avg} = weighted average of the component lamination *LSE* values,

$F_{by\ i}$ = allowable bending stress for the *i*th lamination in the combination which is obtained by multiplying the stress index value from 6.1.1 or 6.1.1.1 by the lower of the stress modification factors from 7.2.2.1 and 7.2.2.2 and modifying for specific conditions from Section 8.

E_i = *LSE* for the *i*th lamination.

5.5 *Compression Parallel to Grain*—The allowable stress for compression parallel to grain shall be calculated as shown by example in Annex A5.

5.6 *Tension Parallel to Grain*—The allowable stress for tension parallel to grain shall be the minimum allowable stress of the individual laminations in the member, which is obtained by multiplying the tension stress index from 6.1.3 by the lower of the stress modification factors from 7.4.2 and 7.4.3 and modifying for specific conditions from Section 8.

5.7 *Member E:*

5.7.1 *Axially Loaded Timbers*—Eaxial shall be the weighted average of the individual lamination grade *LSE* values modified for specific conditions from Section 8.

5.7.2 *Vertically Laminated Timbers*—E_y shall be 95 % of the weighted average of the individual lamination grade *LSE* values modified for specific conditions from Section 8.

5.7.3 *Horizontally Laminated Timbers*—E_x shall be 95 % of the apparent modulus of elasticity as determined by a transformed section analysis using the *LSE* values for each grade in the combination modified for specific conditions from Section 8.

5.8 *Horizontal Shear:*

5.8.1 *Horizontally Laminated Timbers*—For horizontally laminated timbers, the allowable stress in horizontal shear shall be determined using the following equation:

$$F_{vx} = Min\left(\frac{F_{vx,i}}{1 - \left(\frac{c_i}{c}\right)^2}\right) \tag{6}$$

where:

F_{vx} = allowable shear stress for the horizontally laminated member,

$F_{vx,i}$ = allowable shear stress for the *i*th lamination, which is determined by multiplying the shear stress index from 6.1.5 or 6.1.5.1 by the shear stress modification factor from 7.6.1 modified for specific condition from Section 8,

c_i = distance from the neutral axis of the horizontally laminated timber to the innermost fiber of the *i*th lamination,

c = distance from the neutral axis of the horizontally laminated timber to the outermost fiber in the member, and

i = 1 to n.

Because the test procedure referenced in 6.1.5.1 utilizes prismatic beams subject to static, monotonic loading and produces significantly higher values than the procedure described in 6.1.5, shear stress values determined using 6.1.5.1 shall be limited to straight beams of constant cross section, which are not subject to impact or cyclic loads.

5.8.2 *Vertically Laminated Timbers*—For vertically laminated timbers, the allowable stress in horizontal shear shall be the weighted average of the allowable stresses for the individual laminations, which are determined by multiplying the shear stress index from 6.1.5 or 6.1.5.1 by the appropriate shear stress modification factor from 7.6.2 modified for specific conditions from Section 8. Because the test procedure referenced in 6.1.5.1 utilizes prismatic beams subject to static, monotonic loading and produces significantly higher values than the procedure described in 6.1.5, shear stress values determined using 6.1.5.1 shall be limited to straight beams of constant cross section, which are not subject to impact or cyclic loads.

5.9 *Compression Perpendicular to Grain*—Allowable stresses in compression perpendicular to grain for the glulam member shall be determined based on the location of the applied stress. The allowable stress for the lamination, as determined by multiplying the stress index from 6.1.6 by the stress modification factor from 7.7.1 at the location of the applied stress shall be the allowable stress for the glulam member.

5.10 The modulus of rigidity of glued laminated members can be considered to have a constant relationship to the modulus of elasticity. For design purposes, the relationship $G = E_x/K$ shall be used for members consisting of a single grade, where $K = 16$ when specific data is not available. For members consisting of multiple grades of lumber the modulus of rigidity shall be obtained by using the *LSE* of the lowest grade applied to the entire member.

5.11 *Radial Stress in Curved Members:*

5.11.1 *Radial Tension*—The allowable stress for radial tension in curved members shall be equal to the allowable stress for radial tension for the lamination with the lowest value.

5.11.2 *Radial Compression*—The allowable stress for radial compression in curved members shall be equal to the allowable stress for compression perpendicular to the grain for the lamination with the lowest value.

6. Stress Index Values for Laminations

6.1 *Visually Graded Lumber*—Test Methods D2555 provides information on clear wood strength properties and their expected variation for small clear, straight-grained specimens of green lumber. Based on these clear wood properties, stress index values shall be calculated, unless otherwise permitted herein.

6.1.1 *Bending*—The bending stress index shall be determined by calculating the 5th percentile of modulus of rupture in accordance with Test Methods D2555, multiplying by the appropriate factors in Table 1, and 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 As an alternative to 6.1.1, testing and analysis of large glued laminated timber beams of Douglas Fir-Larch, Southern Pine and Hem-Fir indicate that the stress indices given in Table 2 may be used 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 *Compression Parallel to the Grain*—The compression stress index parallel to grain shall be determined by calculating the 5th percentile strength in compression parallel to the grain in accordance with Test Methods D2555 and multiplying by the appropriate factors from Table 1.

6.1.3 *Tension Parallel to the Grain*—The tension stress index parallel to grain shall be five eighths of the bending stress index obtained in 6.1.1 or 6.1.1.1.

6.1.4 *Modulus of Elasticity*—The stress index value for modulus of elasticity shall be the average long span modulus of elasticity as defined in 3.1.6.1.

6.1.4.1 As an alternative to 6.1.4, values from Table 2 based on testing of large samples of lumber of the species groups listed in 6.1.1.1 and multiplied by appropriate factors from Table 6 are permitted to be used for *LSE*.

6.1.5 *Horizontal Shear*—The horizontal shear stress index shall be the lower 5th percentile of clear wood shear strength, determined in accordance with Practice D2915 using the data given in Test Methods D2555 and multiplying by the appropriate factors from Table 1. The horizontal shear stress index for coarse-grain Douglas Fir-Larch and Southern Pine shall be 70 % of the value used for medium-grain materials.

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 D198 with specific loading details as shown in Annex A7. 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 D2915 and the analysis procedures given in Annex A7. The horizontal shear stress index is determined by multiplying the lower 5th percentile tolerance limit of shear strength by $^{1}/_{2.1}$. Reassessment of the horizontal shear stress index derived from this section shall be conducted for beam configurations that are not included in the consideration of the testing described in this section, or if there is a significant change in the lumber resource or in the lamination grading system or the manufacturing process.

6.1.6 *Compression Perpendicular to the Grain*—The stress index value for compression perpendicular to grain shall be determined as follows (**4**):

$$F_{C\perp} = (2674\,SG - 551.3)\,(1.9/1.67) \qquad (7)$$

where:

$F_{C\perp}$ = stress index value in compression perpendicular to grain; and
SG = average green specific gravity from Test Methods D2555 or, for a species group, the standing timber volume weighted average green specific gravity, adjusted as shown in 6.1.6.1, 6.1.6.2, or 6.1.6.3.

6.1.6.1 For purposes of calculating stress index values in compression perpendicular to grain 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 shall be as follows:

Close grain—0.03
Medium grain—0.04

6.1.6.3 As an alternative to the method specified in 5.6.1 of Practice D245, lumber is permitted to be qualified as dense by weighing. The lumber specific gravity, adjusted to a green condition using Test Methods D2395, Appendix X1 conversion formula, shall meet the reduced specific gravity as specified in 6.1.6.1. The reduced value shall be used in Eq 2 to determine the stress index value in compression perpendicular to grain.

6.1.7 *Radial Tension*—The stress index for radial tension shall be limited to one third of the value for horizontal shear as determined in accordance with 6.1.5, except for Douglas Fir-Larch, Hem-Fir, Douglas Fir South, Eastern Spruce, Canadian Spruce Pine, and mixed Softwood Species, which are prescriptively limited to 15 psi (0.10 MPa) for other than wind or earthquake loads. For wind and earthquake loading of all species groups, the allowable stress shall be one third of the allowable stress for horizontal shear determined in accordance with 6.1.5.

6.2 *E-Rated Lumber*—This method is based on lumber that has been *E*-rated and visually graded in accordance with Annex A1. *E*-rated lumber is designated by the modulus of elasticity and the size of the edge characteristics permitted in the grade such as 1.6*E*-⅓, etc. Edge characteristics include knots, knot holes, burls, localized grain deviation or decay (partially or wholly) at edges of wide faces.

6.2.1 Bending stress index values for *E*-rated lumber with various *LSE* values are given in Table 3.

6.2.2 *Compression Parallel to Grain*—Compression parallel to grain stress index values for *E*-rated laminations shall be as given in Table 3.

6.2.3 *Tension Parallel to Grain*—The tension stress index for *E*-rated Laminations shall be five eighths of the bending stress index obtained in 6.2.1.

6.2.4 *Modulus of Elasticity*—The stress index for modulus of elasticity for *E*-rated laminations shall be the *LSE* as defined in 3.1.6.1.

6.2.4.1 *LSE* values shall be permitted to be determined by tests of lumber meeting the criteria of Annex A2.

6.2.5 *Horizontal Shear*—The stress index value for horizontal shear for *E*-rated laminations shall be determined in the same manner as for visually graded laminations in 6.1.5 or 6.1.5.1.

6.2.6 *Compression Perpendicular to Grain*—The stress index in compression perpendicular to grain for *E*-rated laminations shall be determined as follows, using the *LSE* listed in Table 3 and the growth rate classifications.

(1) Dense—If the average *LSE* of the *E*-rated grade 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 per 6.1.6 shall be used.

(2) Medium Grain—If the average *LSE* of the *E*-rated grade is less that the average *LSE* of the species or species groups, but not more than 300 000 psi below the average, the stress index determined for medium grain lumber per 6.1.6 shall be used.

(3) Other—When the average *LSE* of the *E*-rated grade is less than the average *LSE* of the species or species group minus 300 000 psi, the stress index value shall be determined by using a specific gravity of 0.8 times the average specific gravity of the species in solving Eq 2. (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 stress for compression perpendicular to grain is permitted to be determined in accordance with the applicable provisions of Refs (**5-8**).

6.2.7 *Radial Tension*—The stress index in radial tension shall be determined in the same manner as for visually graded laminations in 6.1.7.

7. Stress Modification Factors (SMF) for Laminations

7.1 For some strength properties, knots, slope of grain, and other characteristics may affect the strength and therefore reductions in the stress index values are required. This section discusses the stress modification factors applicable to laminations in structural glued laminated timber.

7.1.1 Special tension lamination grades of lumber as described in 4.3 are required to justify the bending stress modification factors determined in 7.2.1.1.

7.1.2 Slope of grain stress modification factors shall not be applicable to *E*-rated laminations. However, slope of grain restrictions in 4.3.2.3 (*a*) for tension laminations in the outer 5 % of bending members shall apply to *E*-rated laminations.

7.2 *Bending Stress Modification Factor*—The bending stress modification factor for each lamination shall be the lower of the two modification factors determined separately on the basis of knots and on the basis of slope of grain.

7.2.1 *Horizontally Laminated Timbers*—The bending stress modification factor for laminations in horizontally laminated timbers (SMF_{bx}) shall be the lower of the two stress modification factors determined separately for knots and slope of grain as follows:

7.2.1.1 *Knots*—The bending stress modification factor for knots ($SMF_{bx\ knots}$) shall be determined for the lamination at the outer edge of each grade zone. All laminations in the same grade zone shall be permitted to use the same stress modification factor for knots. Transformed section analysis shall be used to locate the neutral axis of the beam. The " half beam" on each side of the neutral axis shall be considered independently after locating the neutral axis. Knots 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 can be 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 the critical cross section and I_G is the gross moment of inertia. Knot properties shall be determined following the procedures given in Annex A3 and I_K/I_G ratios shall be calculated following procedures given in Annex A4. Additional information is given in Refs (**1**) and (**9**). The stress modification factor in bending shall be determined from the following relationship:

$$SMF_{bx\ knots} = \left(1 + 3\frac{I_K}{I_G}\right)\left(1 - \frac{I_K}{I_G}\right)^3\left(1 - \frac{I_K}{2I_G}\right) \quad (8)$$

where:

$SMF_{bx\ knots}$ = bending stress modification factor.

(1) For visually graded laminations, the minimum value of $SMF_{bx\ knots}$ shall not be less than the strength ratio in flatwise bending as determined by formula X1.2 of Practice D245.

(2) For *E*-rated laminations, the minimum value of $SMF_{bx\ knots}$ shall not be less than the appropriate factor from Table 7.

7.2.1.2 *Slope of Grain*—The bending stress modification factor for slope of grain ($SMF_{bx\ SOG}$) for each lamination shall be as given in Table 4. Stress modification factors given for tension shall apply to laminations in the tension side of bending members while those given for compression shall apply to laminations in the compression side.

7.2.2 *Vertically Laminated Timbers*—The bending stress modification factor for laminations in vertically laminated timbers shall be the lower of the two modification factors determined separately for knots and slope of grain as follows:

7.2.2.1 *Knots*—The bending stress modification factor for knots ($SMF_{by\ knots}$) shall be determined from the following empirical relationship (**10**):

$$SMF_{by\ knots} = C_1(SR_1^{\gamma})(N^{\alpha})(1 - 1.645\,\Omega_1/N^{1/2}) \quad (9)$$

where:

C_1 = empirical constant from Table 5,
SR_1 = strength ratio from Practice D245 for an individual piece of lumber loaded on edge,
γ = empirical constant equal to 0.81,
α = 0.329 ($1 - 1.049SR_1$),
N = number of laminations in the member of the same grade or higher up to 5 (for members with five or more laminations of the same grade or higher, $N = 5$), and
Ω_1 = coefficient of variation (COV) of bending strength for individual laminations. The applicable COV for individual laminations of visually graded lumber shall be 0.36. The applicable COV for *E*-rated laminations shall be 0.24, except for grades that permit the edge characteristics to occupy up to one half of the cross section: in which case, the coefficient of variation shall be 0.36.

7.2.2.2 *Slope of Grain*—The bending stress modification factor for slope of grain ($SMF_{by\ SOG}$) for each lamination shall be equal to the appropriate slope of grain stress modification factor for tension from Table 4.

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

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

E-Grade Designation^A	Minimum Stress Modification Factor (SMF) Horizontally Laminated Bending	Vertically Laminated Bending	Compression Parallel to Grain
⅙	0.80	0.70	0.80
¼	0.75	0.65	0.75
½	0.50	0.25	0.50

^{A} The second part of the *E*-grade designation (for example, 2.0-1/6) 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.

7.3.1 The compression stress modification factor (SMF_c) for laminations in members with four or more laminations shall be the lower of the two modification factors determined separately from knots and slope of grain as follows:

7.3.2 *Knots*—A single compression stress modification factor for knots ($SMF_{c\ knots}$) shall be determined for the entire cross section. $SMF_{c\ knots}$ shall be applied to each lamination in the cross section. Tests have shown that the axial compressive strength of short compression members is related to the ratio of the area of knots in the cross section to the gross cross sectional area. Procedures for estimating values of this ratio for compression members are given in Annex A5. The stress modification factor for knots shall be determined from the following empirical relationship.

$$SMF_{c\ knots} = \frac{(A_K/A_G)^3}{4} - (A_K/A_G)^2 - \frac{(A_K/A_G)}{4} + 1 \qquad (10)$$

where:

$SMF_{c\ knots}$ = compression stress modification factor for knots, and

A_K/A_G = ratio of the area of knots in the cross section to gross cross sectional area as defined in Annex A5.

For members with grades of lumber placed unsymmetrically, an additional adjustment, given in Annex A5, is necessary to compensate for additional bending stresses.

7.3.3 *Slope of Grain*—The compression stress modification factor for slope of grain ($SMF_{c\ SOG}$) for each lamination shall be as given in Table 4.

7.3.4 The stress modification factor in compression parallel to grain for laminations in members of two or three laminations shall be the same as the strength ratio determined using Practice D245 for a single piece of lumber of the applicable grade.

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

7.4.1 The stress modification factor for tension parallel to grain (SMF_t) for each lamination shall be the lower of the two modification factors determined separately on the basis of knots and on the basis of slope of grain as follows:

7.4.2 *Knots*—The tension stress modification factor for knots ($SMF_{t\ knots}$) shall be determined as follows:

$$SMF_{t\ knots} = 1 - Y_2 \qquad (11)$$

where:

$SMF_{t\ knots}$ = 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 for visually graded laminations shall be limited to that resulting in an equivalent edgewise bending strength ratio as determined by Practice D245.

7.4.3 *Slope of Grain*—The tension stress modification factor for each lamination shall be as given in Table 4.

7.5 *Modulus of Elasticity (E)*—When *LSE* is determined by test methods other than those described in 3.1.6.1, then modification factors described in section 4.3 of Practice D2915 shall be applied.

7.6 *Horizontal Shear:*

7.6.1 *Horizontally Laminated Timbers*—The stress modification factor for horizontal shear for laminations in horizontally laminated timbers shall be calculated as the ratio of the wane-free width to total surfaced width. Thus, when wane up to ⅙ of the width is allowed along both edges, the stress modification factor shall be ⅔ .

7.6.2 *Vertically Laminated Timbers*—For members consisting of four or more laminations, one out of four pieces is assumed to have a check or split that limits its modification factor in shear to ½ resulting in a modification factor of the composite of ⅞ . For two and three lamination beams, the modification factor is ¾ and ⅚ . For vertically laminated timbers composed of 3, 5, 7, or 9 laminations with unbonded edge joints, an additional modification factor of 0.4 shall be applied to each lamination. For all other vertically laminated timbers composed of laminations with unbonded edge joints, an additional modification factor of 0.5 shall be applied to each lamination.

7.7 *Compression Perpendicular to Grain and Radial Compression:*

7.7.1 A stress modification factor of 1.0 shall be applicable to all laminations.

7.8 *Radial Tension:*

7.8.1 A stress modification factor of 1.0 shall be applicable to all laminations.

8. Adjustment of Properties for End-Use Conditions

8.1 The allowable properties developed using Sections 6 and 7 are based on normal load duration, 12 % average moisture content conditions, and approximately 68°F (20°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.

8.2 *Moisture Content*—Two different moisture conditions are recognized for structural glued laminated timber members: dry service and wet service. Dry service is the use condition where the moisture content of the wood is less than 16 %. Wet service is the use where wood attains moisture contents of 16 % or more. For wet service conditions, properties developed using Sections 6 and 7 shall be multiplied by the appropriate factors given in Table 8.

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

8.3 *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 are permitted to be increased in accordance with Practice D245. For longer durations of load, all properties except E and compression perpendicular to grain shall be decreased in accordance with Practice D245.

8.4 *Flat Use Factor*—For bending members with the load applied parallel to the wide face of the laminations (vertically laminated members), the bending stress shall 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.

8.5 *Volume Factor*—For bending members with the load applied perpendicular to the wide face of the laminations (horizontally laminated members), the bending stress shall be adjusted for sizes greater than the standard size beam (as defined below) by multiplying by the volume effect factor, C_V, defined as follows:

$$C_V = [5.125/w]^{1/x}\,[12/d]^{1/x}\,[21/L]^{1/x} \leq 1.0 \qquad (12)$$

where:

d = beam depth, in.;
w = beam width, in.;
L = length of beam between points of zero moment, ft; and
x = determined by procedures outlined in Annex A8.

The standard beam is assumed to be uniformly loaded and is defined as having a depth of 12 in. (0.3 m), a width of 5⅛ in. (0.13 m) and a length of 21 ft (6.4 m). For other than uniformly loaded members, adjustments for method of loading (Table 9) are necessary.

8.6 *Curvature*—For the curved portion of members, the allowable bending stress shall be reduced by the curvature factor, $C_c = 1 - 2000(t/R)^2$ 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 during manufacture, the t/R ratio should not exceed $1/100$ for hardwoods and southern pine and $1/125$ for other softwood species.

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

8.7 *Treated Wood:*

8.7.1 Allowable properties associated with pressure preservative treated or fire-retardant treated members, whether the lumber is treated prior to gluing or the entire member is treated following gluing, shall take into account possible reductions due to high temperatures, pressure, or chemical effects associated with the treating process. When reductions are applicable they shall be based on tests of material subjected to the specific treatment conditions.

8.7.2 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 shall be based on tests of the incised material.

8.8 *Temperature*—Reductions in some allowable properties are applicable when the member is exposed to abnormally high temperatures, especially for extended periods of time, or for exposure combining high temperatures and high moisture content. Increases to some allowable properties may be applicable for members used in continuous cold climatic conditions. See guidelines given in Ref **(11)**.

8.9 *Shear Deflection*—Member E values for bending combinations, calculated in accordance with Section 5. are applicable for a 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.

9. Keywords

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

ANNEXES

(Mandatory Information)

A1. QUALIFICATION OF LAMINATIONS BY TEST

A1.1 If lumber is to be qualified by test as equivalent to visually graded or *E*-rated laminations, procedures in this section shall be followed. Tests shall include *LSE*, tensile strength, and specific gravity. Values for compression perpendicular to the grain and horizontal shear shall be determined following procedures previously described in this standard.

A1.1.1 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.

A1.1.1.1 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 A1.1—As an example, qualification of a 2.0*E*, ⅙ edge knot grade in nominal 2 by 6 for a tension lamination target will qualify the same grade in 2 by 4 if the same *E* selection levels and edge knot selection criteria are used.

A1.1.1.2 Principles of Practice D2915 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.

A1.2 Qualification by test shall include a flatwise bending modulus of elasticity on a 100:1 span-to-depth ratio (see 3.1.6.2).

A1.2.1 Qualification tests for *LSE* shall be carried out in accordance with Test Methods D198 or D4761.

A1.2.2 To qualify by *E* criterion, the average *LSE* (*E*) of the sample shall meet the following criteria:

$$(E)\left[1+0.237(COV)\right] \geq E_o \qquad (A1.1)$$

where:

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

E_o = average *LSE* of the target grade for which replacement is sought.

NOTE A1.2—For example, assume the target grade is 302-24 from *D.* Fir L with an *LSE* of 2.1 × 10^6 psi. The candidate stock is *MSR* lumber. The *COV* of the qualification sample does not exceed 0.11 as given in the ANSI/AF&PA. The product of *LSE* of the candidate sample and 1.026 must equal or exceed 2.1. As a second example, assume the target grade is 302-24 from Hem-Fir SSS with an *LSE* of 1.8 × 10^6 psi. The candidate stock is visually graded; the ANSI/AF&PA *COV* for visually graded lumber is 0.25. The product of *LSE* of the candidate stock and 1.059 must equal or exceed 1.8.

A1.3 Qualification shall include a strength test of full-size laminations in tension.

A1.3.1 Tensile testing procedures shall follow the principles of Test Methods D198 or D4761 with a minimum gage length of 8 ft (2.4 m).

A1.3.2 To qualify by tensile strength criteria, the lower tolerance limit of the 5th percentile with 75 % confidence shall be determined from the qualification sample. The analysis procedure of Practice D2915 shall be followed.

A1.3.3 For tension laminations, the 5th percentile so determined must equal or exceed the following multiple of the allowable bending property of the target grade for which qualification is desired: for beams over 15 in. (0.38 m) deep-1.67, for beams 12–15 in. (0.30–0.38 m) deep-1.50, and for beams less than 12 in. (0.30 m) deep-1.34.

A1.3.4 For other laminating grades, the 5th percentile shall equal or exceed the 5th percentile of the laminating grade for which replacement is sought.

A2. GLUED LAMINATED TIMBERS MANUFACTURED WITH *E*-RATED LUMBER

A2.1 General

A2.1.1 Glued laminated timbers are permitted to be made with *E*-rated lumber or a combination of *E*-rated lumber and visually graded lumber. For the combination of *E*-rated lumber and visually graded lumber, 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 A2.2 and A2.3.

A2.2 *E*-Rated Requirements

A2.2.1 Any method is permitted to be used for sorting *E*-rated lumber provided that quality control requirements ensure that the *LSE* of the lumber meets or exceeds the requirements for the specified grade mean *LSE* and a lower 5th percentile calculated as follows:

$$E_{05} = 0.955\,E_{\text{mean}} - 0.233 \tag{A2.1}$$

where:

E_{05} = 5th percentile *LSE* (million psi), and
E_{mean} = average *LSE* (million psi).

A2.3 Visual Grading Requirements

A2.3.1 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 indicated by the grade designation. For example, in a 2.1*E*-⅙ grade, the edge characteristics described above must not exceed one sixth of the cross section.

A2.4 Designation

A2.4.1 *E*-rated lumber for laminating shall be designated by the *LSE* and the fraction of the cross section at the edge that may contain the growth characteristics given in A2.3.

A3. SAMPLING OF LUMBER FOR KNOT AND MODULUS OF ELASTICITY DATA

A3.1 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 horizontally laminated timbers and to determine compression parallel to grain strength. Data on *LSE* of the lumber is needed in order to calculate stress distributions in beams and to determine the stiffness of the beams. Different levels of sampling are recognized for collecting these 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 E105. In addition, an alternative method of sampling is given in A3.2.2 when a limited amount of information exists for a particular species of lumber.

A3.2 Knot Data

A3.2.1 *Data Collection:*

A3.2.1.1 *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.

A3.2.1.2 *Confirmation*—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. If the grade is being used by four or less glulam manufacturers, it is recommended that at least two visits be made to collect the sample. This confirming survey shall be used to modify, if necessary, combinations based on the development survey. A3.2.2 of this annex shall be used to evaluate the confirming knot data.

A3.2.1.3 *Use*—After the confirming survey has been made, subsequent surveys shall be conducted at least every three years. The results shall be reviewed in accordance with A3.2.2. Alternatively, a continuous sampling procedure may be used in which knot data are collected on a frequent, periodic basis and the accumulated data reviewed for changes sufficient to require design changes. Accumulated data shall be analyzed at intervals not exceeding two years.

A3.2.1.4 Resampling for knot data is required if knot size measurement or interpretation are changed or if design properties associated with knot data (for example, stress index values, *LSE*) are increased.

A3.2.1.5 Guidelines for measuring knots and for calculating knot properties are given in Annex A6.

A3.2.1.6 Knot data for horizontal 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 (0.06-m) intervals, and the determination of the 99.5-percentile knot size.

A3.2.1.7 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 (0.90-m) length taken at 0.5-ft (0.15-m) intervals.

A3.2.2 *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 Annex A6) is recommended.

A3.2.2.1 *Substantiation*—Where new data is demonstrably well representative of the population, but does not present significant differences stated in Annex A6, 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.

A3.2.2.2 *Augment Existing Data*—Where new data is demonstrably well representative of the population, but does not present significant differences as stated in Annex A6, 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.

A3.2.2.3 *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 the above, 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.

A3.3 *LSE* Data

A3.3.1 The *LSE* as defined in 3.1.6.1 shall be measured on each piece sampled for A3.2 of this annex. The average and variance of *LSE* shall be calculated for the batch lots sampled in accordance with A3.2.1.1 – A3.2.2.3. The mean and variability of *LSE* shall be monitored for samples taken as part of the continuous sampling provisions of A3.2.1.3.

A3.3.2 *LSE* data shall be collected on specimens having 12 ± 2 % MC whenever possible to minimize correction error. Data shall be corrected to 12 % moisture content using Practice D2915.

A3.3.3 *LSE* data may be collected on laminating grades in sampling supplement to those corresponding to A3.2. The same sampling and analysis principles shall be used. Increases in *LSE* identified using the evaluation principles of Annex A7 may not be employed in 6.1.4 unless coincident knot data is collected and evaluated in accordance with A3.2.

A3.3.4 An evaluation of the adequacy of existing *LSE* data shall be made for sampling conducted in concert with A3.2. The general principles of evaluation as outlined for knot data in A3.2 and Annex A6 shall be used.

A3.4 Special Provisions for Initial Development

A3.4.1 An alternative method of establishing knot and *LSE* data for initiation of laminating shall be used where ASTM clear wood properties of a species have not recently been reassessed or the availability of lumber data is too limited to meet the sampling criteria of A3.2.1.1, or both. An example would be a candidate application where only non-structural grades currently exist; thus, generation of representative laminating grades may be difficult until feasibility can be demonstrated. This method requires collecting sufficient candidate lumber to permit measurement of knot frequency and *LSE* on each grade for preliminary layup calculations and beam tests, if necessary. A minimum of 100 pieces of lumber of each of the grades in the outer tension and compression zones is required and 50 pieces of the lumber grades used in other zones. Average length of the pieces should equal or exceed either 10 ft (3.0 m) or the average length of the lumber intended for production.

A3.4.2 It is intended that these data will be superseded by the practices of A3.2 and A3.3 once production of glulam timber using the lumber begins. The application of this alternative is intended to be limited by elapsed time or quantity of production.

A3.4.3 The following special quality control procedures shall be during the application of these special provisions of Annex A3.

A3.4.3.1 *Qualification*—The lumber sampled in A3.4.1 shall form the basis for determining the material properties and the basis for subsequent quality control parameters. For lumber selected for beam production, knot properties and *LSE* shall be measured on sample sizes of lumber similar to those given in A3.4.1. Measurement of specific gravity is recommended as an additional index of wood quality during this initial phase. Knot data shall be analyzed for *x*-bar and *h*, both for use in the layup analysis and for subsequent use in quality control. Knot and *LSE* properties of this sample shall be consistent with that developed in A3.4.1.

A3.4.3.2 *Quality Control*—Lumber shall be randomly sampled to determine wood quality during production. Knot data and *LSE* of these samples shall be determined; measurement and control of specific gravity is also recommended.

A3.4.4 *Reassessment*—If the quality control procedures in A3.4.3.2 indicate out-of-conformance with the sample of A3.4.1, production shall be stopped and standard procedures taken to assess production lots for conformance before resuming production. Significant changes noted in the lumber properties require reassessment of the appropriateness of the layup combination, including the initial lumber property assumptions. Quality control data may form the basis for a new set of properties to use in A3.4.1.

A4. ANALYSIS OF A HORIZONTALLY LAMINATED GLULAM BEAM

INTRODUCTION

This annex provides procedures and an example for applying the principles outlined in 7.2 and 4.3.

A4.1 *Procedures*— The following steps shall be followed in the analysis of horizontally laminated beams.

A4.1.1 The location of the neutral axis of the transformed section shall be determined using Eq A4.1, and the distance from the neutral axis to the edges of each grade zone in the beam shall be determined using Eq A4.2 and A4.3.

$$\bar{y} = \frac{\sum_{j=1}^{n_1}\left[\frac{E_j}{2}\left(y_j^2 - y_{(j-1)}^2\right)\right]}{\sum_{j=1}^{n_1}\left[E_j\left(y_j - y_{(j-1)}\right)\right]} \tag{A4.1}$$

where:

$\bar{y}$ = distance from bottom of beam to neutral axis,
E_j = long span modulus of elasticity for *j*th zone,
y_j = distance from bottom of beam to top of *j*th zone,
$y_{(j\text{-}1)}$ = distance from bottom of beam to bottom of *j*th zone, and
n_1 = total number of zones in beam.

$$N_j = \left(y_j - \bar{y}\right) \qquad \text{(A4.2)}$$

$$N_{(j-1)} = \left(y_{(j-1)} - \bar{y}\right) \qquad \text{(A4.3)}$$

where:

N_j = distance from neutral axis to upper edge of *j*th zone, and
$N_{(j\text{-}1)}$ = distance from neutral axis to lower edge of *j*th zone.

NOTE A4.1—A negative result from Eq A4.2 or Eq A4.3 indicates that the zone boundary is below the neutral axis. A positive result indicates that the zone boundary is above the neutral axis.

A4.1.2 The transformed moment of inertia for each zone about the neutral axis shall be calculated using Eq A4.4, and the moment of inertia of the transformed section shall be calculated using Eq A4.5.

$$I_j = b\left(\frac{E_j}{E_T}\right)\frac{\left(N_j^3 - N_{(j-1)}^3\right)}{3} \qquad \text{(A4.4)}$$

where:

I_j = transformed moment of inertia of *j*th laminations about neutral axis,
E_T = modulus of elasticity of transformed section, and
b = untransformed width of laminations.

$$I_T = \sum_{j=1}^{n_1} I_j \qquad \text{(A4.5)}$$

where:

I_T = transformed moment of inertia of the section.

A4.1.3 The moment of inertia of the untransformed (gross) section shall be calculated using Eq A4.6.

$$I_g = \frac{bD^3}{12} \qquad \text{(A4.6)}$$

where:

I_g = gross moment of inertia of the section, and
D = depth of the section.

A4.1.4 Weighting factors, O_j and P_j shall be calculated for each zone using Eq A4.7 and A4.8.

$$O_j = 2\left(N_j^3 - N_{(j-1)}^3\right) \qquad \text{(A4.7)}$$

$$P_j = \frac{2}{5}\left(9N_j^5 - 5N_j^3 + N_j - 9N_{(j-1)}^5 + 5N_{(j-1)}^3 - N_{(j-1)}\right) \qquad \text{(A4.8)}$$

A4.1.5 An I_k/I_g ratio shall be calculated for each zone using Eq A4.9.

$$\left(\frac{I_k}{I_g}\right)_j = \frac{\sum_{i=1}^{j}\left(x_i\left(\frac{E_i}{E_j}\right)(O_i)\right) + \sqrt{\sum_{i=1}^{j}\left(h_i^2\left(\frac{E_i}{E_j}\right)(P_i)\right)}}{2d_j^3} \qquad \text{(A4.9)}$$

where:

x_j = average knot size, expressed in decimal fraction of width, for the grade of lamination in the *j*th zone;
h_j = difference between the 99.5 percentile and average knot size, expressed in decimal fraction of the width, for the grade of lamination in the *j*th zone; and
d_j = distance between the outermost edge of the *j*th zone and the neutral axis.

A4.1.6 The stress modification factor for knots, $SMF_{bx\ knots\ j}$, shall be calculated for each zone using Eq A4.10, subject to the minimum strength ratio from 7.2.1.1.

$$SMF_{bx\ knots\ j} = \left(1 + 3\left(\frac{I_k}{I_g}\right)_j\right)\left(1 - \left(\frac{I_k}{I_g}\right)_j\right)^3\left(1 - \left(\frac{I_k}{2I_g}\right)_j\right) \geq SR_{bxminj} \qquad \text{(A4.10)}$$

A4.1.7 The stress modification factor for slope of grain, $SMF_{bx\ SOG\ j}$ shall be determined for each zone from Table 4.

A4.1.8 The stress modification factor for each zone shall be determined using Eq A4.11.

$$SMF_{bx\ j} = \min\left\{SMF_{bx\ knots\ j}, SMF_{bx\ SOG\ j}\right\} \qquad \text{(A4.11)}$$

A4.1.9 The maximum stress permitted on each zone, $F_{\max,\ j}$ shall be calculated using Eq A4.12.

$$F_{\max,\ j} = K\left(BSI_j\right)\left(SMF_{bx\ j}\right) \qquad \text{(A4.12)}$$

where:

$F_{\max,\ j}$ = maximum stress allowed at outer edge of *j*th zone,
BSI_j = bending strength index of laminations in *j*th zone,
$SMF_{bx\ j}$ = strength ratio for bending,
= min($SR_{bx\ knots}$, $SR_{bx\ SoG}$),
K = 1.4 for flexural compression, and
= 1.0 for flexural tension.

A4.1.10 The apparent outer fiber stress on the beam corresponding to $F_{\max,\ j}$ for each zone shall be calculated using Eq A4.13.

$$\sigma_{apparent,\ j} = F_{\max,\ j}\left(\frac{D/2}{d_j}\right)\left(\frac{E_T}{E_j}\right)\left(\frac{I_T}{I_g}\right) \qquad \text{(A4.13)}$$

A4.1.11 The allowable flexural design stress (F_{bx}) shall be determined using Eq A4.14 and rounded according to the rules given in 5.2.

$$F_{bx} = \min\left\{\sigma_{apparent,\ j}\right\}(TL) \qquad \text{(A4.14)}$$

where:

TL = tension lamination factor,
= 1.0 if tension laminations meeting the requirements of 4.3 are used,
= 0.85 if tension laminations meeting the requirements of 4.3 are not used and $d \leq 15$ in., and
= if tension laminations meeting the requirements of 4.3 are not used and $d > 15$ in.

A4.1.12 The required strength ratio of the tension lamination (SR_{TL}) shall be calculated using Eq A4.15, and the tension lamination grading requirements of 4.3 shall be determined, if a tension lamination factor of 1.0 is used in Equation Eq A4.14.

$$SR_{TL} = \frac{F_{bx}\left(\frac{2d_{TL}}{D}\right)\left(\frac{E_{TL}}{E_T}\right)\left(\frac{I_g}{I_T}\right)}{BSI_{TL}} \qquad \text{(A4.15)}$$

where:

d_{TL} = distance from neutral axis to outer edge of tension lamination,

E_{TL} = long-span modulus of elasticity of the lumber in the outermost tension zone, and

BSI_{TL} = bending stress index of the lumber in the outermost tension zone.

A4.2 *Example*—Given the 20-lamination beam shown in Fig. A4.1 and the lumber grade data in Table A4.1, determine the allowable bending stress and tension lamination grading requirements for flexure with compression at the top of the section.

A4.2.1 The neutral axis is located relative to the bottom of the beam using Eq A4.1. For convenience, distances are measured in number of laminations.

$$\bar{y} = \frac{\left(\frac{2.1}{2}\right)(2^2)+\left(\frac{1.8}{2}\right)(7^2-2^2)+\left(\frac{1.1}{2}\right)(15^2-7^2)+\left(\frac{1.8}{2}\right)(19^2-15^2)+\left(\frac{2.1}{2}\right)(20^2-19^2)}{2.1(2)+1.8(7-2)+1.1(15-7)+1.8(19-15)+2.1(20-19)}$$

$$\bar{y} = 9.740 \text{ laminations from the bottom}$$

A4.2.1.1 The core zone is split by the neutral axis into two zones for the analysis and the zones are numbered from the bottom of the beam. The distance from the neutral axis to the edges of each zone (Fig. A4.1) are determined using Eq A4.2 and A4.3.

$$N_0=(0-9.740)=-9.740$$
$$N_1=(2-9.740)=-7.740$$
$$N_2=(7-9.740)=-2.740$$
$$N_3=(9.740-9.740)=0$$
$$N_4=(15-9.740)=5.260$$
$$N_5=(19-9.740)=9.260$$
$$N_6=(20-9.740)=10.260$$

A4.2.1.2 Negative results indicate that the zone boundaries represented by N_0, N_1, and N_2 are below the neutral axis. Positive results indicate that the zone boundaries represented by N_4, N_5, and N_6 are above the neutral axis.

A4.2.2 The transformed moment of inertia for each zone about the neutral axis is calculated using Eq A4.4. For convenience, the width of the untransformed section, *b*, will be set equal to unity.

$$I_6=\left(\frac{2.1}{2.1}\right)\frac{(10.26^3-9.260^3)}{3}=95.34$$
$$I_5=\left(\frac{1.8}{2.1}\right)\frac{(9.260^3-5.260^3)}{3}=185.3$$
$$I_4=\left(\frac{1.1}{2.1}\right)\frac{(5.260^3-0^3)}{3}=25.41$$
$$I_3=\left(\frac{1.1}{2.1}\right)\frac{(0^3-(-2.740)^3)}{3}=3.592$$
$$I_2=\left(\frac{1.8}{2.1}\right)\frac{((-2.740)^3-(-7.740)^3)}{3}=126.6$$
$$I_1=\left(\frac{2.1}{2.1}\right)\frac{((-7.740)^3-(-9.740)^3)}{3}=153.4$$

A4.2.2.1 The moment of inertia of the transformed section is calculated using Eq A4.5.

$$I_T = I_1+I_2+I_3+I_4+I_5+I_6 = 153.4+126.6+3.592+25.41+185.3+95.34 = 589.6$$

A4.2.3 The moment of inertia of the untransformed (gross) section is calculated using Eq A4.6.

$$I_g = \frac{20^3}{12} = 666.7$$

A4.2.4 Weighting factors, O_j and P_j are calculated for each zone using Eq A4.7 and A4.8.

$$O_6 = 2(10.26^3 - 9.260^3) = 572.0$$

$$P_6 = \frac{2}{5}(9(10.26)^5 - 5(10.26)^3+(10.26) - 9(9.260)^5+5(9.260)^3 - (9.260)) = 163.6(10^3)$$

$$O_5 = 2(9.260^3 - 5.260^3) = 1297$$

$$P_5 = \frac{2}{5}(9(9.260)^5 - 5(9.260)^3+(9.260) - 9(5.260)^5+5(5.260)^3 - (5.260)) = 229.3(10^3)$$

$$O_4 = 2(5.260^3 - 0^3) = 291.1$$

$$P_4 = \frac{2}{5}(9(5.260)^5 - 5(5.260)^3+(5.260) - 9(0)^5+5(0)^3 - (0))$$

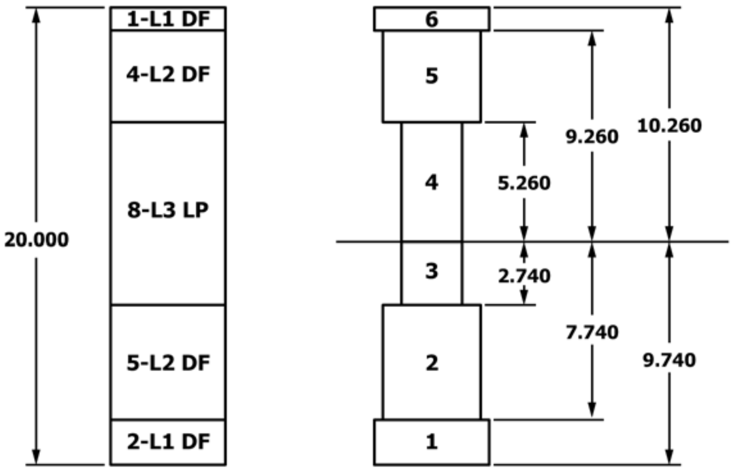


FIG. A4.1 Example of a 20-Lamination Beam

TABLE A4.1 Lumber Data for Analysis of Glulam Beam Bending Stress (see Ref (12))

Grade and Species^A	Modulus of Elasticity^B		Bending Stress Index^C		Knot Data^D			$SR_{bx\ min}$ ^{E}
					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	0.75
L2 Douglas fir	1 800 000	12 400	3000	20.7	10.9	54.9	44.0	0.67
L3 Lodgepole pine	1 100 000	7 600	1933	13.3	23.0	78.8	55.8	0.5

^{A} Graded in accordance with WWPA and WCLIB rules under the American Lumber Standard **(5 and 6)**. L3 lodgepole pine graded under rules for L3 Douglas fir.
^{B} Based on 6.1.4 for Douglas fir and 6.1.4 and 7.5 for lodgepole pine.
^{C} Based on 6.1.1.1 for Douglas fir and 6.1.1 for lodgepole pine.
^{D} Based on knot surveys and analysis in accordance with Annex A3 and Annex A6.
^{E} As determined by formula X1.2 of Practice D245, in accordance with 7.2.1.1 (*1*).

$$= 14.21(10^3)$$

$$O_3 = 2(0^3 - (-2.740)^3) = 41.14$$

$$P_3 = \frac{2}{5}(9(0)^5 - 5(0)^3 + (0) - 9(-2.740)^5 + 5(-2.740)^3 - (-2.740))$$

$$= 515.9$$

$$O_2 = 2((-2.740)^3 - (-7.740)^3) = 443.1$$

$$P_2 = \frac{2}{5}(9(-2.740)^5 - 5(-2.740)^3 + (-2.740) - 9(-7.740)^5 + 5(-7.740)^3 - (-7.740)) = 98.56(10^3)$$

$$O_1 = 2((-7.740)^3 - (-9.740)^3) = 920.7$$

$$P_1 = \frac{2}{5}(9(-7.740)^5 - 5(-7.740)^3 + (-7.740) - 9(-9.740)^5 + 5(-9.740)^3 - (-9.740)) = 214.6(10^3)$$

A4.2.5 An I_k/I_g ratio is calculated for each zone using Eq A4.9.

$$\left(\frac{I_k}{I_g}\right)_6 = \frac{(0.069)\left(\frac{2.1}{2.1}\right)(572.0) + (0.109)\left(\frac{1.8}{2.1}\right)(1297) + (0.230)\left(\frac{1.1}{2.1}\right)(291.1)}{2(10.26)^3} + \frac{\sqrt{(0.353)^2\left(\frac{2.1}{2.1}\right)^2(163.3(10^3)) + (0.440)^2\left(\frac{1.8}{2.1}\right)^2(229.3(10^3)) + (0.558)^2\left(\frac{1.1}{2.1}\right)^2(14.21(10^3))}}{2(10.26)^3}$$

$$\left(\frac{I_k}{I_g}\right)_6 = 0.198$$

$$\left(\frac{I_k}{I_g}\right)_5 = \frac{(0.109)\left(\frac{1.8}{1.8}\right)(1297) + (0.230)\left(\frac{1.1}{1.8}\right)(291.1)}{2(9.260)^3} + \frac{\sqrt{(0.440)^2\left(\frac{1.8}{1.8}\right)^2(229.3(10^3)) + (0.558)^2\left(\frac{1.1}{1.8}\right)^2(14.21(10^3))}}{2(9.260)^3}$$

$$\left(\frac{I_k}{I_g}\right)_5 = 0.2499$$

$$\left(\frac{I_k}{I_g}\right)_4 = \frac{(0.230)\left(\frac{1.1}{1.1}\right)(291.1) + \sqrt{(0.558)^2\left(\frac{1.1}{1.1}\right)^2(14.21(10^3))}}{2(5.260)^3}$$

$$\left(\frac{I_k}{I_g}\right)_4 = 0.4585$$

$$\left(\frac{I_k}{I_g}\right)_3 = \frac{(0.230)\left(\frac{1.1}{1.1}\right)(41.14) + \sqrt{(0.558)^2\left(\frac{1.1}{1.1}\right)^2(515.9)}}{2(2.740)^3}$$

$$\left(\frac{I_k}{I_g}\right)_3 = 0.5381$$

$$\left(\frac{I_k}{I_g}\right)_2 = \frac{(0.109)\left(\frac{1.8}{1.8}\right)(443.1) + (0.230)\left(\frac{1.1}{1.8}\right)(41.14)}{2(7.740)^3} + \frac{\sqrt{(0.440)^2\left(\frac{1.8}{1.8}\right)^2(98.56(10^3)) + (0.558)^2\left(\frac{1.1}{1.8}\right)^2(515.9)}}{2(7.740)^3}$$

$$\left(\frac{I_k}{I_g}\right)_2 = 0.2075$$

$$\left(\frac{I_k}{I_g}\right)_1 = \frac{(0.069)\left(\frac{2.1}{2.1}\right)(920.7) + (0.109)\left(\frac{1.8}{2.1}\right)(443.1) + (0.230)\left(\frac{1.1}{2.1}\right)(41.14)}{2(9.740)^3} + \frac{\sqrt{(0.353)^2\left(\frac{2.1}{2.1}\right)^2(214.6(10^3)) + (0.440)^2\left(\frac{1.8}{2.1}\right)^2(98.56(10^3)) + (0.558)^2\left(\frac{1.1}{2.1}\right)^2(515.9)}}{2(9.740)^3}$$

$$\left(\frac{I_k}{I_g}\right)_1 = 0.1688$$

A4.2.6 The stress modification factor for knots is calculated for each zone using Eq A4.10, subject to the minimum strength ratio from 7.2.1.1 *(1)* (Table A4.1).

$$SMF_{bx\ knots\ 6} = (1+3(0.1980))(1-(0.1980))^3\left(1-\left(\frac{0.1980}{2}\right)\right) \geq 0.75$$
$$SMF_{bx\ knots\ 6} = 0.741 \geq 0.75$$
$$SMF_{bx\ knots\ 6} = 0.75$$

$$SMF_{bx\ knots\ 5} = (1+3(0.2499))(1-(0.2499))^3\left(1-\left(\frac{0.2499}{2}\right)\right) \geq 0.67$$
$$SMF_{bx\ knots\ 5} = 0.646 \geq 0.67$$
$$SMF_{bx\ knots\ 5} = 0.67$$

$$SMF_{bx\ knots\ 4} = (1+3(0.4585))(1-(0.4585))^3\left(1-\left(\frac{0.4585}{2}\right)\right) \geq 0.50$$
$$SMF_{bx\ knots\ 4} = 0.291 \geq 0.50$$
$$SMF_{bx\ knots\ 4} = 0.50$$

$$SMF_{bx\ knots\ 3} = (1+3(0.5381))(1-(0.5381))^3\left(1-\left(\frac{0.5381}{2}\right)\right) \geq 0.50$$
$$SMF_{bx\ knots\ 3} = 0.211 \geq 0.50$$
$$SMF_{bx\ knots\ 3} = 0.50$$

$$SMF_{bx\ knots\ 2} = (1+3(0.2075))(1-(0.2075))^3\left(1-\left(\frac{0.2075}{2}\right)\right) \geq 0.67$$
$$SMF_{bx\ knots\ 2} = 0.724 \geq 0.67$$
$$SMF_{bx\ knots\ 2} = 0.724$$

$$SMF_{bx\ knots\ 1} = (1+3(0.1688))(1-(0.1688))^3\left(1-\left(\frac{0.1688}{2}\right)\right) \geq 0.75$$
$$SMF_{bx\ knots\ 1} = 0.792 \geq 0.75$$
$$SMF_{bx\ knots\ 1} = 0.792$$

A4.2.7 The stress modification factor for slope of grain is determined for each zone from Table 4, using the factors for compression for the zones above the neutral axis and the factors for tension for the zones below the neutral axis.

$$SMF_{bx\ SOG\ 6} = 0.87$$
$$SMF_{bx\ SOG\ 5} = 0.82$$
$$SMF_{bx\ SOG\ 4} = 0.66$$
$$SMF_{bx\ SOG\ 3} = 0.53$$
$$SMF_{bx\ SOG\ 2} = 0.69$$
$$SMF_{bx\ SOG\ 1} = 0.74$$

A4.2.8 The stress modification factor for each zone is determined using Eq A4.11.

$$SMF_{bx\ 6} = \min\{0.75, 0.87\} = 0.75$$
$$SMF_{bx\ 5} = \min\{0.67, 0.82\} = 0.67$$
$$SMF_{bx\ 4} = \min\{0.5, 0.66\} = 0.5$$
$$SMF_{bx\ 3} = \min\{0.5, 0.53\} = 0.5$$
$$SMF_{bx\ 2} = \min\{0.724, 0.69\} = 0.69$$
$$SMF_{bx\ 1} = \min\{0.792, 0.74\} = 0.74$$

A4.2.9 The maximum stress permitted on each zone is calculated using Eq A4.12.

$$F_{\max,6} = 1.4\ (3500\text{ psi})\ (0.75) = 3675\text{ psi}$$
$$F_{\max,5} = 1.4\ (3000\text{ psi})\ (0.67) = 2814\text{ psi}$$
$$F_{\max,4} = 1.4\ (1930\text{ psi})\ (0.50) = 1351\text{ psi}$$
$$F_{\max,3} = 1.0\ (1930\text{ psi})\ (0.50) = 965\text{ psi}$$
$$F_{\max,2} = 1.0\ (3000\text{ psi})\ (0.69) = 2070\text{ psi}$$
$$F_{\max,1} = 1.0\ (3500\text{ psi})\ (0.74) = 2590\text{ psi}$$

A4.2.10 The apparent outer fiber stress on the beam corresponding to $F_{\max,\,j}$ for each zone is calculated using Eq A4.13.

$$\sigma_{apparent,6} = 3675\text{ psi}\left(\frac{10}{10.26}\right)\left(\frac{2.1}{2.1}\right)\left(\frac{589.6}{666.7}\right) = 3168\text{ psi}$$

$$\sigma_{apparent,5} = 2814\text{ psi}\left(\frac{10}{9.26}\right)\left(\frac{2.1}{1.8}\right)\left(\frac{589.6}{666.7}\right) = 3135\text{ psi}$$

$$\sigma_{apparent,4} = 1351\text{ psi}\left(\frac{10}{5.26}\right)\left(\frac{2.1}{1.1}\right)\left(\frac{589.6}{666.7}\right) = 4336\text{ psi}$$

$$\sigma_{apparent,3} = 965\text{ psi}\left(\frac{10}{2.74}\right)\left(\frac{2.1}{1.1}\right)\left(\frac{589.6}{666.7}\right) = 5946\text{ psi}$$

$$\sigma_{apparent,2} = 2070\text{ psi}\left(\frac{10}{7.74}\right)\left(\frac{2.1}{1.8}\right)\left(\frac{589.6}{666.7}\right) = 2759\text{ psi}$$

$$\sigma_{apparent,1} = 2590\text{ psi}\left(\frac{10}{9.74}\right)\left(\frac{2.1}{2.1}\right)\left(\frac{589.6}{666.7}\right) = 2352\text{ psi}$$

A4.2.11 The allowable flexural design stress (F_{bx}) is determined using Eq A4.14 and rounded according to the rules given in 5.2.

$$F_{bx} = (\min\{3168,\ 3135,\ 4336,\ 5946,\ 2759,\ 2352\}\text{ psi})(1.0) = 2352\text{ psi}$$

(1) Rounding in accordance with 5.2 gives:

$$F_{bx} = 2400\text{ psi}$$

A4.2.12 The required strength ratio of the tension lamination (SR_{TL}) is calculated using Eq A4.15.

$$SR_{TL} = \frac{2400\text{ psi}\left(\frac{2(9.74)}{20}\right)\left(\frac{2.1}{2.1}\right)\left(\frac{666.7}{589.6}\right)}{3500\text{ psi}} = 0.755$$

(1) The maximum permitted grain deviations in the tension laminations for the outermost 5 % of the depth on the bottom of the beam are determined as follows:

$$GDS_C = 1.82(1-0.755) = 0.446$$
$$GDS_E = 1.55(1-0.755) = 0.380$$

(2) Because the required strength ratio of the tension lamination is greater than 0.60, the general slope of grain must not exceed 1:16.

$$SOG \leq 1{:}16$$

(3) The maximum size knots (expressed as fraction of lamination width) in the next inner 5 % of the depth on the bottom of the beam are determined as follows:

$$KE = 0.66 - 0.45(0.755) = 0.320$$
$$KC = 1.20 - 0.93(0.755) = 0.498$$

A5. PROCEDURE FOR DETERMINING DESIGN STRESSES IN COMPRESSION PARALLEL TO GRAIN

A5.1 Procedural Steps

A5.1.1 The transformed area factor, T_a, shall be determined as follows:

$$T_a = \frac{\sum_{k=1}^{n} E_k A_k}{E_1 \sum_{k=1}^{n} A_k} \quad \text{(A5.1)}$$

where:

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

A5.1.2 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, values for composite average knot size (m_c) and composite standard deviation knot size (σ_c) shall be calculated for the combination as follows:

$$m_c = \frac{\sum_{k=1}^{n} (E_k A_k m_k)}{E_1 \sum_{k=1}^{n} A_k} \quad \text{(A5.2)}$$

$$\sigma_c = \frac{\left\{ \sum_{k=1}^{n} \left(E_k^2 A_k^2 \sigma_k^2 \right) \right\}^{\frac{1}{2}}}{E_1 \sum_{k=1}^{n} A_k} \qquad \text{(A5.3)}$$

A5.1.2.1 For glulam members made with single-grade laminations, Eq A5.3 can be reduced to:

$$\sigma_c = \frac{s}{n^{\frac{1}{2}}} \qquad \text{(A5.4)}$$

where:

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

A5.1.3 The composite knot size at the 99.5 percentile, Y_1, shall be computed as follows:

$$Y_1 = m + 2.576\sigma \qquad \text{(A5.5)}$$

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

A5.1.4 The stress modification factor from Eq 4 (see 7.3.2) shall be computed and compared with that determined by the slope of grain for each grade.

A5.1.5 The allowable compressive stress on the actual combination for each grade at the interface between grades shall be calculated as follows:

$$f_{ci} = CSI_i \times SMF_{ci} \qquad \text{(A5.6)}$$

where:

f_{ci} = allowable compressive stress for ith lamination,
CSI_i = stress index in compression for ith lamination, and
SMF_{ci} = stress modification factor in compression for ith lamination (Eq 4 in 7.3.2).

A5.1.6 For asymmetric combinations, relative stress factors for each interface shall be calculated for each grade zone to account for bending stresses induced by the loading eccentricity as follows:

$$S_i = \left(\frac{E_i}{E_1} \right) \left(\frac{1}{T_a} \pm \frac{12ax_i}{T_i d_1^2} \right) \qquad \text{(A5.7)}$$

where:

S_i = relative stress factor for the ith zone,
E_i = long-span modulus of elasticity of laminations in ith zone,
E_1 and T_a = as defined in Eq A5.1,
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 outermost edge of the ith zone.

A5.1.6.1 The sign plus (+) or minus (−) depends upon whether the induced bending stress is compressive or tensile, respectively. For symmetric combinations, $S_i = E_i/(E_1 T_a)$.

A5.1.7 The allowable compression stress on the combination, F_c, shall be the lowest value of f_{ci}/S_i.

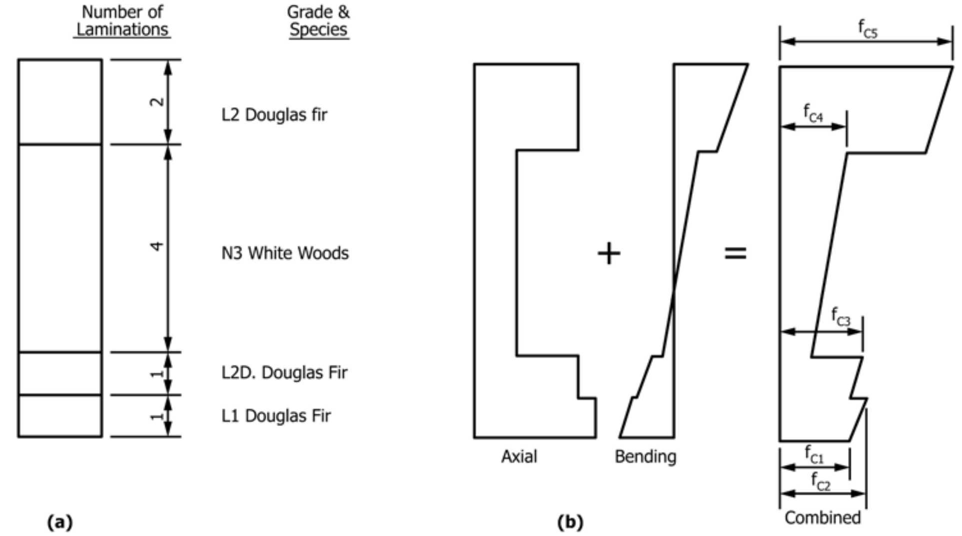
$$F_c = \min \left\{ \frac{f_{ci}}{S_i} \right\} \qquad \text{(A5.8)}$$

A5.2 Example—Analysis of an Eight-Lamination Member

A5.2.1 *Given*—An eight-lamination compression member as shown in Fig. A5.1, lumber properties as shown in Table A5.1, and the following data:

$$T_i = 0.845$$

$$a = 0.120$$



(a)

Actual 8 Lamination Column

(b)

Stress Distribution

FIG. A5.1 Axially Loaded Member with Unsymmetric Grades

TABLE A5.1 Number Data for Analysis of Compression Parallel to Grain Stress

Grade and Species	Modulus of Elasticity	Compression Stress Index		Knot Data[A]	
	million-psi	psi	MPa	m	σ
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.

$$d_1 = 8$$

A5.2.1.1

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

A5.2.1.2

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

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

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

$$= 0.0364$$

A5.2.1.3

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

A5.2.1.4 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.

A5.2.1.5 Calculate allowable stresses using stress indexes shown in Table A5.1 as follows:

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

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

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

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

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

A5.2.1.6 Calculate relative stress factors as follows:

$$S_2 = \frac{2.1}{2.1}\left[\frac{1}{0.643} - \frac{12(0.120)}{0.845(64)}(2.88)\right] = 1.555 - 0.0266\,(2.88) = 1.478$$

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

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

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

A5.2.1.7 Determine which f_c is the lowest of f_{cix}/S_{ix}. Lowest is f_{c4}/S_4 = 990 psi. Therefore, f_c = 990 psi, or 1000 psi (rounded to nearest 50 psi).

A6. GUIDELINES FOR DETERMINING ACCEPTANCE OF NEW KNOT DATA

A6.1 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 A3) shall be physically measured (mapped) to determine the percent 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.

A6.2 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)

A6.2.1 See Figs. A6.1-A6.10 for each type of knot and associated measurements. Note that there purposely is no knot Type 8.

A6.2.2 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.

A6.3 Calculation

A6.3.1 Knot *X*-bar and *h* values computed by these methods are based on the principles presented in USDA Technical Bulletin 1069 (**9**). The value, *X* -bar, is defined as the average of the sum of all knot sizes within any 1-ft length along the 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*.

A6.3.2 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 (**9**). The underlying assumption for using this procedure is that an analysis, which handles the knot data as normally distributed, is satisfactory. USDA Bulletin 1069 (**9**) 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 at infinity and it 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.

A6.3.3 Two possible options for the selection of the knot size range over which to calculate the linear regression are as follows:

A6.3.3.1 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.

A6.3.3.2 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 one-eighths 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 one-eighths 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 zero-eighths 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.

A6.3.3.3 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.

A6.4 Acceptance

A6.4.1 *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.

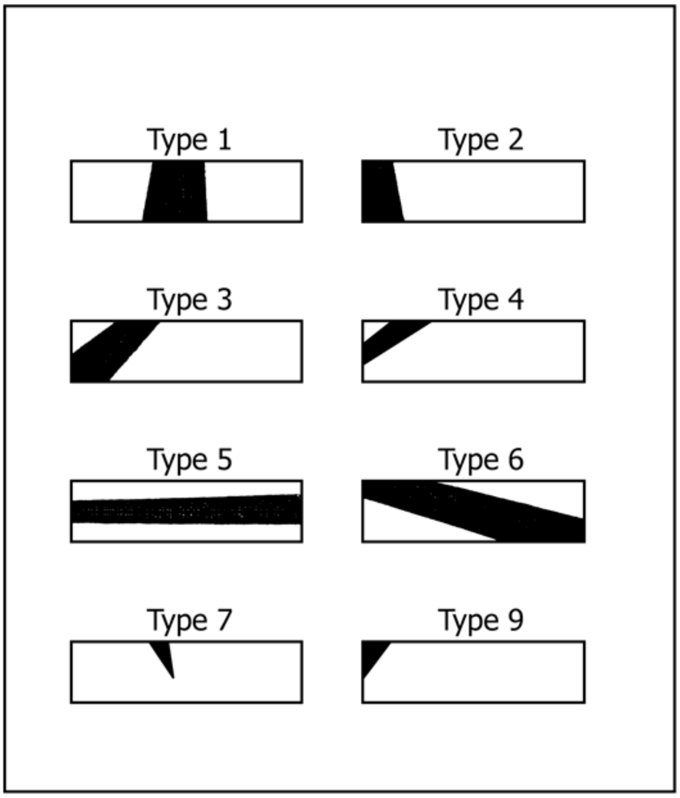
A6.4.2 *Statistical Comparison*—Statistical comparison of the new and existing data consists of a three-step process:

A6.4.2.1 Conduct a joint probability test for means and variances.

A6.4.2.2 Conduct an equivalency test for the quantities (usually 99.5 percentile).

A6.4.2.3 If necessary, conduct tests of distribution fit.

A6.4.2.4 *Decision Procedure*—Based on the results of A6.4.1, take action based on a sequence of analysis and decision such as the one in Table A6.1.



NOTE 1—Minimum knot size = ⅜ in.

FIG. A6.1 Knot Types

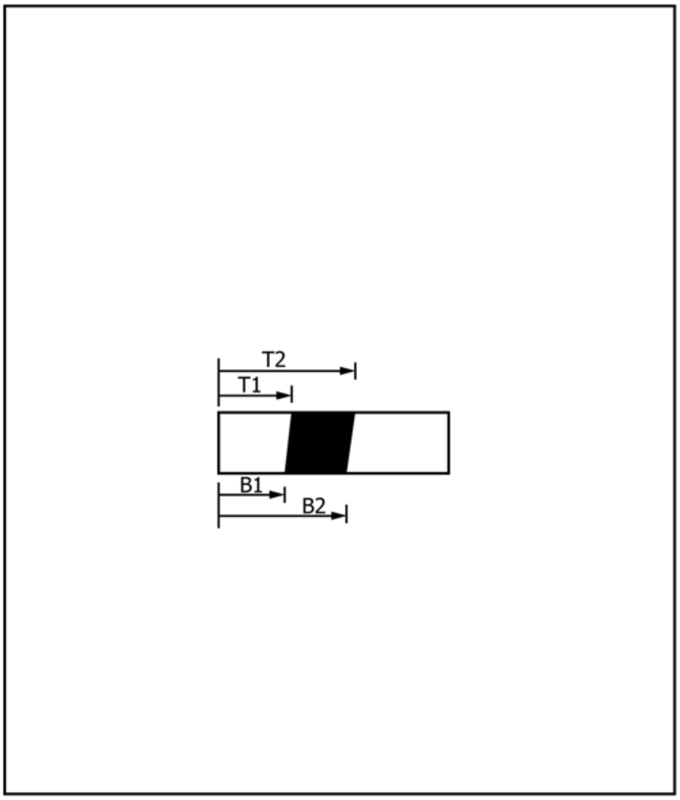


FIG. A6.2 Type 1

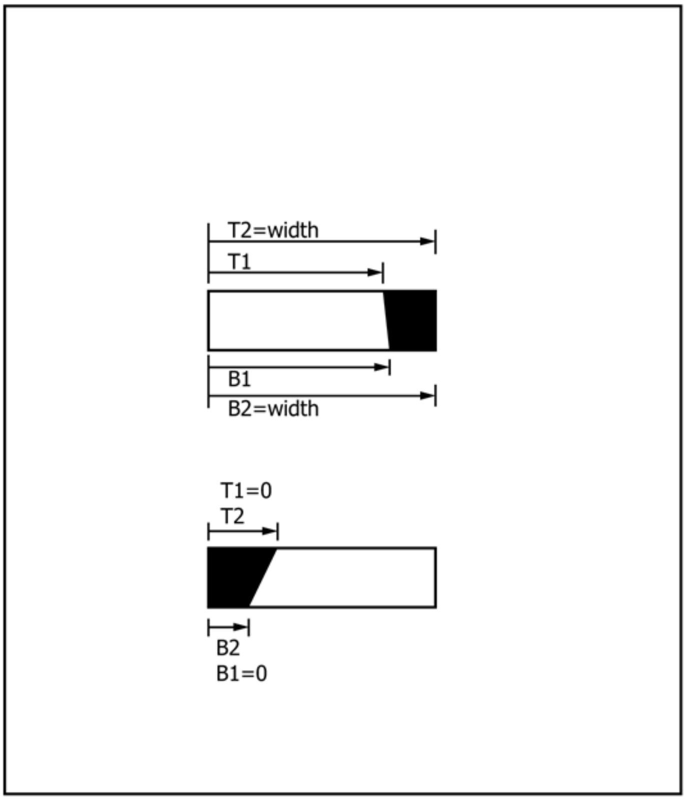


FIG. A6.3 Type 2

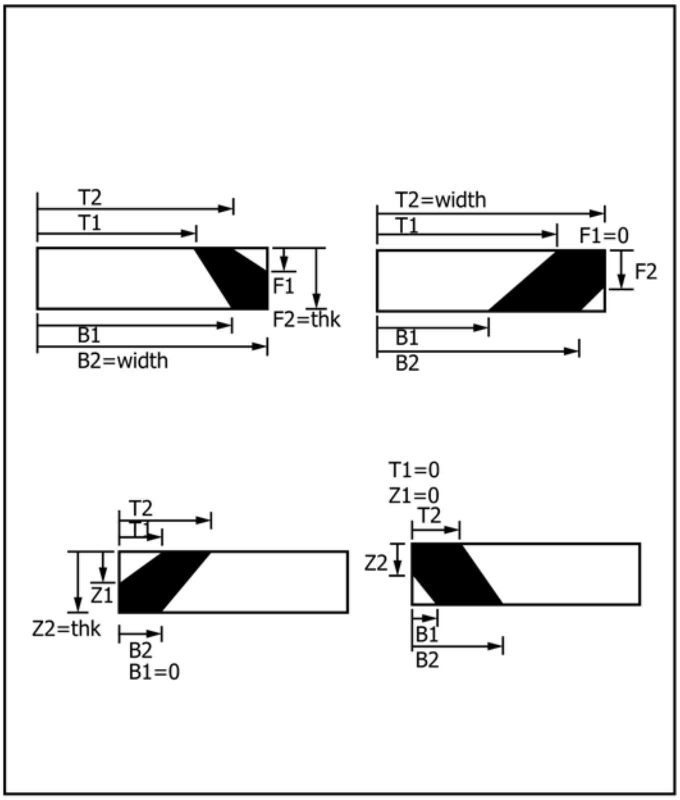


FIG. A6.4 Type 3

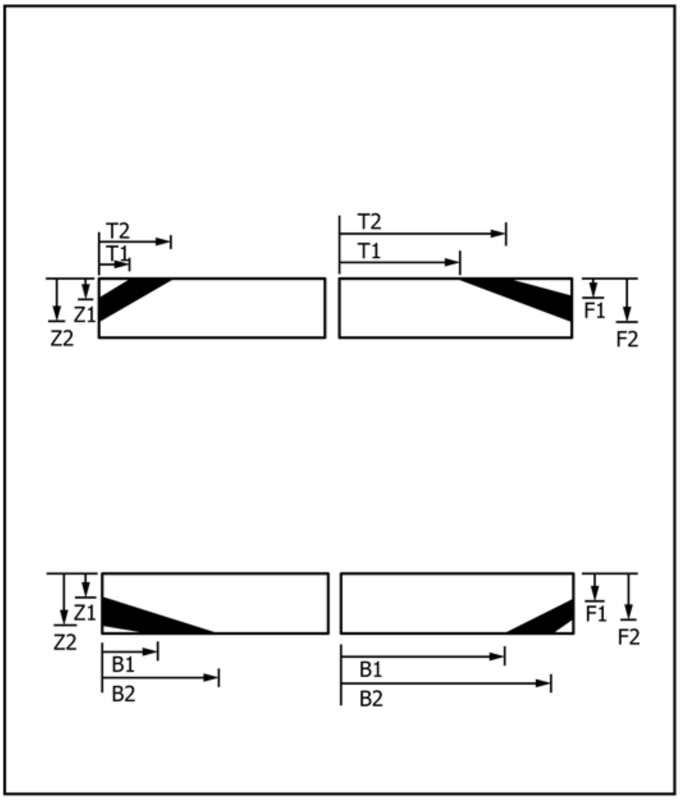


FIG. A6.5 Type 4

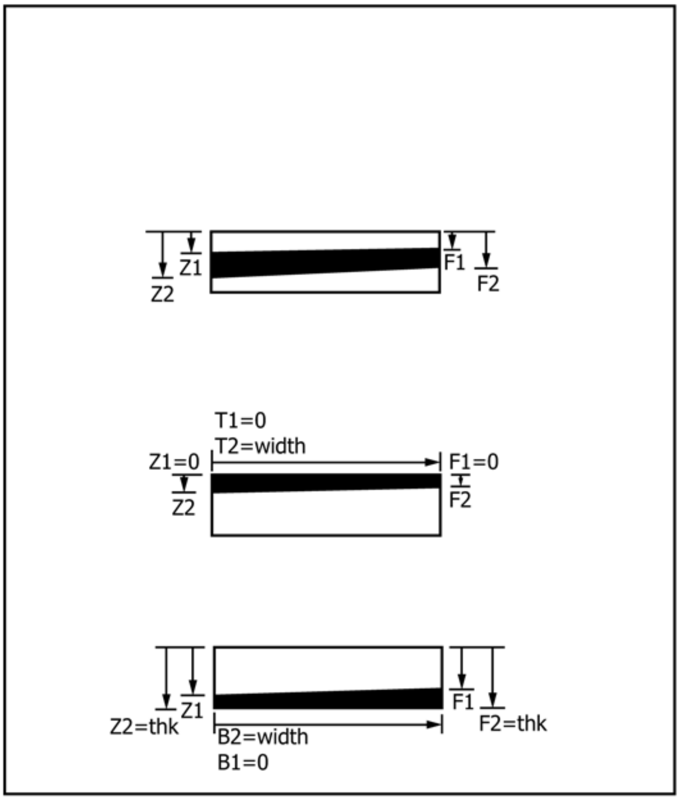


FIG. A6.6 Type 5

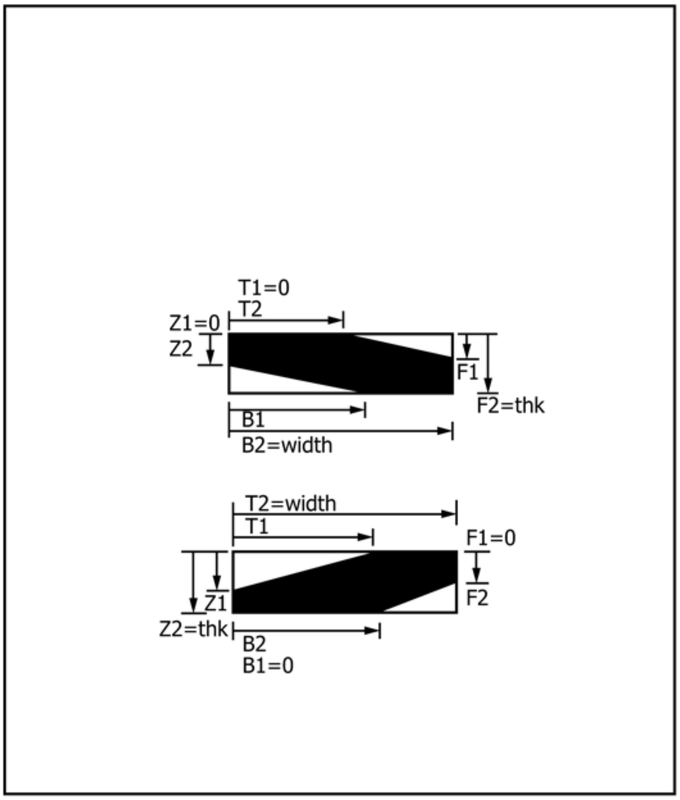


FIG. A6.7 Type 6

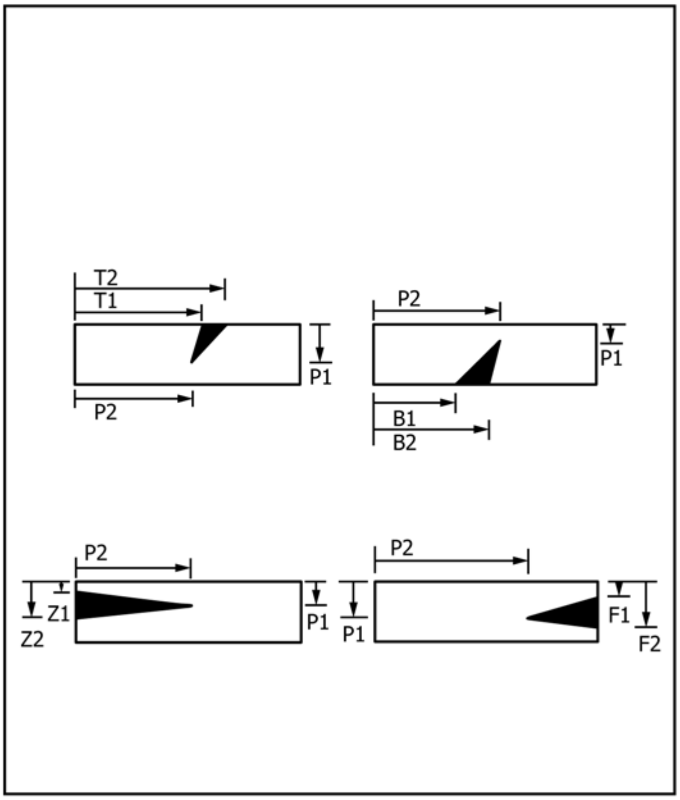


FIG. A6.8 Type 7a

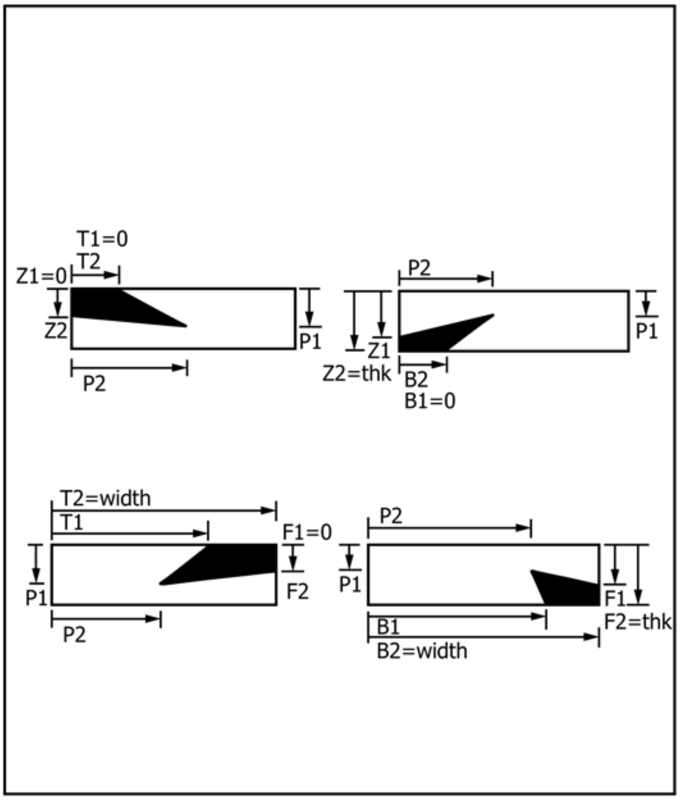


FIG. A6.9 Type 7b

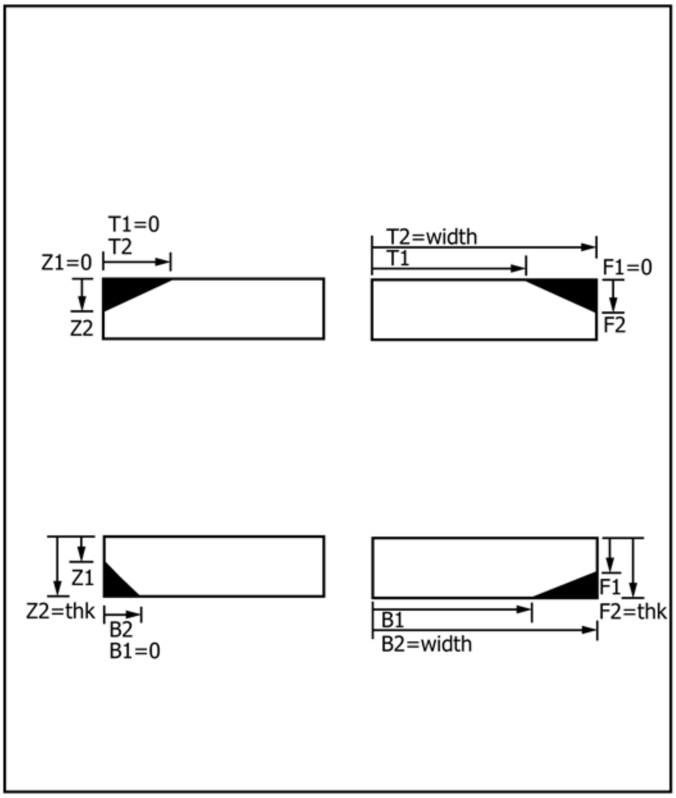


FIG. A6.10 Type 9

TABLE A6.1 Example Decision Sequence Composed of Analysis and Subsequent Decisions

Means 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. If not large enough, take additional samples. (*b*) If not normal, go to 4*b*.
3. Equal	Equal	No changes in knot data.
4. Equal	Unequal	Examine distribution fit. (*a*) If normal, accept new data, apply "practical significance" test. (*b*) If not normal, seek help of competent statistician.

A7. TEST SETUP AND DATA ANALYSIS PROCEDURE FOR DETERMINING HORIZONTAL SHEAR STRESS BY FULL SCALE BEAM TESTS

A7.1 *Test Method*—A two-point load method, as shown in Fig. A7.1, 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 D198. When unavoidable, exceptions to Test Methods D198 and the requirements of this annex shall be documented.

A7.1.1 The clear distance between the edge of the bearing plate to the edge of the nearest load bearing block shall be at least two times the specimen depth. The minimum width of the specimen shall be 6 in. (0.15 m) (nominal) and the minimum depth shall be approximately 18 in. (0.46 m) (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. The bearing length should be sufficient to avoid bearing failure, but not greater than the beam depth. 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 (**13**) provides a detailed example of a typical test setup. All failure modes shall be recorded to permit the use of either a censored or uncensored data set analysis as discussed in A7.2. 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.

A7.2 *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. End joints shall be avoided whenever possible in the critical tension laminations of the test beams.

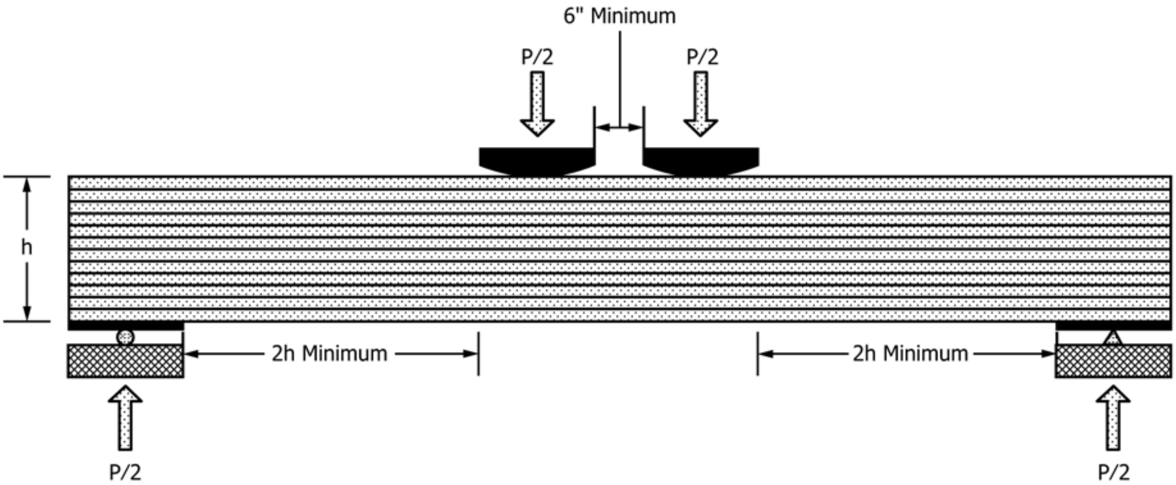


FIG. A7.1 Test Setup Based on Test Methods D198 (not drawn to scale)

A7.3 *Analysis Methods*—The shear stresses (f_v) at the time of specimen failure shall be calculated using the following equation:

$$f_v = \frac{3P_{ult}}{4bh} \qquad (A7.1)$$

where:

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

A7.3.1 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 D2915.

A7.3.2 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 A7.1. 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 **(13)**. In either case, a lower 5th percentile tolerance limit with 75 % confidence shall be determined.

A7.3.3 For the censored data analysis, the uncensored mean and standard deviation can be estimated by using the methodology for the maximum likelihood estimators (*MLE*s), as described in Lawless **(14)**. 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.

A7.4 *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 ($8/9$).

A7.4.1 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 $1/2.1$, which can then be applied to the shear test results of full-size glulam beams to establish design values.

A7.5 *Published Values*—The calculated shear stress may be reduced by 10 % to allow for occasional seasoning checking in accordance with industry recommended practice.

A8. DETERMINATION OF EXPONENTS FOR THE VOLUME EFFECT FACTOR

A8.1 To develop the exponent x to be used in the volume effect equation given in 8.5 for a specific species or species grouping, a series of full scale bending tests shall be conducted. This test program shall involve testing at a range of beam sizes sufficient to define the volume effect equation. To accomplish this, a series of beams of varying sizes shall be produced using a representative layup combination and tested in accordance with Test Methods D198.

A8.2 Agencies or organizations desiring to establish such an exponent should use reported test programs **(15-19)** as guidance for developing a test program and analysis methodology.

APPENDIXES

(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 5th percentiles of the two distributions (for example, the modified Conover chi-squared test).

X1.3.5 If any of these tests are 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.

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 D245. If the new data remains different from the old, proceed.
2	Apply the rounded new data to a Practice D3737-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.

X2. COMMENTARY

(See the table below.)

Section	Comments
Section C4	Materials Requirements
C4.1.1	The models in this practice were developed using laminations of 2 in. or smaller net thickness. Their applicability to thicker lumber has not been verified. Glulam manufacturing standards such as ANSI/AITC A190.1 and CSA O122 typically include similar thickness limitations because of difficulties in bonding thicker laminations.
C4.1.2	One of the advantages of structural glued laminated timber is that it can be produced in much longer lengths than traditional sawn timbers. Structural end joints are used to develop continuity of laminations and ensure adequate strength to carry the design loads. Recognized manufacturing standards have specific requirements for end joint strength and quality control procedures required to verify and maintain that strength. The typical end joint configuration in modern glulam is a finger joint. Scarf joints were typically used prior to the mid 1960s. Butt joints were also allowed to a limited extent in older glulam manufacturing standards; however, butt joints and other non-structural joint types are not typically permitted in modern glulam. The models in this practice assume structural continuity of the laminations, so its provisions are not applicable to glulam containing non-structural end joints.
C4.1.3	Structural glued laminated timber is sometimes manufactured in wider widths than are readily available in structural lumber. To accomplish this, multiple pieces of lumber are used to make up the width of the member. The pieces may be edge-bonded or simply placed side by side with unbonded edge joints staggered a prescribed distance between courses (typically required to be staggered a distance equal to or greater than the lamination thickness).
C4.1.4	Grading of the lumber used in laminations ensures repeatability in the manufacture and reasonable consistency in products. The models in this practice rely on physical and mechanical properties measured from and assigned to established grades of lumber.
C4.1.5	Annex A1 provides a method for establishing equivalence to established grades through testing to verify mechanical properties.
C4.1.6	The mathematical models of this practice are based on timbers with all laminations having the same thickness. The use of multiple lamination thicknesses within a member requires careful consideration and judgment.
C4.1.7	The models presented in this practice require data for each grade used including: density (visual growth rate and percent summerwood) or specific gravity, flatwise long-span modulus of elasticity, maximum permitted knot size, maximum permitted slope of grain, and knot size and distribution statistics measured on representative samples.
C4.1.7.1	Historically, the measurement of lumber characteristics has been conducted on 2 × 6 material for each grade. These properties have been used for modeling all widths of timbers. Effects of width on glulam timber performance are accounted for separately, such as through the application of the volume and flat-use factors described in Section 8. For *E*-rated lumber, it should be noted that modulus of elasticity is measured and assigned to each width of lumber used, but the required knot surveys are based on 2 × 6 lumber.
C4.2.1	The models in this Practice assume fully composite action between laminations and that bond strength is not the weak link in the composite member. Adhesives must be sufficiently rigid and strong for the analysis procedures to be valid. Manufacturing standards such as ANSI/AITC A190.1 and CSA O122 dictate specific requirements for qualification and quality control of adhesive bonds.
C4.2.2	This practice does not attempt to define service life, but requires that the adhesives used to manufacture the laminated timber be sufficiently durable to avoid strength and stiffness degradation that will violate the assumptions discussed in C4.2.1 for its anticipated lifetime.
C4.3	The design properties for horizontally laminated beams as calculated by this Practice require the use of specially graded tension laminations or the application of reduction factors where these specially graded laminations are not used.
C4.3.2.3	Eq 1 and 2 can be traced back to tension lamination grades used in FPL 292 **(1)**.[7] In that study, criteria for four tension lamination grades was presented. The grades, designated “65”, “70”, “75” and “80” in that study, limited knots and associated grain deviations to those shown in Table C4.3.2.3 (1). The grades limited centerline knots and associated grain deviations to sizes similar to those allowed by the previously developed AITC 301-20, 301-22, 301-24, and 301-26 grades, respectively. Edge knots (*GDE*) were restricted to a maximum of 6⁄7 of the allowed size of centerline knots (*GDC*).

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[7] The boldface numbers in parentheses refer to a list of references at the end of this standard.

TABLE X2.1 TABLE C4.3.2.3 (1) Characteristics of Tension Laminations From FPL 292

Grade	GDE	GDC	SoG	AITC Grade GDC was Based on
65	43	50	1:12	301–20
70	36	42	1:16	301–22
75	30	35	1:16	301–24
80	24	28	1:16	301–26

AITC's tension lamination grades had been developed based on knowledge obtained from previous studies (**20**, **21**) and strength ratios had been assigned to each grade as shown in C4.3.2.3 (2) (AITC "Brown Book" (**22**), AITC Standard 500 (**23**)). The AITC grades, however, did not allow for larger centerline knots than edge knots (AITC 117-71 (**24**), AITC 117-74 (**25**)).

TABLE X2.2 TABLE C4.3.2.3 (2) Strength Ratios Assigned to AITC Tension Lamination Grades

Grade	SR_{tl}
301–20	0.675
301–22	0.725
301–24	0.775
301–26	0.825

FPL 292 (**1**) assumed that the tension lamination grades used in that study were similar the AITC grades shown in Table C4.3.2.3 (1) and assigned the AITC strength ratios to those grades for some of the analyses conducted. However, the tension lamination grades developed for FPL 292 (**1**) were generally higher than the AITC grades, because the edge knots were more restrictive than required by the AITC grades.

Judgment used in the development of Eq 1 and 2 determined that the AITC strength ratios would apply to tension laminations with edge defects of the sizes given for centerline defects in FPL 292 (**1**). With this judgment, Eq 1 was determined from a simple linear regression of the values in Table C4.3.2.3 (3) as shown in Fig. C4.3.2.3 (1).

TABLE X2.3 TABLE C4.3.2.3 (3) Tension Lamination Strength Ratios Assigned to Edge Characteristics

GDE	SR_{tl}
0.5	0.675
0.42	0.725
0.35	0.775
0.28	0.825

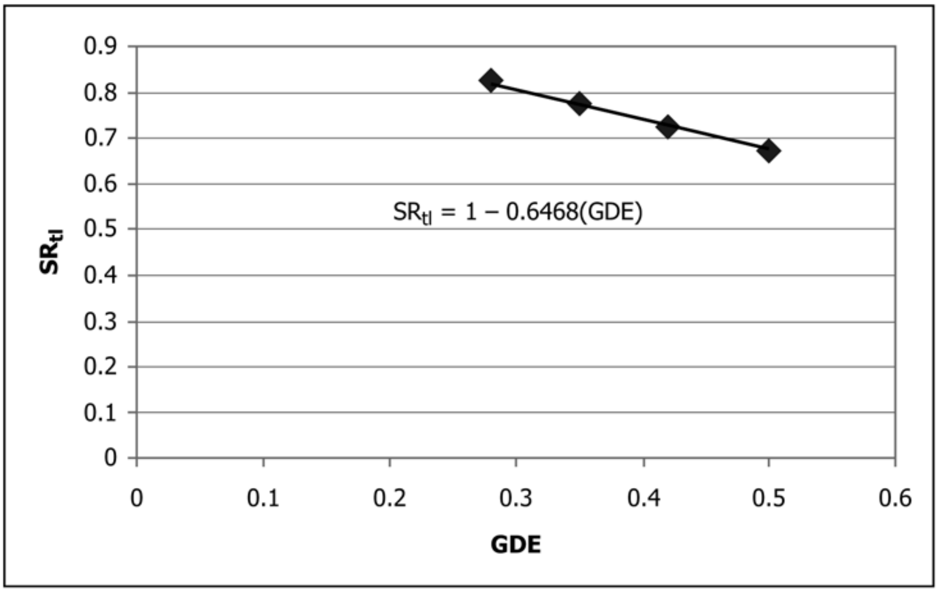

FIG. C4.3.2.3 (1) Regression of SR_{tl} Based on GDE

The regression was constrained through an intercept value of 1.0 resulting in the following equation:

$$SR_{tl} = 1 - 0.6468\,(GDE) \tag{X2.1}$$

Solving Eq X2.1 for *GDE*, gives the following equation, which matches Eq 1:

$$GDE = \frac{(1 - SR_{tl})}{0.6468} = 1.55\,(1 - SR_{tl}) \tag{X2.2}$$

The restriction on centerline knots is determined by multiplying Eq X2.2 by 1.175 (slightly larger than ⅞) based on industry judgment:

$$GDC = 1.175GDE = (1.175)\,[1.55\,(1 - SR_{tl})] = 1.82\,(1 - SR_{tl}) \tag{X2.3}$$

Commercial tension lamination grading rules consider all characteristics within a one-foot length as occurring in the same cross section. This practice uses the term "*GDS*" and Fig. 1 to explain how multiple grain deviations within the same cross section should be measured. For clarity, commercial grading rules for tension laminations typically require a minimum amount of clear, straight-grained wood in a cross section, rather than attempting to describe allowable combinations of defects.

The origins of Eq 3 and 4 are not documented. They allow laminations in the "next inner 5 %" to be of a lower grade, but prevent the grade from being too much lower, to prevent premature beam failure caused by the inner tension lamination(s). For beams requiring the commercial tension lamination grades of 302-26 or 302-24, the inner tension laminations must approximately meet the knot restrictions of L1 or N1 grades. For beams requiring tension lamination grades 302-22 or 302-20, the inner tension laminations must meet knot restrictions approximately similar to the requirements of L2 or N2. Laminations of L3 or N3 are effectively prohibited from the "next inner 5 %" of beams designed with special tension laminations.

C4.3.2.4 Initial research leading to the development of special tension lamination requirements **(20, 21)** was focused on large beams (ten laminations or more). Subsequent research **(26, 27)** indicated the need for special tension laminations for shallow beams, although of somewhat lower quality. To allow for the lower quality tension laminations, the calculated strength ratio for the beam is reduced before applying Eq 1 and 2. "Large" beams for the purpose of specifying special tension laminations were originally defined as beams 16.25 in. or deeper (ten laminations of 1.625 in. thickness each). Subsequent changes in standard lamination thickness caused the criterion to be revised to 15 in. or deeper (ten laminations of 1.5 in. thickness each).

C4.3.2.5 See C4.3.2.4.

Section C5 Allowable Properties for Glued Laminated Timber Members

The models presented in this practice have been derived from empirical models that relate strength reducing characteristics to stress modification factors (also known as strength ratios), which are applied to stress indices determined from clear wood stresses. In general, stress modification factors and stress indices are determined for each lamination in a member, and the resulting allowable property of the member is determined based on the properties and locations of the individual laminations within the cross section.

C5.1 Stress indices are assigned for use with each grade of lumber as prescribed in Section 6. Stress modification factors are determined based on knots and slope of grain as prescribed in Section 7. The lower strength ratio associated with knots and slope of grain is applied for the lamination.

C5.2 Section 5.2 describes the rounding convention used in the development of design values.

C5.3 *Horizontally Laminated Beam Flexure*—See commentary for Annex A4.

C5.4 *Vertically Laminated Beam Flexure*—Eq 5 adjusts the allowable stress for each lamination (which would apply to the transformed section for *y-y* bending) to an equivalent apparent beam stress (based on actual section dimensions). The lowest apparent stress is assigned as the allowable stress for the beam. The lowest allowable lamination stress is set as a lower bound for the assigned value for the beam based on judgment. This is the value that would be calculated as if the entire beam section consisted of laminations of the lowest grade.

C5.5 *Compression Parallel to Grain*—See commentary for Annex A5.

C5.7.1 *Axially Loaded Timbers*—The weighted average of the individual lamination *LSE*'s is mathematically equivalent to the apparent *E* of the section determined by transformed section analysis.

C5.7.2 *Vertically Laminated Timbers*—The apparent modulus of elasticity of the section as calculated using the *LSE*'s (span-to-depth ratio of 100:1) of the laminations does not account for shear deformations expected at shorter span-to-depth ratios. The design modulus of elasticity for the cross section is 95 % of the apparent modulus of elasticity. The 5 % reduction adjusts from a *LSE* basis (span-to-depth ratio of 100:1) to a span-to-depth ratio of 21:1 to account for shear deformation in practical applications. As a result, most glulam beams can be designed without calculating the shear deflection separately from the flexural deflection.

C5.7.3 *Horizontally Laminated Timbers*—The apparent modulus of elasticity of the section as calculated using the *LSE*'s (span-to-depth ratio of 100:1) of the laminations does not account for shear deformations expected at shorter span-to-depth ratios. The design modulus of elasticity for the cross section is 95 % of the apparent modulus of elasticity. The 5 % reduction adjusts from a *LSE* basis (span-to-depth ratio of 100:1) to a span-to-depth ratio of 21:1 to account for shear deformation in practical applications. As a result, most glulam beams can be designed without calculating the shear deflection separately from the flexural deflection. Studies have confirmed the appropriateness of the 5 % reduction factor based on full-scale beam tests **(12, 1)**.

C5.8.1 *Horizontally Laminated Timbers*—Eq 6 assumes a parabolic distribution of shear stresses through the depth of the timber. Consequently the shear strengths of laminations away from the neutral axis of the beam have less impact on the shear capacity of the member. If the allowable shear stress for each lamination is known, Eq 6 can be used to determine an equivalent design stress for the member as governed by that particular lamination. The minimum design stress from the set of laminations is assigned as the design stress for the member.

The assumption of a parabolic stress distribution ignores the effect of lamination stiffness. Transformed section analysis would modify the shear stress distribution, however, the effect is generally small and is neglected based on committee judgment.

C5.8.2 *Vertically Laminated Timbers*—The simple weighted average approach ignores the effect of lamination stiffness on the shear stress distribution. Transformed section analysis would modify the shear stress distribution, however, the effect is generally small and is neglected based on committee judgment.

C5.9 *Compression Perpendicular to Grain*—For forces applied to the bottom face of the member (such as occur at beam supports), the allowable compression stress perpendicular to grain is assigned as the allowable stress for the bottom lamination. Likewise, for forces applied to the top face of the member, the allowable stress is assigned as the allowable stress for the top lamination. For forces applied to a side face of the member, the allowable compression perpendicular to grain stress is assigned as the allowable stress of the lowest grade laminations in the member (typically the core laminations). This typically results in three allowable stresses for compression perpendicular to grain for each lay-up, depending on location of the applied force.

C5.11 *Radial Stresses*—Radial stresses occur in curved members that are bent in such a way as to change the radius of curvature. The term *radial* in this context is not related to the term as used to denote the direction relative to the growth rings of a tree or piece of wood. Its usage refers to the direction of the stresses relative to the curvature of the member, irregardless of growth ring orientation.

C5.11.1 *Radial Tension*—Radial tension stresses occur in curved members that are bent in such a way as to straighten or flatten the curvature (increasing the radius of curvature). Even though stresses are highest at the neutral axis of the beam, the allowable stress for the member is conservatively limited to the weakest lamination used, regardless of placement. However, most glulam beams are manufactured with the weakest laminations at the core, which coincides with the location of highest radial stresses.

C5.11.2 *Radial Compression*—Radial compression stresses occur in curved members that are bent in such a way as to increase the curvature (decreasing the radius of curvature). Even though stresses are highest at the neutral axis of the beam, the allowable stress for the member is conservatively limited to the weakest lamination used, regardless of placement. However, most glulam beams are manufactured with the weakest laminations at the core, which coincides with the location of highest radial stresses.

Section C6 Stress Index Values for Laminations

C6.1 *Visually Graded Lumber*—Stress indices used in this practice represent wood properties that were determined from small, clear, straight-grained wood tested in the green condition. The properties from Practice D2555 are used to estimate a 5th percentile clear wood green stress value which is then modified for use in this practice.

C6.1.1 *Bending*—The data presented in Practice D2555 represent the testing of small, clear, straight grained specimens in the green condition. The factor of 0.743 adjusts the data from tests of 2-in. deep beams with a span-to-depth ratio of 14:1 to equivalent values for a 12-in. deep member with a span-to-depth ratio of 21:1, under uniform load. The factors in Table 1 adjust for dry-use conditions, duration of load, and a general factor of safety.

C6.1.1.1 FPL Bulletin 1069 **(9)** presented clear wood stress values of 3200 psi for dense Southern Pine and dense Douglas fir and 2750 psi for medium grain of both species. Those stresses were based on dry use and long term (permanent) loading. Multiplying those values by a factor of $^{10}/_{9}$ to adjust to the current design basis of 10-year load duration yields values of 3555 psi and 3055 psi, for dense and medium grain, respectively. Close grain Douglas fir was assigned a value of 2950 psi which is equivalent to 3275 psi when adjusted to 10-year load duration.

Subsequent analysis of glulam beam tests led to the development of an alternative procedure for assigning bending stress indices **(12, 1)**. The alternative procedure coupled with industry judgment and considering past practice led to the assignment of the stress indices in Table 2. This procedure also formed the basis for bending stress indices for *E*-rated laminations.

C6.1.2 *Compression Parallel to the Grain*—See C6.1.1.

C6.1.3 *Tension Parallel to the Grain*—Prior to the mid 1960s, the tensile strength of wood was assumed to be equal to the flexural strength based the results of small, clear wood tests and on the observation that members tested in bending ultimately fail (rupture) due to tensile stresses in the beam. Test equipment prior to that era was not capable of testing full-size members to failure in tension, due to problems in gripping the specimen adequately without crushing the ends of the member. The development of improved testing equipment led to the discovery that lumber specimens tested directly in tension were considerably weaker than similar specimens tested in flexure. The ratio of tensile strength to flexure strength was observed to range from approximately 50 % – 80 % with the ratio increasing with lumber quality **(28)**.

In about 1970, published tension values for visually graded lumber were reduced to approximately 55 % of the bending value and glulam tension values were reduced to 80 % of the bending value. Subsequent testing of approximately 350 tension specimens of Douglas fir glulam performed at Oregon State University indicated that a ratio of 5⁄8 was more appropriate for use in assigning glulam tension design values in conjunction with the knot size model used in 7.4.2 **(29)**.

C6.1.5 *Horizontal Shear*—The horizontal shear stresses published in Practice D2555 are based on tests of small shear blocks in accordance with Test Methods D143. The clear wood strength from Practice D2555 is adjusted by increasing by a factor of 1.13 to account for increases in strength due to drying. It is also adjusted by a factor of 1⁄4.1 for softwoods and 1⁄4.5 for hardwoods, which includes adjustments for duration of load and other effects and also includes a safety factor.

C6.1.5.1 The alternative test method described in this section and in Annex A7 was developed to address overly conservative results for some applications associated with using the small shear block method. This method results in allowable shear stresses 40 % – 50 % higher than those obtained through the method of C6.1.5 due in part to the major difference in the adjustment factors used to derive the allowable shear stress (1⁄4.1 for the block shear and 1⁄2.1 for the full-scale shear). The applicability of the higher shear values to cases which were not tested is unknown, so the applicability of the stresses determined by the methods of C6.1.5 and Annex A7 are currently limited to cases similar to the test case, that is, prismatic beams, subject to static, monotonic loading (See 5.8.1 and 5.8.2).

C6.1.6 *Compression Perpendicular to the Grain*—In visually graded lumber of some species, growth rate characteristics including ring width and summerwood proportion are used to estimate specific gravity. In some other species, density is determined directly by weight.

Eq 7 represents a simple linear regression model with the mean compression perpendicular to grain stress (green condition) predicted by green specific gravity (oven dry mass/green volume) further adjusted for moisture content and growth ring angle. Nine species were included in the referenced study. The study included both hardwood and softwood species representing a range of specific gravities: coast Douglas fir, interior north Douglas fir, shortleaf pine, western hemlock, Engelmann spruce, white spruce, Pacific Silver fir, aspen, and northern red oak **(30)**.

The factor of 1.9 adjusts from a green basis to an assumed average moisture content of 12 %. The divisor of 1.67 adjusts the test results to account for variations in growth ring angle which may occur in practice relative to the angle of the growth rings prescribed for the test in Test Methods D143 **(30)**. Specifically, the 1.67 factor adjusts from the test basis (load applied parallel to growth rings) to the most conservative basis (45° growth ring angle).

C6.1.7 *Radial Tension*—The tensile strength of small specimens tested in tension perpendicular to grain generally exceeds 1⁄3 of the shear strength determined from small shear block tests (see Wood Handbook **(31)**). However, structural problems observed in pitched and tapered curved beams under sustained gravity loads led the laminated timber industry to adopt and recommend a maximum value of 15 psi for several species. Mechanical reinforcement is generally used to increase the capacity of curved beams manufactured from those species to resist radial tension.

C6.2.1 *Bending*—Bending stress indices were established for a range of E-values based on analysis presented in USDA Forest Products Laboratory report FPL 292 **(1)**. (See C6.1.1.1.)

C6.2.2 *Compression Parallel to Grain*—Compression stress indices for *E*-rated laminations were set at similar levels to visually graded lumber having the same bending stress index. (See also C6.2.1.)

C6.2.3 *Tension Parallel to Grain*—The same procedure is used as for visually graded lumber (See C6.1.3).

C6.2.5 *Horizontal Shear*—See C6.1.5 and C6.1.5.1.

C6.2.6 *Compression Parallel to Grain*—Modulus of elasticity provides a reasonable estimate of specific gravity within a species. The pieces with higher MOE also tend to be the more dense pieces of the species. For the purposes of assigning compression perpendicular to grain design values, modulus of elasticity values that are expected to provide specific gravities similar to visual sorts based on growth rate have been specified.

C6.2.6.1 For mechanically graded lumber surfaced at a maximum moisture content of 19 % (average MC ~15 %) the lumber grading rules referenced prescribe the following equation to assign compression perpendicular to grain design values for grades which are qualified by test and quality controlled for specific gravity.

$$F_{c\perp} = (2252.4 \text{ psi})\,(SG) - 48 \text{ psi} \tag{X2.4}$$

where:
$F_{c\perp}$ = compression perpendicular to grain design value, and
SG = specific gravity measured at oven-dry weight and oven-dry volume.

Some rules **(19)** allow compression perpendicular-to-grain values to be increased by an additional 16 % for lumber dried to a maximum moisture content of 15 % (average MC ~12 %).

C6.2.7 *Radial Tension*—See C6.1.7.

Section C7 Stress Modification Factors (SMF) for Laminations

C7.1 The stress indices presented in Section 6, do not account for the effects of knots, slope of grain, and other strength reducing characteristics. Stress modification factors presented in subsequent sections modify the stress indices to determine allowable lamination stresses.

C7.1.1 See C4.3, C4.4, and Annex A4.

C7.1.2 *E*-rated grades typically specify minimum values for slope of grain in segments where modulus of elasticity is not evaluated by the machine, such as near the ends of the pieces. However, the stress indices assigned for *E*-rated laminations can be considered to include the effects of slope of grain, so the stress modification factors based on slope of grain are not applied separately.

C7.2.1.1 *Knots*—The ratio of the moment of inertia of knots in a beam cross section to the moment of inertia of the gross cross section (I_k/I_g) was empirically related to a bending strength ratio in Bulletin 1069 **(9)**. Subsequent modifications, including incorporation of transformed section analysis and increased allowable stresses for the compression side of beams, were made to the model based on research conducted at the Forest Products Laboratory **(12, 1)**. See Commentary for Annex A4.

(1) *Minimum Strength Ratio – Visually Graded Laminations*—The I_k/I_g model was found to be overly conservative for shallow beams, therefore, a minimum strength ratio for knots is prescribed for each lumber grade. The minimum strength ratio was derived assuming that the maximum permitted knot is present in every lamination of the member at the cross section. This condition represents a theoretical lower bound on the stress modification factor. The minimum strength ratio can be estimated as one minus the fractional knot size (that is, a grade permitting a 25 % knot has a minimum strength ratio of 75 %).

(2) *Minimum Strength Ratio – E-rated Laminations*—In the 1960s, machine grading technology began to be implemented. By 1970, WCLIB and WWPA had included rules for machine stress rated (MSR) lumber into their grade rules. Interest in using mechanically graded lumber in structural glued laminated timber was also growing. *E*-rated grades were developed directly from the established MSR grades of the time. AITC included combinations with *E*-rated lumber as early as 1979 (AITC 117-79 **(32)**). Rules governing the use of *E*-rated lumber were added to this practice in 1983.

The 1970 grading rules for WCLIB **(33)** and WWPA **(34)** included the following bending design values (Table C7.2.1.1 (2–1)).

TABLE X2.4 TABLE C7.2.1.1 (2–1) Selected MSR Grades From 1970 Western Grade Rules

Edgewise MOE (psi)	Edgewise F_b* (psi)	Edge Knot Restriction
1 500 000	1650	1/4
1 800 000	2100	1/6
2 000 000	2400	1/6
2 200 000	2700	1/6

*Stresses are for lumber loaded on edge. When loaded flatwise, stresses are permitted to be increased based on lumber width.

Minimum Strength Ratios for E-Rated Laminations:

The MSR *E*-values shown in Table C7.2.1.1 (2–1) were converted to equivalent *LSE* values, and minimum strength ratios for each grade were established by dividing the bending design value published in the grade rules by the bending stress indices established for *E*-rated grades (see C6.2.1). Table C7.2.1.1 (2–2) summarizes this information.

TABLE X2.5 TABLE C7.2.1.1 (2–2) Summary of E-grade Information

Edgewise E (psi)	Long Span EE (psi)	Edgewise Fb*E (psi)	BSIE (psi)	Minimum Strength Ratio	Edge Knot Limitation
1 500 000	1 600 000	1650	2560	0.64	1/4
1 800 000	1 900 000	2100	3000	0.70	1/6
2 000 000	2 100 000	2400	3500	0.69	1/6
2 200 000	2 300 000	2700	4000	0.68	1/6

The *LSE* values, the bending stress indices, the edge knot limitations, and the minimum strength ratios were published in this practice in 1983. Later versions of this practice published the minimum strength ratios as 0.65 for grades allowing ¼ edge knots and 0.7 for grades allowing ⅙ edge knots. These minimum strength ratios were applied to bending for both horizontally and vertically laminated beams until 2004. No increase was taken for flatwise bending of the laminations. For horizontally laminated beams, the minimum strength ratio was further restricted to 0.5 for beams greater than 15 in. deep.

Due to observed inconsistencies between the procedures for *E*-rated laminations and visually graded laminations, the AITC Technical Advisory Committee recommended changes to this practice, which were balloted and adopted in 2004 as described below.

Comparison of E-Rated and Visually Graded Strength Ratios:

The different methods used to determine minimum strength ratios led to significant differences between *E*-rated and visually graded laminations. A comparison of a common *E*-rated grade to a visual grade with the same *LSE* is shown in Table C7.2.1.1 (2–3). As shown, the minimum strength ratio for the *E*-rated grade was significantly lower than the ratio for the visual grade, even though the *E*-rated grade has more restrictive limitations on edge knots. Furthermore, because the minimum strength ratio for the *E*-rated grade dropped to 0.5 for beams greater than 15 in. deep, the I_k/I_g strength ratio will govern the beam design value at a shallower depth for *E*-rated layups than for visual layups with possible strength ratios even less than 0.7. This difference in minimum strength ratios meant that 2.1E6 could not be substituted into a combination for L1 (dense) to get the same design values by analysis. The net effect was that *E* -rated combinations required more high grade material than comparable visually graded combinations.

TABLE X2.6 TABLE C7.2.1.1 (2–3) Comparison of L1 and 2.1E6 Grades (Practice D3737-03)

Grade	L1 (dense)	2.1E6
Knot Restriction	1/4	1/6*
Long Span E (psi)	2 100 000	2 100 000
Bending Stress Index (psi)	3500	3500
Minimum Strength Ratio	0.75	0.70 for depth of 15 in. or less 0.50 for depths of more than 15 in.

*Limitation on edge knots. Centerline knots are unrestricted in size, except at ends of the piece where they are not allowed to exceed the centerline knot size of the middle section of the piece.

Solution:

To correct the inequity between the grading systems, some changes to this practice were made in the rules for *E*-rated laminations. The reduction in strength ratio to 50 % for beams deeper than 15 in. was removed for consistency with the rules for visually-graded laminations. Additionally, changes were made in determining the minimum strength ratio for *E*-rated laminations.

An appropriate flat use factor was chosen to apply to the minimum strength ratios for edgewise bending. Based on the 1970 and current grading rules, a factor of 1.15 was chosen. This factor is the flat use factor assigned to 2x × 6 MSR lumber. This resulted in calculated flatwise bending strength ratios of 0.80 and 0.75 for *E* -rated laminations with ⅙ and ¼ edge knot limitations, respectively.

C7.2.2.1 *Knots*—The strength ratio for knots is determined by an empirical equation based on full-scale beam tests and theoretical derivation presented in FPL 333 **(35)**. Design values published by the glulam industry are typically based on members with two, three, and “four or more” laminations.

C7.3.2 *Knots*—The procedure for determining the stress modification factor based on knots for compression parallel to the grain is analogous to the I_k/I_g procedure used to determine the stress modification factor for bending. However, the individual laminations are all given the same weight, rather than weighting the laminations based on position. The assumption is that the primary stresses on the section are compression, rather than bending. An empirical relationship between the ratio of the area of knots in a cross section to the area of the cross section was developed in Bulletin 1069 **(28)**. Testing was performed using laminated members 3 ft in length, so the statistical data for knot sizes is based upon the sum of knot sizes in any 3-ft length.

For members with unbalanced lay-ups, the neutral axis will not coincide with the geometric center of the member. Assuming the compression load is located at the geometric center of the cross-section, an eccentricity will exist relative to the actual neutral axis. The eccentric loading will cause the section to bend, increasing the compression on one side of the member. Equations for accounting for the changed stress distribution are included in Annex A5. See Commentary to Annex A5.

C7.3.4 Compression strength ratios for two and three lamination members are identical to the minimum bending strength ratios assigned to laminations in horizontally laminated beams. The compression strength ratio is also applied as a minimum value for four or more laminations in practice. (See also C7.2.1.1.)

C7.4.1 Eq 11 has been included in this practice since its inception in 1978. It was used as the basis for determining an appropriate tension stress index based on tests of glulam tension members (see C6.1.3).

C7.4.2 *Knots*—See C6.1.3.

C7.5 *Modulus of Elasticity*—The intent of this practice is not to prohibit the use of modulus of elasticity data based on shorter span-to-depth ratios than 100:1 as prescribed in 3.1.6.1, however, adjustment for span-to-depth ratio is required for consistent results when smaller span-to-depth ratios are used.

C7.6.1 *Horizontally Laminated Members*—Wane occurring on the corners of laminations will effectively reduce the area of the bondline to resist shear. A proportional reduction in shear capacity is assumed.

C7.6.2 *Vertically Laminated Members*—For members consisting of four or more laminations, one out of four pieces is assumed to have a check or split that limits its individual capacity to resist shear to ½ . The capacity of the member is then taken as the average capacity of the individual laminations or ⅞ . For two and three lamination beams one lamination is assumed to have a split that reduces its capacity to ½, resulting in composite capacities of ¾ and ⅚ , for two and three lamination beams, respectively.

To manufacture members with widths greater than the width of commonly available lumber, it is necessary to use multiple piece laminations (across the width). The manufacturer has the option to use a structurally bonded edge joint or to use unbonded edge joints staggered by a minimum of one lamination thickness in adjacent laminations. When unbonded edge joints are used, a weak plane occurs near the mid-depth of the beam where shear forces will be highest. These factors account for the possibility of shear failure on the plane containing the most unbonded joints. For five lamination beams, the effective width to resist shear is reduced to the thickness of two laminations resulting in an expected capacity of ⅖ of the gross section capacity. For three lamination members, the factor is calculated as ⅓, however, it is not considered likely that the split assumed to occur in ⅓ of the laminations will occur at the same location as the unbonded edge joints in the other laminations. For members with odd numbers of laminations, the expected capacity approaches 0.5, asymptotically as the number of laminations increases. A single factor of 0.4 is used to minimize complexity in design. For members with even numbers of laminations, the ratio is 0.5.

C7.7.1 The effect of knots and slope of grain on compression perpendicular to grain and radial compression is expected to be small relative to the effects of specific gravity, which is considered during the assignment of a stress index for these properties.

Section C8 Adjustment of Properties for End-Use Conditions

C8.2 *Moisture Content*—Dry-use design values for glulam are based on an assumed average moisture content of 12 %. This condition is obtained in practice by limiting laminating lumber to a maximum moisture content of 16 %. Theoretically, wet-use adjustment factors would vary between 12 % MC and the fiber saturation point, however, for simplicity in design, a single factor is applied for moisture contents of 16 % or more.

C8.4 *Flat Use Factor*—The name “flat use factor” is a misnomer in that it does not depend on the aspect ratio of the glulam beam, but rather on the orientation of the applied bending load. Prior to the 1990s, this factor was referred to as the “size factor” and was applied to design values in both *x-x* bending (horizontally laminated) and *y-y* bending (vertically laminated). With the adoption of the “volume factor” for *x-x* bending, the name of this factor was changed to “flat-use factor” to coincide with a factor of the same name adopted for lumber and to avoid confusion between “size” and “volume.”

It has long been recognized that the size of a wood member affects its apparent strength. At least as far back as the 1920s, the USDA Forest Products Laboratory had recommended an adjustment factor to account for size effects. The factor currently referred to as the “flat use factor” in this practice was developed through research done at the USDA Forest Products Laboratory and presented in Bohannan **(36)**.

C8.5 *Volume Factor*—A concise history on the development of the Volume Factor and previous size factors is presented in AITC Technical Note 21 **(37)**.

C8.6 *Curvature Factor*—This factor accounts for residual stresses in the curved member due to the bending of the individual laminations before bonding them together. It has been used at least as far back as the 1930s **(38)**. Its relationship to test data for Douglas fir, Southern Pine, and Sitka Spruce was also presented in Bulletin 1069 **(9)**.

C A1 (Annex A1) Qualification of Laminations by Test

CA1.1 The models in this practice are based on clear wood properties modified for characteristics that occur in structural lumber. They have been verified and calibrated with full-size beam test results. However, they do not directly relate lamination strength to member strength. To allow for the use of lumber that does not match the *E*-rated or visual grades of lumber established for laminating, particularly for grades that have criteria or controls based on mechanical properties, rules for determining equivalence with an existing grade have been established. One source of published properties for established lamination grades is AITC Standard 407 **(39)**.

CA1.1.1 The use of “next smallest width” presupposes the use of standard nominal U.S. dimension lumber sizes. The intent of the section is to allow qualification tests for a given size to apply to a smaller size with no more than 2 in. (51 mm) smaller width.

CA1.2.2 Eq A1.1 ensures that the upper bound of the 90 % confidence interval of the qualification sample mean exceeds the assigned grade *E* for a sample size of 50 specimens. Properties for established lamination grades are published in AITC Standard 407 **(39)**.

CA1.3 Tensile strength is generally considered the most critical property for laminations in horizontally laminated timbers. Tension tests are generally more sensitive than bending tests for detecting weaknesses.

CA1.3.3 The allowable bending property referred to in this section is the allowable strength of a 12 in. deep, horizontally laminated beam, subject to normal duration loads (10 year basis), normal temperature conditions, and dry use. For these factors to apply, the outer fiber stress (based on transformed section analysis) on the tension lamination should be no more than 10 % higher than the apparent beam stress.

CA1.3.4 Properties for established lamination grades are published in AITC Standard 407 **(39)**.

C A4 (Annex A4) Analysis of Horizontally Laminated Glulam Beams

CA4.1 *Neutral Axis*—The first step to analyze a horizontally laminated beam is to locate the neutral axis. For symmetric (balanced) lay-ups, it will be located at mid-depth. For unbalanced lay-ups the neutral axis will shift toward the stiffer side of the beam (generally the tension side). For simplicity in programming a spreadsheet or computer software, Eq A1.1 can be used to locate the neutral axis for both balanced and unbalanced lay-ups.

CA4.1.1 Eq A1.1 is a mathematically concise way of locating the neutral axis based on laminated beam theory or transformed section analysis. It assumes that every lamination in the laminated beam has the same width. Eq A4.2 and A4.3 locate the zone boundaries in relation to the neutral axis.

CA4.1.2 Eq A4.4 calculates the moment of inertia of each lamination or grade zone about the neutral axis. Adding the moments of inertia of the individual zones gives the total moment of inertia for the beam (transformed section) by Eq A4.5.

CA4.1.3 Eq A4.6 yields the gross moment of inertia of the untransformed section.

CA4.1.4 The moment of inertia of knots in a beam is based on a statistical analysis of the beam using measurements of the frequency and size of knots occurring in graded lumber **(9)**. Knot surveys in accordance with Annex A3 are necessary to measure and characterize the knot properties for each lamination grade.

Statistical Analysis

The statistical analysis assumes that the moment of inertia of knots in each lamination (I_{ki}) is normally distributed with mean = x_i and standard deviation = s_i. The moment of inertia of knots in the beam is the weighted sum of the moments of inertia for the knots in the individual laminations. The moment of inertia of knots in the beam at the 99.5 percentile is determined by the analysis.

The distribution of a sum of independent, weighted, Normal variates will also be Normal with the following distribution parameters **(40)**:

$$\mu = \sum_{i=1}^{n} F_i x_i \qquad (X2.5)$$

$$\sigma^2 = \sum_{i=1}^{n} F_i^2 s_i^2 = \sum_{i=1}^{n} F_i^2 \left(\frac{h_i}{k_{99.5}}\right)^2 \qquad (X2.6)$$

where:
μ = average moment of inertia of knots in cross section of beam,
σ^2 = variance of moment of inertia of knots in cross section of beam,
F_i = weighting factor for *i*th lamination in the beam,
x_i = average size of knots within a 1 ft length for the grade of the *i*th lamination,
s_i = standard deviation of knot size within a 1 ft length for the *i*th lamination grade,
h_i = difference between 99.5 percentile and average knot size for the grade, and
$k_{99.5}$ = factor used to calculate 99.5 percentile using formula ($x + ks$).

The 99.5 percentile moment of inertia of the knots in the beam is calculated by:

$$I_k = \mu + k_{99.5}\sigma \qquad (X2.7)$$

$$I_k = \sum_{i=1}^{n} F_i x_i + k_{99.5}\sqrt{\sum_{i=1}^{n} F_i^2 \left(\frac{h_i}{k_{99.5}}\right)^2} \qquad (X2.8)$$

$$I_k = \sum_{i=1}^{n} F_i x_i + \sqrt{\sum_{i=1}^{n} F_i^2 h_i^2} \qquad (X2.9)$$

Weighting Factors for Position in Cross Section

The weighting factors are calculated based on the un-transformed moment of inertia of each lamination with Eq X2.10 or Eq X2.11.

$$Z_i = (3N_i^2 - 3N_i + 1) \qquad (X2.10)$$

$$Z_i = N_i^3 - N_{(i-1)}^3 \qquad (X2.11)$$

where:
Z_i = untransformed section weighting factor for knots in *i*th lamination.

NOTE 1—For constant lamination thickness, $N_{(i-1)} = (N_i - \text{thickness})$. This practice assumes a lamination thickness of unity, which means $N_{(i-1)} = (N_i - 1)$.

Weighting Factors for Lamination E (transformed section)

Eq X2.12 takes into account the transformed section for the knots, assuming the material lost due to knots has the same *LSE* as the lamination in which they occur.

$$F_i = \left(\frac{E_i}{E_T}\right) Z_i \qquad (X2.12)$$

where:
F_i = transformed section weighting factor for knots in *j*th lamination, and
E_T = modulus of elasticity used for transformed section analysis.

The I_k/I_g ratio is calculated by Eq X2.13 for a half beam section (one side of neutral axis).

$$\frac{I_k}{I_g} = \frac{\left(\sum_{i=1}^{n_2}(x_i F_i) + \sqrt{\sum_{i=1}^{n_2}(h_i F_i)^2}\right)}{\sum_{i=1}^{n_2} Z_i} = \frac{\left(\sum_{i=1}^{n_2}\left(x_i Z_i \frac{E_i}{E_T}\right) + \sqrt{\sum_{i=1}^{n_2}\left(h_i Z_i \frac{E_i}{E_T}\right)^2}\right)}{\sum_{i=1}^{n_2} Z_i} \qquad (X2.13)$$

where:
I_k = transformed moment of inertia of knots in half cross section,
I_g = gross, untransformed moment of inertia of half cross section,
x_i = average knot size for lumber in *i*th lamination,
h_i = difference between 99.5 percentile knot size and average knot size for lumber in *i*th lamination, and
n_2 = number of laminations in half beam.

NOTE 1—To be mathematically correct, the denominator of Eq X2.13 should be ΣF_i, instead of ΣZ_i. This error was introduced in the original application of the transformed section in FPL 236 (**12**), and it has been incorporated into the design procedure for three decades. Because the model has been calibrated by the use of special tension laminations that aren't accounted for in the model, correcting this equation would require extensive work to re-calibrate the model. If the model were correct, the modulus of elasticity, E_T, used for the transformed section would be irrelevant. However, for consistency with established procedures, E_T must be chosen as the modulus of elasticity of the outermost zone of the half beam.

The previous equation is general for a half beam with N2 laminations. To facilitate programming this equation for computerized calculations, it is useful to divide the half beam into an arbitrary number of zones of constant grade. By doing so, Eq X2.13 can be simplified to the following:

$$\frac{I_k}{I_g} = \frac{\sum_{j=1}^{a_1}\left(x_j \frac{E_j}{E_T}\left[\sum_{i=1}^{c_1} Z_i - \sum_{i=1}^{b_1} Z_i\right] + \sqrt{h_j^2\left(\frac{E_j}{E_T}\right)^2\left[\sum_{i=1}^{c_1} Z_i^2 - \sum_{i=1}^{b_1} Z_i^2\right]}\right)}{\sum_{i=1}^{n_2} Z_i} \tag{X2.14}$$

where:
j = zone number
a_1 = number of zones in half beam,
b_1 = number of lamination located at inner edge of *j*th zone, and
c_1 = number of lamination located at outer edge of *j*th zone.

Through mathematically induction, the following solutions (Eq X2.15 and X2.16) can be proven for the summations of the weighting factors in a half beam.

$$\sum_{j=1}^{n_2} Z_j = N_{n_2}^3 \tag{X2.15}$$

$$\sum_{j=1}^{n_2} Z_j^2 = \frac{1}{5}\left(9N_{n_2}^5 - 5N_{n_2}^3 + N_{n_2}\right) \tag{X2.16}$$

Eq X2.15 is valid for any number of laminations including partial laminations (such as when the neutral axis does not coincide with the surface of a lamination). Eq X2.16, however, was derived with the assumption of laminations with a constant thickness. There is a small error associated with applying Eq X2.16 to the case where the distance to the first lamination boundary from the neutral axis is only a fraction of the lamination thickness.

Bulletin 1069 **(9)** and this practice use the following equations to calculate the summations of weighting factors for a full beam (or two symmetrical half-beams).

$$\sum_{j=1}^{n_2} Z_j = 2N_{n_2}^3 \tag{X2.17}$$

$$\sum_{j=1}^{n_2} Z_j^2 = \frac{2}{5}\left(9N_{n_2}^5 - 5N_{n_2}^3 + N_{n_2}\right) \tag{X2.18}$$

NOTE 1—Eq X2.18 is mathematically incorrect. The coefficient for the equation should be 4⁄5 , rather than 2⁄5 . This error was introduced in the original presentation of the I_k/I_g model in Bulletin 1069 **(9)** and has remained a part of the model for five decades. Because the model has been calibrated with this error, Eq X2.17 and X2.18 must be used to obtain results consistent with the tested database. While Eq X2.15 and X2.16 are mathematically correct, it is not appropriate to use them in the model, unless the model is recalibrated with the errors corrected.

Using Eq X2.17 and X2.18, the following weighting factors can be determined for each zone:

$$O_j = 2\left(N_j^3 - N_{(j-1)}^3\right) \tag{X2.19}$$

$$P_j = \frac{2}{5}\left(9N_j^5 - 5N_j^3 + N_j - 9N_{(j-1)}^5 + 5N_{(j-1)}^3 - N_{(j-1)}\right) \tag{X2.20}$$

CA4.1.5 Substitution of the weighting factors derived previously into Eq X2.14 yields the following simplification:

$$\left(\frac{I_k}{I_g}\right) = \frac{\sum_{a=1}^{j}\left(x_a\left(\frac{E_a}{E_j}\right)(O_a)\right) + \sqrt{\sum_{a=1}^{j}\left(h_a^2\left(\frac{E_a}{E_j}\right)^2(P_a)\right)}}{2d_j^3} \tag{X2.21}$$

where:
x_a = the average knot size, expressed in decimal fraction of width, for the grade of lamination in the *a*th zone,
h_a = the difference between the 99.5 percentile and average knot size, expressed in decimal fraction of the width, for the grade of lamination in the *a*th zone, and
d_j = the distance between the outermost edge of the *j*th zone and the neutral axis.

CA4.1.6 The I_k/I_g ratio is related to the strength ratio of the outermost lamination of the half beam by an empirical relationship, Eq X2.22, which was developed in Bulletin 1069 **(9)**.

$$SR_{bx\ n_2} = \left(1 + 3\frac{I_k}{I_g}\right)\left(1 - \frac{I_k}{I_g}\right)^3\left(1 - \frac{I_k}{2I_g}\right) \tag{X2.22}$$

where:
$SR_{bx\ n_2}$ = strength ratio for outer lamination.

Strength ratios for other laminations in the half beam are calculated by excluding laminations farther away from the neutral axis in the calculation of I_k/I_g. Strength ratios are typically calculated only for laminations at the outer edge of a grade zone. The strength ratio for each zone is also subject to a minimum strength ratio for each lamination grade (see C7.2.1.1 (1)).

CA4.1.7 See C7.2.1.2.

CA4.1.8 The lowest of the stress modification factors for knots and slope of grain is assigned as the stress modification factor for the zone.

CA4.1.9 Transformed section analysis for unbalanced lay-ups shows that the neutral axis will shift toward the stiffer side of the section (typically the tension side). By analysis, the outer fiber stresses on the less stiff side (typically the compression side) will be higher than on the tension side. Tests of beams, however, indicate that strength is typically controlled by rupture of the tension laminations.

The use of an unbalanced lay-up, with higher stiffness laminations on the bottom (tension side) of a beam than on the top (compression side), shifts the neutral axis downward, resulting in a smaller section modulus for the top of the beam than for the bottom. Consequently, the flexural stresses on the top of the beam necessarily exceed the stresses on the bottom. In theory, this would cause the design of most unbalanced lay-ups to be limited by the strength of the laminations on the top of the beam. However, in full-scale beam tests, compression failures are rarely observed prior to tension failures. To reconcile differences between theory and observation of beam tests, Moody recommended the use of a “compression bonus” of 1.3 to 1.5 for the design of unbalanced lay-ups, based on research presented in FPL 292 **(1)**. His stated intent was to allow for more efficient use of the laminating resource. A factor of 1.4 is applied in this practice. Its application is not conceptually limited to unbalanced lay-ups, and its inclusion won’t change the results for balanced lay-ups, so it can be conveniently applied here.

CA4.1.10 *Apparent Outer Fiber Stress*—Eq A4.13 determines the apparent outer fiber stress (based on rectangular cross section with neutral axis at mid-depth, which is the accepted design basis) corresponding to the maximum allowed stress on each zone.

Application of the allowable lamination stresses directly in design would require a complete transformed section analysis and published allowable stresses for each grade of lamination. For convenience in structural design, the transformed section analysis is performed as part of the process of assigning design values. The maximum stress permitted on any lamination (or zone) (in the transformed section) is mathematically converted to an equivalent, apparent outer fiber stress on a beam with rectangular cross section with neutral axis at mid-depth. The lowest of the apparent stresses is then assigned as the allowable stress for the beam. The designer can then design the beam without the necessity of performing a transformed section analysis and without knowing individual allowable stresses for each lamination.

CA4.1.11 Eq A4.14 determines the allowable design value for the beam and applies the tension lamination factor required by the standard. (See 4.3.)

CA4.1.12 Eq A4.15 calculates the required strength ratio, which is used to determine required tension lamination quality. Eq A4.15 takes into account the effect of stresses on the outer lamination due to lamination stiffness by transformed section analysis (see also CA4.1.10). The rounded value of F_{bx} should be used in the equation.

CA4.2 *Example*—The example is for an unbalanced lay-up, which is the more complex case. Some steps could be omitted for a balanced lay-up, such as locating the neutral axis, however, the procedures illustrated will work equally well for both balanced and unbalanced lay-ups, facilitating programming into a spreadsheet or other software. The knot data in Table A4.1 were taken from FPL 236 **(12)**. While sufficient for the purposes of illustration, they should not be relied upon for glulam lay-up design, because they do not necessarily match knot survey data currently in use.

REFERENCES

(1) Moody, R. C., “Improved Utilization of Lumber in Glued Laminated Beams,” *Research Paper FPL 292*, U.S. Forest Products Laboratory, 1977.

(2) Marx, C. M., and Moody, R. C., “Strength and Stiffness of Shallow Glued-Laminated Beams with Different Qualities of Tension Laminations,” *Research Paper FPL 381*, U.S. Forest Products Laboratory, 1981.

(3) Fox, S. P., “Bending Strength of a Proposed Douglas-fir 20f Glulam Stress Grade,” *Western Forest Products Laboratory Information Report VP-X-175*, Vancouver, B.C., Canada, 1978.

(4) Bendtsen, B. A. and Galligan, W. L., “Mean and Tolerance Limit Stresses and Stress Modeling for Compression Perpendicular to Grain in Hardwood and Softwood Species,” *Research Paper FPL 337*, U. S. Forest Product Laboratory, 1979.

(5) Western Wood Products Association, *Western Lumber Grading Rules 81*, 1998.

(6) West Coast Lumber Inspection Bureau, *Standard Grading Rules for West Coast Lumber*, No. 17, 1996.

(7) Southern Pine Inspection Bureau, *Standard Grading Rules for Southern Pine Lumber*, 1994.

(8) National Lumber Grades Authority (NLGA), *Standard Grading Rules for Canadian Lumber*, 1997.

(9) Freas, A. D., and Selbo, M. L., “Fabrication and Design of Glued Laminated Wood Structural Members,” *Technical Bulletin No. 1069*, USDA Forest Products Laboratory, Madison, WI, 1954.

(10) Wolfe, R. W., and Moody, R. C., “Bending Strength of Vertically Glued Laminated Beams with One to Five Plies,” *Research Paper FPL 333*, U.S. Forest Products Laboratory, 1979.

(11) Forest Products Laboratory “Wood Handbook,” *Agriculture Handbook No. 72*, U.S. Department of Agriculture, 1987.

(12) Moody, R. C., “Design Criteria for Large Structural Glued-Laminated Timber Beams Using Mixed Species of Visually Graded Lumber,” *Research Paper FPL 236*, USDA Forest Products Laboratory, Madison, WI, 1974.

(13) Yeh, B., Williamson, T. G., and O’Halloran, M. R., “Shear Strength of Structural Glued Laminated Timber Based on Full-Size Flexure Tests,” *Proceedings of the 1999 Pacific Timber Engineering Conference*, Rotorua, New Zealand, 1999.

(14) Lawless, J. F., *Statistical Models and Methods for Lifetime Data*, John Wiley and Sons, New York, NY, 1982.

(15) Moody, R., Falk, R., and Williamson, T., “Strength of Glulam Beams-Volume Effects,” *Proceedings of the 1990 International Timber Engineering Conference*, Vol 1, Tokyo, Japan, 1980, pp. 176–182.

(16) Moody, R., Dedolph, C., and Plantinga, P. “Analysis of Size Effect for Glulam Beams,” *Proceedings of the 1988 International Timber Engineering Conference*, Vol 1, Seattle, WA, 1988 , pp. 892–898.

(17) Manbeck, H., Janowiak, J., Blankenhorn, P., Laborsky, P., Moody, R., and Hernandez, R., “Performance of Red Maple Glulam Timber Beams,” *Research Paper FPL-RP-519*, USDA Forest Products Laboratory, Madison, WI, 1993.

(18) Moody, R. Hernandez, R., Davalos, J., and Somnath, S., “Yellow Poplar Glulam Timber Beam Performance,” *Research Paper FPL-RP-520*, SDA Forest Products Laboratory, Madison, WI, 1993.

(19) Shedlauskas, J. P., Manbeck, H., Janowiak, J., Hernandez, R., Moody, R., Blackenhorn, P., and Labosky, P., “Efficient Use of Red Oak for Glued-Laminated Beams,” *Transactions of ASCE*, Vol 39, No. 1, 1996, pp. 203–209.

(20) Bohannan, B., “Flexural Behavior of Large Glued-Laminated Beams,” *Research Paper FPL 72*, USDA Forest Products Laboratory, Madison, WI, 1966.

(21) Bohannan, B., and Moody, R. C., “Large Glued-Laminated Beams with Two Grades of Tension Laminations", *Research Paper FPL 113*, USDA Forest Products Laboratory, Madison, WI, 1969.

(22) AITC "Brown Book"

(23) AITC Standard 500

(24) AITC 117–71

(25) AITC 117–74

(26) Marx, C. M., "Bending Strength of Shallow Glued-Laminated Beams of a Uniform Grade," *Research Paper FPL 380*, USDA Forest Products Laboratory, Madison, WI, 1981.

(27) Marx, C. M., "Strength and Stiffness of Small Glued-Laminated Beams with Different Qualities of Tension Laminations," *Research Paper FPL 381*, USDA Forest Products Laboratory, Madison, WI, 1981.

(28) Galligan, W. L., Gerhards, C. C., and Ethington, R. L., "Evolution of Tensile Design Stresses for Lumber," *General Technical Report FPL 28*, USDA Forest Products Laboratory, Madison, WI, 1979.

(29) Brassell, T, "Allowable Stresses in Glued Laminated Timbers," AITC files, undated correspondence explaining proposed changes to 1976 Uniform Building Code.

(30) Bendtsen, B. A., and Galligan, W. L., "Modeling the Stress-Compression Relationships in Wood in Compression Perpendicular to Grain," *Forest Products Journal*, Vol 29, No. 2, 1979, pp. 42–48.

(31) Forest Products Laboratory, "Wood Handbook – Wood as an Engineering Material," *General Technical Report FPL-GTR-113*, USDA Forest Products Laboratory, Madison, WI, 1999.

(32) AITC 117–79

(33) WCLIB, *Grading Rules for West Coast Lumber*, West Coast Lumber Inspection Bureau, Portland, OR, 1970.

(34) WWPA, *Western Lumber Grading Rules*, Western Wood Products Association, Portland, OR, 1970 .

(35) Wolfe, R. W., and Moody, R. C., "Bending Strength of Vertically Glued Laminated Beams with One to Five Plies," *Research Paper FPL 333*, USDA Forest Products Laboratory, Madison, WI, 1979.

(36) Bohannan, B., "Effect of Size on Bending Strength of Wood Members," *Research Paper FPL 56*, USDA Forest Products Laboratory, Madison, WI, 1966.

(37) AITC Technical Note 21

(38) Wilson, T. R. C., "The Glued Laminated Wooden Arch," *Technical Bulletin No. 691*, USDA Forest Products Laboratory, Madison, WI, 1939.

(39) AITC Standard 407

(40) Ang, A. H-S., and Tang, W. H., *Probability Concepts in Engineering Planning and Design*, Volume 1: Basic Principles, John Wiley and Sons, New York, NY, 1975, p. 179.

(41) American Institute of Timber Construction (AITC), *Standard Specifications for Structural Glued Laminated Timber of Hardwood Species,* Englewood, CO, 1996, pp. 119–196.