Designation: D7199 – 07 (Reapproved 2012)

Standard Practice for Establishing Characteristic Values for Reinforced Glued Laminated Timber (Glulam) Beams Using Mechanics-Based Models[1]

This standard is issued under the fixed designation D7199; 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 mechanics-based requirements for calculating characteristic values for the strength and stiffness of reinforced structural glued laminated timbers (glulam) manufactured in accordance with applicable provisions of ANSI/AITC A190.1, subjected to quasi-static loadings. It addresses methods to obtain bending properties parallel to grain, about the x-x axis (F_{bx} and E_x) for horizontally-laminated reinforced glulam beams. Secondary properties such as bending about the y-y axis (F_{by}), shear parallel to grain (F_{vx} and F_{vy}), tension parallel to grain (F_t), compression parallel to grain (F_c), and compression perpendicular to grain ($F_c\perp$) are beyond the scope of this practice. When determination of secondary properties is deemed necessary, testing according to other applicable methods, such as Test Methods D143, D198 or analysis in accordance with Practice D3737, is required to establish these secondary properties. Reinforced glulam beams subjected to axial loads are outside the scope of this standard. This practice also provides minimum test requirements to validate the mechanics-based model.

1.2 The practice also describes a minimum set of performance-based durability test requirements for reinforced glulams, as specified in Annex A1. Additional durability test requirements shall be considered in accordance with the specific end-use environment. Appendix X1 provides an example of a mechanics-based methodology that satisfies the requirements set forth in this standard.

1.3 Characteristic strength and elastic properties obtained using this standard may be used as a basis for developing design values. However, the proper safety, serviceability and adjustment factors including duration of load, to be used in design are outside the scope of this standard.

1.4 This practice does not cover unbonded reinforcement, prestressed reinforcement, nor shear reinforcement.

1.5 The values stated in SI units are to be regarded as standard. The mechanics based model may be developed using SI or in.-lb units.

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

2. Referenced Documents

2.1 *ASTM Standards:*[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
D905 Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading
D1990 Practice for Establishing Allowable Properties for Visually-Graded Dimension Lumber from In-Grade Tests of Full-Size Specimens
D2559 Specification for Adhesives for Bonded Structural Wood Products for Use Under Exterior Exposure Conditions
D2915 Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products
D3039/D3039M Test Method for Tensile Properties of Polymer Matrix Composite Materials
D3410/D3410M Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading
D3737 Practice for Establishing Allowable Properties for Structural Glued Laminated Timber (Glulam)
D4761 Test Methods for Mechanical Properties of Lumber and Wood-Base Structural Material
D5124 Practice for Testing and Use of a Random Number

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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.

Generator in Lumber and Wood Products Simulation

2.2 *Other Standard:*

ANSI/AITC A190.1 Structural Glued Laminated Timber[3]

3. Terminology

3.1 *Definitions*—Standard definitions of wood terms are given in Terminology D9 and standard definitions of structural glued laminated timber terms are given in Practice D3737.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *bonded reinforcement*—a reinforcing material that is continuously attached to a glulam beam through adhesive bonding.

3.2.2 *bumper lamination*—a wood lamination continuously bonded to the outer side of reinforcement.

3.2.3 *compression reinforcement*—reinforcement placed on the compression side of a flexural member.

3.2.4 *conventional wood lamstock*—solid sawn wood laminations with a net thickness of 2 in. or less, graded either visually or through mechanical means, finger-jointed and face-bonded to form a glulam.

3.2.5 *development length*—the length of the bond line along the axis of the beam required to develop the design tensile strength of the reinforcement.

3.2.6 *fiber-reinforced polymer (FRP)*—any material consisting of at least two distinct components: reinforcing fibers and a binder matrix (a polymer). The reinforcing fibers are permitted to be either synthetic (for example, glass), metallic, or natural (for example, wood), and are permitted to be long and continuously-oriented, or short and randomly oriented. The binder matrix is permitted to be either thermoplastic (for example, polypropylene or nylon) or thermosetting (for example, epoxy or vinyl-ester).

3.2.7 *laminating effect*—an apparent increase of lumber lamination tensile strength because it is bonded to adjacent laminations within a glulam beam. This apparent increase may be attributed to a redirection of stresses around knots and grain deviations through adjacent laminations.

3.2.8 *partial length reinforcement*—reinforcement that is terminated within the length of the timber.

3.2.9 *reinforcement*—any material that is not a conventional lamstock whose mean longitudinal ultimate strength exceeds 20 ksi for tension and compression, and whose mean tension and compression MOE exceeds 3000 ksi, when placed into a glulam timber. Acceptable reinforcing materials include but are not restricted to: fiber-reinforced polymer (FRP) plates and bars, metallic plates and bars, FRP-reinforced laminated veneer lumber (LVL), FRP-reinforced parallel strand lumber (PSL).

3.2.10 *shear reinforcement*—reinforcement intended to increase the shear strength of the beam. This standard does not cover shear reinforcement.

3.2.11 *tension reinforcement*—reinforcement placed on the tension side of a flexural member.

3.3 *Symbols:*

Arm = moment arm, distance between compression and tension force couple applied to beam cross-section

b = beam width

C = total internal compression force within the beam cross-section (see Fig. 2)

CFRP = carbon fiber reinforced polymer

d = beam depth

E = long-span flatwise-bending modulus of elasticity for wood lamstock (Test Methods D4761; also see Fig. 1)

F_b = allowable bending stress parallel to grain

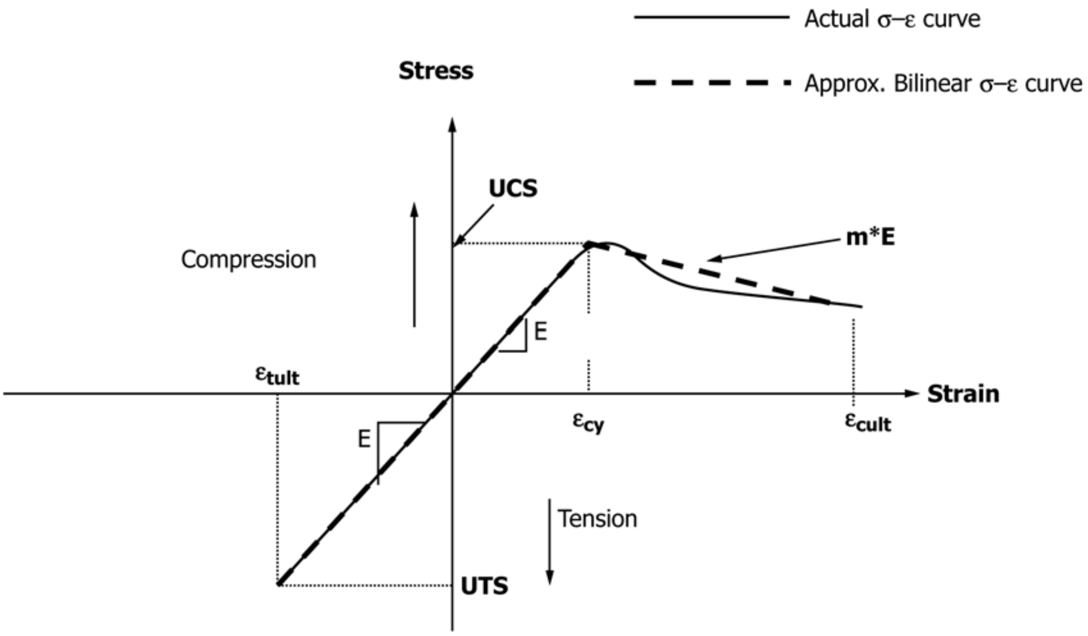

FIG. 1 Typical Stress-Strain Relationship for Wood Lamstock, with Bilinear Approximation

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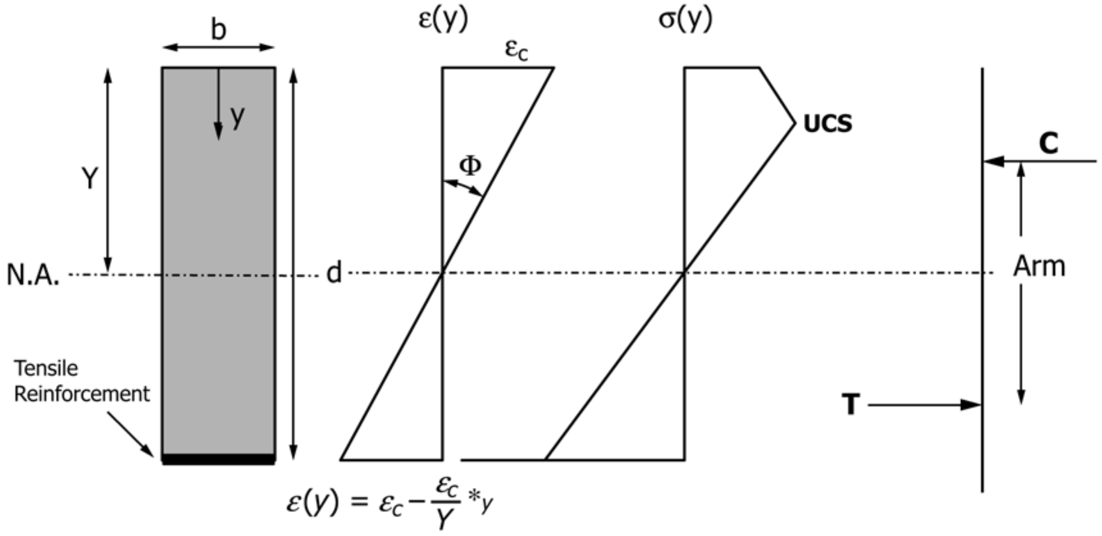
[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.



NOTE 1—A simplified rectangular block stress distribution can be used but it must be shown that it accurately represents the stress distribution.

FIG. 2 Example of Beam Section with Strain, Stress, and Force Diagrams

F_x = internal horizontal force on the beam cross-section (see Eq 2)

GFRP = Glass fiber-reinforced polymer

LEL = lower exclusion limit (point estimate with 50 % confidence, includes volume factor)

LTL = lower tolerance limit (typically calculated with 75 % confidence)

$M_{applied}$ = external moment applied to the beam cross-section

$M_{internal}$ = internal moment on the beam cross-section

MC = moisture content (%)

MOE = modulus of elasticity

MOR = modulus of rupture

$MOR_{5\%}$ = 5 % one-sided lower tolerance limit for modulus of rupture, including the volume factor

$MOR_{BL5\%}$ = 5 % one-sided lower tolerance limit for modulus of rupture corresponding to failure of the bumper lamination, including the volume factor

$m*E$ = downward slope of bilinear compression stress-strain curve for wood lamstock (see Fig. 1)

N.A. = neutral axis

T = total internal tension force within the beam cross-section (see Fig. 2)

UCS = ultimate compressive stress parallel to grain

UTS = ultimate tensile stress parallel to grain

Y = distance from extreme compression fiber to neutral axis (see Fig. 2)

y = distance from extreme compression fiber to point of interest on beam cross-section (see Fig. 2)

ε_c = strain at extreme compression fiber of beam cross-section (see Fig. 2)

ε_{cult} = compression strain at lamstock failure (see Fig. 1)

ε_{cy} = compression yield strain at lamstock UCS (see Fig. 1)

ε_{tult} = tensile strain at lamstock failure (see Fig. 1)

$\varepsilon(y)$ = strain distribution through beam depth (see Fig. 2)

ρ = tension reinforcement ratio (%); cross-sectional area of tension reinforcement divided by cross-sectional area of beam between the c.g. of tension reinforcement and the extreme compression fiber

ρ' = compression reinforcement ratio (%); cross-sectional area of compression reinforcement divided by cross-sectional area of beam between the c.g. of compression reinforcement and the extreme tension fiber

$\sigma(y)$ = stress distribution through beam depth (see Fig. 2)

4. Requirements for Mechanics-Based Analysis Methodology

NOTE 1—At a minimum, the mechanics-based analysis shall account for: *(1)* Stress-strain relationships for wood laminations and reinforcement; *(2)* Strain compatibility; *(3)* Equilibrium; *(4)* Variability of mechanical properties; *(5)* Volume effects; *(6)* Finger-joint effects; *(7)* Laminating effects; and *(8)* Stress concentrations at termination of reinforcement in beams with partial length reinforcement. In addition to the above factors, characteristic values developed using the mechanics-based model need to be further adjusted to address end-use conditions including moisture effects, duration of load, preservative treatment, temperature, fire, and environmental effects. The development and application of these additional factors are outside the scope of this practice. Annex A1 addresses the evaluation of durability effects. The minimum output requirements for the analysis are mean MOE (based on gross section) and 5% LTL MOR with 75 % confidence (based on gross section), both at 12 % MC. These analysis requirements are described below.

4.1 *Stress-strain Relationships:*

4.1.1 *Conventional Wood Lamstock:*

4.1.1.1 The stress-strain relationship shall be established through in-grade testing following Test Methods D198 or Test Methods D4761, or other established relationships as long as the resulting model meets the criteria established in Section 5. Test lamstock shall be sampled in sufficient quantity from enough sources to insure that the test results are representative of the lamstock population that will be used in the fabrication of the beams. Follow-up testing shall be performed annually in order to track changes in lamstock properties over time, so that the layup designs may be adjusted accordingly.

4.1.1.2 The stress-strain relationship shall be linear in tension. The stress-strain relationship shall be nonlinear in compression if compression is the governing failure mode. In this case, a bilinear approximation is acceptable, and shall be used throughout this standard (see Fig. 1). In the bilinear model both tension and compression MOE shall be permitted to be approximated by using the long-span flatwise-bending MOE obtained using Test Methods D4761. In Fig. 1, m*E is the downward slope of the compression stress-strain curve, defined as the best-fit downward line through the point (UCS, ε_{cy}) on the compression stress-strain curve. The downward best-fit line shall be permitted to be terminated at the point where the ultimate compressive strain ε_{cu} is approximately 1 %.

4.1.2 *Reinforcement:*

4.1.2.1 The stress-strain relationship shall be established through material-level testing in accordance with Test Method D3039/D3039M and D3410/D3410M.

4.1.2.2 Nonlinearities in the stress-strain relationship shall be included in the analysis, if present.

4.1.2.3 Acceptable stress-strain models for unidirectional E-glass FRP (GFRP), Aramid, or Carbon FRP (CFRP) in tension are linear-elastic. Acceptable models for hybrid E-glass/Carbon composites in tension are linear or bilinear. Acceptable models for mild steel reinforcement are elastic-plastic. Similar models may also apply in compression.

4.2 *Strain Compatibility:*

4.2.1 Fig. 2 shows the cross section of a beam with a linear strain and bilinear stress distribution, with the neutral axis a distance Y below the top of the beam. Using the extreme compression fiber as the origin, the strain distribution for a given applied moment ($M_{applied}$) is defined by the equation:

$$\varepsilon(y) = \varepsilon_c - \varepsilon_c{}^*(y/Y) \tag{1}$$

4.3 *Equilibrium:*

4.3.1 In order to maintain equilibrium, the cross-section shall satisfy the conditions of horizontal equilibrium (Eq 2), and the internal moment ($M_{internal}$) shall equal the external moment applied to that cross section ($M_{applied}$) (Eq 3). See Fig. 2 as an example of strain compatibility and equilibrium:

$$\sum F_x = 0 \Rightarrow \int_{depth} \sigma(y)dA = 0 \tag{2}$$

$$M_{applied} = M_{internal} = C(\text{or } T)^*Arm = \int_{depth} -y^*\sigma(y)^*dA \tag{3}$$

4.4 *Variability of Mechanical Properties:*

4.4.1 The model shall properly account for the variability of the mechanical properties of the wood lamstock and the FRP reinforcement. This includes variability of individual properties and correlations among those properties as appropriate. The mechanics-based analysis shall address statistical properties for and correlations between Ultimate Tensile Stress (UTS), Ultimate Compressive Stress (UCS) and long-span flatwise-bending modulus of elasticity (*E*). One example of how this may be achieved is provided in Appendix X1.

4.4.2 These correlation values are obtained from test data. Test lamstock shall be sampled in sufficient quantity, from enough sources to insure that the test results are representative of the lamstock population that will be used in the fabrication of the beams. Follow-up testing shall be performed annually in order to track changes in lamstock properties over time, so that the layup designs may be adjusted accordingly.

4.5 *Volume Effects:*

4.5.1 The model shall properly account for changes in beam strength properties as affected by beam size. In conventional glulam, this is achieved by using a volume factor C_v, which was derived from laboratory test data. With adequate reinforcement, glulams can achieve a reduction or even elimination of volume effects. The model shall properly account for this phenomenon. One possible approach to address the volume effect is described in Appendix X1.

4.6 *Finger-Joint Effects:*

4.6.1 Finger joints affect the mechanical properties of lamstock used in glulams. The model shall account for these effects on both the mean and variability of the beam mechanical properties. One example of how this may be achieved is provided in Appendix X1.

4.7 *Laminating Effects:*

4.7.1 The laminating effects may be predicted by the model or else developed outside the model (and applied in the model) using an empirical, numerical or analytical approach. One way to achieve this for a beam subjected to 4-point bending is described in Appendix X1.

4.8 *Stress Concentrations at Termination of Reinforcement in Beams with Partial Length Reinforcement:*

4.8.1 Beams with partial length reinforcement have stress concentrations near the ends of the reinforcement. These stress concentrations are in the form of tension or compression stresses parallel to grain, combined with peeling stresses perpendicular to grain. The model shall have the ability to account for the effects of these stress concentrations if partial length reinforcement will be used.

4.9 *Mechanical Properties Predicted by Model:*

4.9.1 The model shall at a minimum predict the following properties, including the effects of a bumper lamination if one is used, which are the basis for design values.

4.9.2 *Bending Strength:*

4.9.2.1 The bending strength calculated by the model assumes adequate bond development length is provided for the reinforcement. The model shall predict the lower 5 % tolerance limit for modulus of rupture ($MOR_{5\%}$) for the reinforced layup being analyzed. Beam MOR shall be based on gross (full width and depth) cross section properties:

$$MOR = \frac{6^*M_{max}}{b^*d^2} \tag{4}$$

Where M_{max} is the maximum moment applied to the beam, and b and d are respectively the full width and depth of the beam cross-section. The transformed section properties shall not be used.

4.9.2.2 If a bumper lamination is used, an additional characteristic bending strength value $MOR_{BL5\%}$ corresponding to bumper lamination failure shall also be reported. It should be noted that the model-predicted bending strength characteristic values MOR$_{5\%}$ and MOR$_{BL5\%}$ shall include the volume effect, so that the volume factor will not be applied separately.

4.9.3 *Bending Stiffness:*

4.9.3.1 The model shall predict the mean modulus of elasticity (MOE) for the reinforced layup being analyzed. MOE shall be based on gross (full width and depth) cross-section properties. If a bumper lamination is present, the model shall predict the beam stiffness properties before and after failure of the bumper lamination.

4.9.3.2 If a bumper lamination is used, the model shall be able to predict failure of the bumper lamination, as well as its contribution to beam strength and stiffness. The modeling approach described in Appendix X1 is an example of how to accomplish this.

NOTE 2—A bumper lamination, if used, will likely fail prior to reaching the ultimate capacity of the reinforced beam. In tests of GFRP-reinforced glulam with 1.1 % to 3.3 %, the bumper lam failure load was typically 10-20 % below the ultimate strength. This range will differ depending on the reinforcement type, reinforcement ratio, beam layup, and grade of the bumper lamination.

4.10 *Secondary Properties:*

4.10.1 Secondary properties such as bending about the y-y axis (F_{by}), shear parallel to grain (F_{vx} and F_{vy}), tension parallel to grain (F_t), compression parallel to grain (F_c), and compression perpendicular to grain ($F_{c\perp}$) shall be determined following methods described in Practice D3737.

4.10.2 Analysis has shown that with the level of FRP extreme fiber tension reinforcement typically envisioned (up to 3 % GFRP or 1 % CFRP), the maximum shear stress at the reinforced beam neutral axis is very similar to that of an unreinforced rectangular section. In addition, under the same conditions, the shear stress at the FRP-wood interface is always significantly smaller than the shear stress at the reinforced beam neutral axis.

4.11 *Numerical Solution Methodology:*

4.11.1 Any numerical solution methodology[4] shall be permitted for use, so long as it incorporates the nonlinearities in mechanical properties for wood and FRP as specified in section 4.1, and satisfies the conditions of strain compatibility (section 4.2), and equilibrium (section 4.3).

TABLE 1 Initial Qualification Using Primary Species: DF, SP or SPF—Minimum Beam Test Matrix for Mechanics-Based Model Validation^{A,B}

Beam Size	Reinforcement Ratio ρ %		
	Min^{C}	Typical^{C}	Max^{C}
5⅛ in. by 12 in. by 21 ft	10	10	10
6¾ in. by 24 in. by 42 ft.	10	10	10

^{A} All beams shall use the same layup, species, reinforcement type, and wood lam thickness.

^{B} A larger set may be required in order to keep the Standard Error less than 0.1 * (5%LEL). See Practice D2915, Section 3.4.3.2 for determining a minimum sample size.

^{C} See Table 3. The model will only be considered valid for ρ within the tested minimum and maximum.

TABLE 2 Subsequent Qualification of Additional Species (DF, SP, SPF or hardwoods)—Minimum Beam Test Matrix for Mechanics-Based Model Validation^{A,B}

Beam Size	Reinforcement Ratio ρ %		
	Min^{C}	Typical^{C}	Max^{C}
5⅛ in. by 18 in. by 32 ft.	10	—	10

^{A} All beams shall use the same layup, species, reinforcement type, and wood lam thickness.

^{B} A larger set may be required in order to keep the Standard Error less than 0.1 * (5%LEL). See Practice D2915 Section 3.4.3.2 for determining a minimum sample size.

^{C} See Table 3. The model will only be considered valid for ρ within the tested minimum and maximum.

TABLE 3 Typical Reinforcement Ratios^{A}

	Reinforcement Material			
	E-glass FRP	Aramid FRP	Carbon FRP	Steel Plate
MOE (ksi)	6 000	10 000	20 000	30 000
Minimum ρ^{B} %	1	0.6	0.3	0.2
Typical ρ %	2	1.2	0.6	0.4
Maximum ρ %	3	1.8	0.9	0.6

^{A} The Reinforcement Ratios presented in this table represent typical values. The manufacturer may use any minimum, maximum, or typical value considered appropriate, although the model will only be valid within the range tested.

^{B} ρ = Tension reinforcement ratio (%); cross-sectional area of tension reinforcement divided by cross-sectional area of beam above c.g. of tension reinforcement.

5. Standard Methodology for Validating Mechanics-Based Models which Satisfy the Requirements Set Forth in This Standard

5.1 Mechanics-based models which satisfy the requirements set forth in this standard shall be validated through physical testing as shown in Tables 1-3. Being mechanics-based, the model shall be validated using 60 beams for one primary wood species (Table 1), and 20 beams for each additional wood species (Table 2). All beams in Table 3 shall utilize the same wood layup, and the same type of reinforcement.

5.2 The predicted 5% LEL using the mechanics-based model (5% LEL$_{model}$) shall be compared with the 5% LEL calculated from the test results (5% LEL$_{test}$) for each of the eight cells in Tables 1 and 2. Conditions of model acceptance are as follows:

$|(5\%\ LEL_{model} - 5\%\ LEL_{test})|\ /\ 5\%\ LEL_{model} < 0.10$
for each of the 8 cells in Tables 1 and 2
$⅛\ \Sigma\ (5\%\ LEL_{model} - 5\%\ LEL_{test})\ /\ 5\%\ LEL_{model} < 0.06$
for all 8 cells in Tables 1 and 2

5.3 Similarly, conditions for model acceptance include the mean MOE in the linear elastic range based on gross section dimensions as follows:

$|(\text{mean } MOE_{model} - \text{mean } MOE_{test})|\ /\ \text{mean } MOE_{model} < 0.10$
for each of the 8 cells in Tables 1 and 2
$⅛\ \Sigma\ (\text{mean } MOE_{model} - \text{mean } MOE_{test})\ /\ \text{mean } MOE_{model} < 0.06$
for all 8 cells in Tables 1 and 2

5.4 It is important to stress that a test sample size larger than indicated in Tables 1 and 2 shall be considered in order to keep the Standard Error less than 0.1 * (5 % LEL). Section 3.4.3.2 of Practice D2915 shall be used for determining an adequate minimum test sample size.

5.5 In addition to the 5 % LEL predictions, the predominant mode of failure shall be identified by the model for each

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[4] Typical solutions for the nonlinear set of Eq 1-3 may be Newton-Raphson or other iterative techniques.

reinforcement level tested, and this mode of failure shall compare with the mode of failure observed in the laboratory testing program. For the beam confirmation testing the characteristics of the wood laminations (for example, finger-joint spacing, lumber grade etc.) need to be consistent with the model.

5.6 In addition to Test Methods D198 test reporting requirements, the report shall include: *(1)* details of the layups tested including grades, distribution of finger-joint spacings and strengths, reinforcement location, strength and stiffness, *(2)* failure modes (predicted and lab test results), *(3)* load to failure (predicted and lab test results), *(4)* load-deflection curves (predicted and lab test results), *(5)* 5 % LEL analysis (predicted and lab test results as described above).

ANNEX

(Mandatory Information)

A1. PERFORMANCE-BASED DURABILITY REQUIREMENTS

A1.1 *Reinforcement*—The reinforcement shall maintain adequate strength and stiffness based on the anticipated end-use conditions over the lifetime of the structure. Synergistic effects of the exposure conditions described in Table A1.1 shall be considered if appropriate for the end-use environment, using the appropriate ASTM standards.

A1.1.1 Beams reinforced with FRP shall not be post-treated unless testing verifies that the required FRP strength and stiffness retentions can be achieved. Tests results have shown that post-treatment with CCA causes significant strength degradation of E-glass FRP reinforcement. It should be noted that for other reasons, the laminating industry specifically recommends against post-treatment of glulam beams with any waterborne treatments.

A1.1.2 After fabrication, reinforcement shall not be cut, drilled, or otherwise damaged (including penetration by fasteners) unless proper mechanics-based engineering analyses are conducted to verify net section capacity, including effects of stress-concentrations and potential for accelerated degradation.

A1.2 *Bond*—The bond is to provide strain compatibility between the wood and the reinforcement through the length of the reinforcement and be effective during the design life of the structure.

TABLE A1.1 Potential Reinforcement Exposure Conditions

Condition	Static	Fatigue
Water	X	X
Hot Water	X	X
Salt water	X	X
$CaCO_3$	X	
Diesel Fuel	X	
Freeze-thaw	X	X
Heat Aging	X	
UV Cycling	X	X
Fire	X	
Wood Preservatives	X	X
Sustained Loading	X	X

A1.2.1 *Wood-to-Wood Bond*—Wood-to-wood bonds shall comply with requirements of ANSI/AITC A190.1 as well as Specification D2559.

A1.2.2 *Wood-to-Reinforcement Bond:*

A1.2.2.1 *Shear by Compression Loading*—Wood-to-reinforcement bond strength shall be evaluated for resistance to shear by compression loading as specified in Specification D2559 with the following modifications:

(1) When reinforcement sheets are too thin to allow proper application of the compression load in the Test Method D905 test apparatus, the FRP sheets shall be backed up by another wood layer (as shown in Fig. A1.1(*b*)).

(2) The bonding protocol including wood and FRP surface preparation, primers, adhesive spread rates, open and closed times, clamping pressures, and ambient conditions shall be clearly stated in the test report.

(3) The resistance to shear by compression loading shall be tested in the air dry (10 to 12 % MC) and the wet (vacuum-pressure soaked) conditions of Specification D2559. Shear block strength retention following the vacuum-pressure-soak cycle conditions shall be at least 75 %.

(4) In the case of FRP reinforcement, percent material failure includes both wood and reinforcement failure. Since material failure is predominantly in one face (the wood face), the minimum acceptable limit shall be 60 % material failure under dry conditions. In the case of steel or metallic reinforcement, material failure is restricted to one face, and the acceptable limit is reduced to 50 %.

(5) In addition, durability of wood-reinforcement bonds shall be evaluated according to: *(1)* resistance to delamination during accelerated exposure to wetting and drying; and *(2)* resistance to deformation under sustained static load as specified in the Specification D2559 with modifications to the delamination test procedures as follows:

A1.2.2.2 *Accelerated Hygrothermal Cycling:*

(1) The reinforcement shall be applied to the Specification D2559 glulam test billet in a way that best reflects the specifics of the real structural section to be qualified (either on top/bottom or on side of the billet).

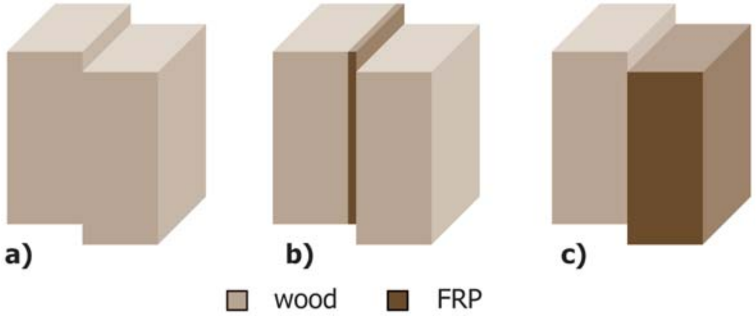

FIG. A1.1 Block Shear Specimens for Modified Specification D2559 Test
(*a*) Regular Wood-Wood Specimen; (*b*) Modified Reinforcement-Wood Specimen—for Thin Reinforcement Sheets; (*c*) Modified Reinforcement-Wood Specimen for Thick Reinforcement Sheets

(2) Specimens with maximum and minimum thickness of reinforcement manufactured for the specific application being qualified shall be used in the delamination test (see Fig. A1.2). Fig. A1.2(*a*) and (*b*) shall include multiple layers of FRP, as well as a flat-sawn bumper lams (with bark both facing and away from FRP), if this represents the intended end-use application.

(3) Since the FRP behaves more like a hardwood surface than a softwood surface, acceptable delamination limits for the wood-to-FRP bond lines are 8 % as opposed to 5 % for the softwood-softwood bond lines.

(4) If preservative-treated wood is used, the testing shall also be conducted using preservative-treated specimens, keeping the same standards for delamination as for untreated specimens. Note that the long-term adhesive/reinforcement/preservative interaction may require further study.

A1.2.2.3 *Creep*—The following modifications to Specification D2559 test procedure for resistance to deformation under sustained static load apply:

(1) The internal layer of the test billet shall be fabricated from the reinforcement material.

(2) Of the two testing conditions in the standard: elevated relative humidity at ambient temperature versus elevated temperature at ambient humidity, the second regime shall be used due to relatively low glass transition temperatures of some adhesives used for wood-reinforcement bonding.

A1.2.3 *Reinforcement-to-Reinforcement Bond*—Reinforcement-to-reinforcement mean bond strength shall equal to or exceed the mean strength of the wood-to-wood bond for the species of wood used in the beam, under both dry and wet conditions, tested using the compression shear test from Test Method D905.

A1.3 *Fatigue*:

A1.3.1 When fatigue is a design consideration, fatigue testing at the coupon level shall be conducted to insure proper performance of the FRP under fatigue loading under the specific end-use environment. Full-scale fatigue testing is required when partial-length reinforcement is used to evaluate the effectiveness of reinforcement end-confinement detail. Unconfined, partial-length reinforcement shall not be permitted in situations where fatigue loading exists.

A1.3.2 If the reinforcement increases the $MOR_{5\,\%}$ of the beam by more than 75 % relative to the strength of the unreinforced beam, full-scale reinforced beam fatigue testing shall be conducted if fatigue is a design consideration. Under these conditions flexural compression, flexural tension, and flexural shear fatigue failures in the wood laminations have been observed in reinforced glulam beams.

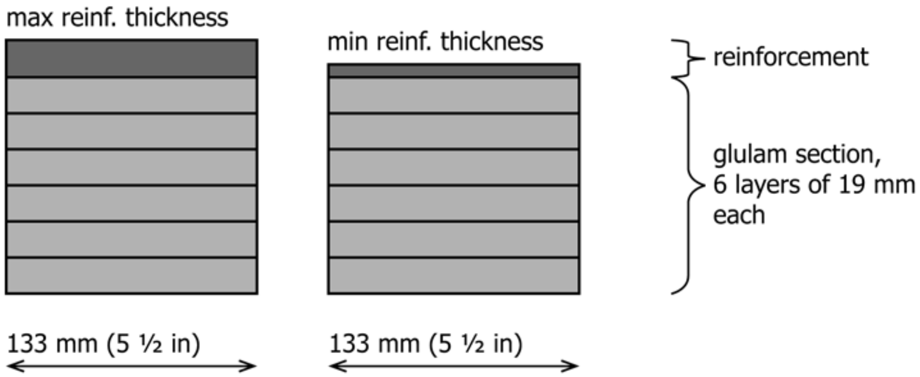

FIG. A1.2 Delamination Specimens for Modified Specification D2559 Test
(*a*) Maximum Thickness of the Reinforcement Layer(s); (*b*) Minimum Thickness of the Reinforcement Layer(s)

APPENDIX

(Nonmandatory Information)

X1. EXAMPLE OF MECHANICS-BASED FRP-GLULAM BEAM ANALYSIS THAT MEETS THE REQUIREMENTS SET FORTH IN THIS STANDARD

INTRODUCTION

For illustration purposes, this Appendix describes a mechanics-based reinforced glulam analysis that meets the requirements set forth in this standard. The methodology consists of a deterministic Moment-Curvature (M-Φ) analysis, along with Monte Carlo simulation. The Monte Carlo method is used to simulate the reinforced beam properties. The simulated beam is analyzed using M-Φ, and the process is repeated.

X1.1 *Deterministic M-Φ Analysis*:

X1.1.1 The M-Φ numerical model follows the bending behavior of a reinforced glulam from initial load to failure. Although applied in this case to the analysis of tension-reinforced glulams, the M-Φ method is general and could easily be applied to doubly reinforced and wood beams.

X1.1.2 The objective of the M-Φ analysis method is to calculate the curvature and stresses at a particular cross section subject to a bending moment. M-Φ analysis has been used for nonlinear materials such as prestressed concrete (Lin and Burns, 1981). An acceptable constitutive relationship for the in-grade lamstock is linear in tension and bilinear in compression, as defined by Bazan (1980) and Buchanan (1990) (see Fig. 1). The mechanical property parameters used are as follows:

X1.1.2.1 *E*—Long-span flatwise-bending modulus of elasticity for in-grade lamstock, used here for lamstock in both tension and compression (Test Methods D4761).

X1.1.2.2 *UTS*—Ultimate tensile stress for in-grade lamstock (Test Methods D198 and D4761).

X1.1.2.3 *UCS*—Ultimate compressive stress for in-grade lamstock (Test Methods D198 and D4761).

X1.1.2.4 *m*—Falling slope of the compression stress-strain relationship for in-grade lamstock (Buchanan, 1990) as a ratio to E (Fig. 1).

X1.1.3 Using these constitutive relationships, the M-Φ relationship for the beam cross-section from initial load to failure is calculated. Fig. 2 shows the cross section of a beam with a strain and stress distribution, with the neutral axis a distance Y below the top (compression face) of the beam. The strain distribution through the depth is given in Eq 1.

X1.1.4 Using the constitutive relationships for lamstock and FRP (see Fig. 1) the stress (σ(y)) throughout the depth of the section is calculated (see Fig. 2). A tension lamination is considered to have failed when the average stress through the thickness of the lamination, equivalent to the tensile stress at the lamination mid-height, exceeds the lamination UTS.

X1.1.5 In the compression region of the beam, the stresses are checked at the top and bottom of each lamination. If the stress within a lamination exceeds the UCS, the yield point within the lamination is identified (ε_{cy} in Fig. 2),. Equilibrium conditions are defined by Eq 2 and 3.

X1.1.6 The location of the neutral axis is found by treating the linear strain function (Eq 1) and the constitutive relationship (Fig. 1) as a system of equations, which are bound by the condition of horizontal equilibrium (Eq 2). Therefore, for a given ε_c, a depth to the neutral axis (Y) is found to satisfy the equilibrium condition:

$$f(Y) = \int \sigma(y)dA = 0 \qquad \text{(X1.1)}$$

X1.1.7 Eq X1.1 is treated as a boundary value problem, which is solved using Newton's method (Stein, 1987).

X1.1.8 Fig. X1.1 shows the elevation of a unit length of

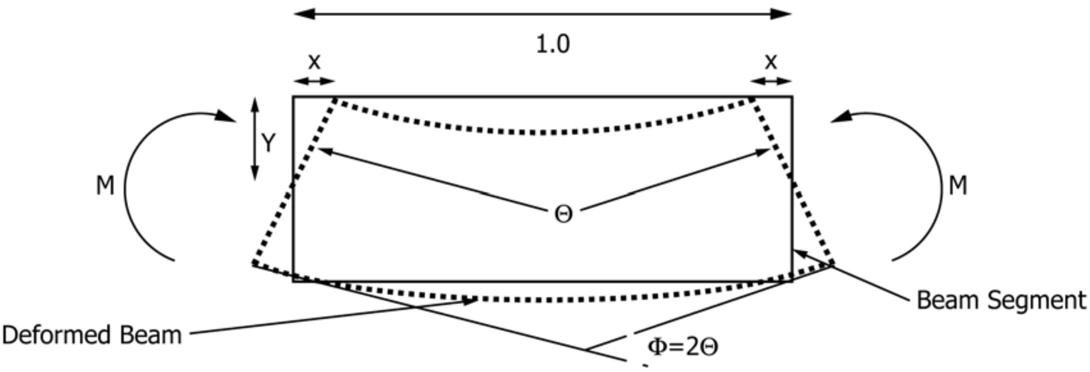

FIG. X1.1 Curvature (Φ) of a Unit Length of Beam

beam subjected to a bending moment M. Under the applied moment, the ends of the segment rotate an angle Θ, compressing the top of the beam a distance of 2x. The angle of intersection of the tangents from each side of the segment is the curvature of the segment (Φ), equal to 2Θ. The compression strain across the top of the section is 2x (undeformed length of section = 1.0). Hence, the curvature (Φ) is:

$$\Phi = 2*\Theta = \frac{2*x}{Y} = \frac{\varepsilon_c}{Y} \tag{X1.2}$$

where:

ε_c = the strain at the extreme compression fiber (see Fig. 2).

X1.1.9 Using the moment diagram and the calculated M-Φ relationship, the curvature diagram for the beam is calculated for a specific moment. Defining y as the vertical beam deflection and x as a location along the length of the beam, curvature is expressed as (West, 1989):

$$\Phi(x) = \frac{d^2y}{dx^2} \tag{X1.3}$$

X1.1.10 Deflection over the length of the beam is calculated by taking the second integration of the curvature over the span of the beam (West, 1989):

$$y(x) = \int\int_{span} \Phi(x)dx \tag{X1.4}$$

X1.1.11 Beam analysis begins by calculating the moment and associated curvature in the cross-section under unit strain of $\varepsilon_c = 0.0001$ at the extreme compression fiber. The compression strain ε_c is increased by increments of $\Delta\varepsilon_c = 0.0001$, and the M-Φ analysis is repeated for each increment. Reinforced glulam bending failure is defined when one of the following conditions is reached:

X1.1.11.1 The beam no longer carries load:

$$M = \int -y*\sigma(y)dA = 0 \quad \text{Or,}$$

X1.1.11.2 A specified limit strain (ε_{cult}; see Fig. 2) of 0.01 is reached in the extreme compression fiber of the cross section (Sliker, 1962; Krueger and Eddy, 1974; Krueger and Sandberg, 1974).

X1.1.12 A flowchart for the M-Φ analysis used this example is shown in Fig. X1.2.

X1.2 *Monte Carlo Simulation*:

X1.2.1 The model parameters E, UTS, UCS, and m are treated as random variables, and can be modeled using empirical distribution functions (Marx and Evans, 1986, 1988; Taylor

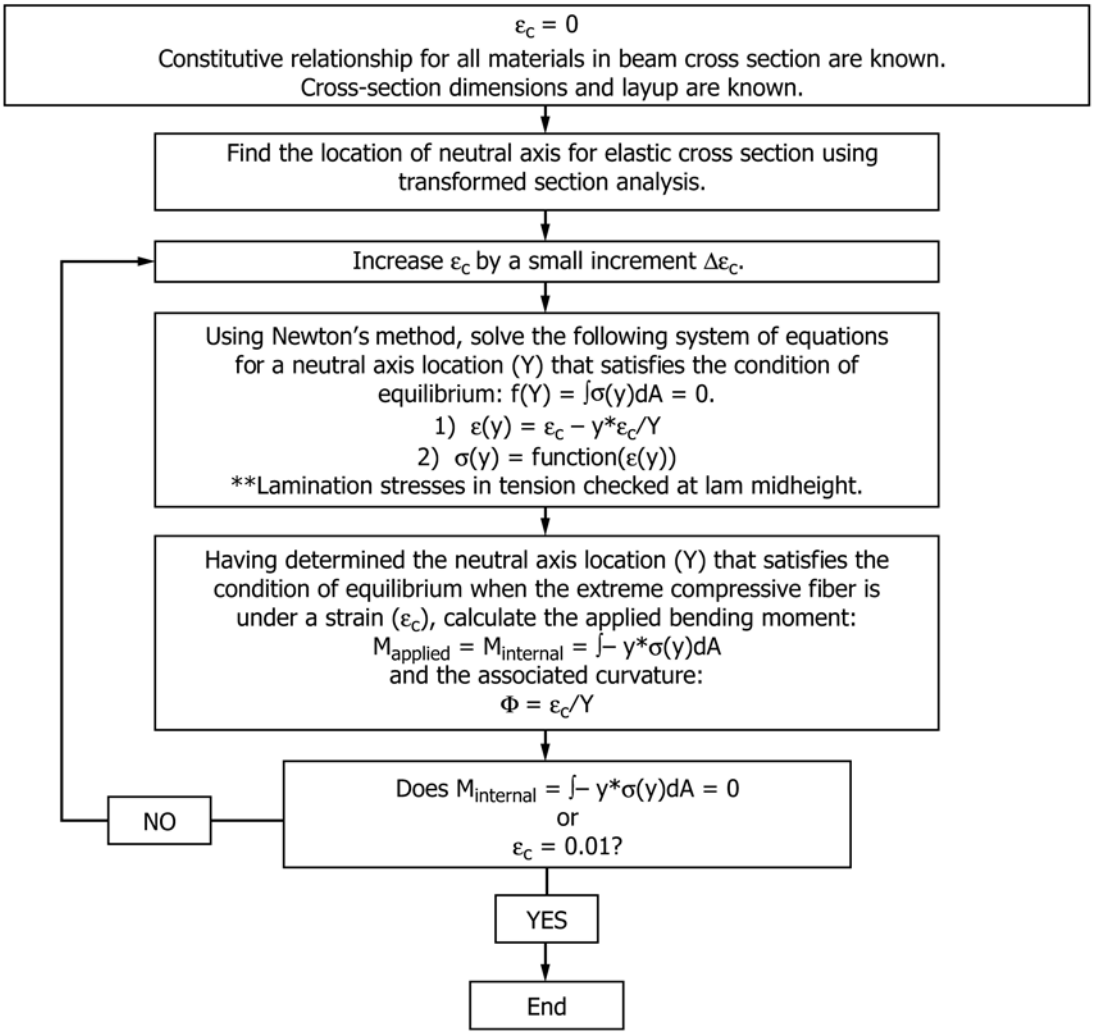

FIG. X1.2 Deterministic M-Φ Solution Methodology and Bender, 1991). Correlated observations for E, UTS, and UCS are developed using test data following the process outlined by Taylor and Bender (1988):

X1.2.1.1 Generate and shuffle an array of pseudo-random, standard uniform numbers (UNIF[0,1]).

X1.2.1.2 Using the polar method (Practice D5124), create an uncorrelated random vector ($\{z\}_{3x1}$) from the standard normal distribution (N[0,1]).

X1.2.1.3 Obtain the lower triangular matrix $[T]_{3x3}$ from the correlation matrix for E, UTS, and UCS $[C]_{3x3}$.

$$[C]_{3x3} = [T]*[T]^T \qquad (X1.5)$$

X1.2.1.4 Obtain the correlated standard normal vector $\{X\}_{3x1}$ by linearly combining the uncorrelated standard normal random vector $\{z\}_{3x1}$ with [T]:

$$\{X\}_{3x1} = [T]_{3x3}*\{z\}_{3x1} \qquad (X1.6)$$

X1.2.1.5 Transform observations from the correlated standard normal vector $\{X\}_{3x1}$ to the $N[\mu_I,\sigma_I]$ or $LN[\lambda_i,\xi_i]$ observation using methods described in Practice D5124, where μ and σ are respectively the mean and standard distribution of the normally distributed variable, and λ and ξ, are the mean and standard deviation of the logarithms of the lognormally distributed variable.

X1.2.1.6 For observations from the 3-parameter Weibull distribution, observations from $\{X\}_{3x1}$ are first transformed to correlated standard uniform variates (UNIF[0,1]) using inverse transformation (Ayyub and McCuen, 1997). From the correlated standard uniform variates, observations from the 3-parameter Weibull distribution are determined using the method described in Practice D5124.

X1.2.2 While initial lamstock testing indicated the parameter m is not correlated to E, UTS, or UCS, the model could easily be modified to generate correlated observations of m if future studies indicate the need.

X1.2.3 In addition to E, UTS, UCS, and m, this method can also treat beam width (b), depth (d), and MC as random variables.

X1.3 *The Volume Factor*:

X1.3.1 The volume factor is calculated within the model; therefore, the bending strength characteristic value $MOR_{5\%}$ output by the mechanics model is already reduced by the appropriate volume factor. For a beam subjected to four-point bending, the volume effect may be derived numerically with sufficient accuracy by considering the properties of the wood in tension between the points of load application (Lindyberg, 2000). The methodology uses the in-grade properties of the tension laminations of different widths and lengths, as well as the effects of finger joints on tensile strength. While E, UTS, and UCS all vary along the length of a piece of lamstock, only UTS has demonstrated a discernible length effect where strength decreases with increasing length (Showalter et al., 1987; Taylor and Bender, 1991). The UTS used for the wood laminations is entered at a 2 ft. length, adjusted from the Methods D198 recommended test length (8 ft. clear distance between the grips for nominal 2x6 lamstock) using the length adjustment formula from Practice D1990:

$$UTS(2) = UTS(1)*\left[\frac{L(1)}{L(2)}\right]^{0.14} \qquad (X1.7)$$

X1.3.2 This model analyzes beams in four-point bending. To account for the length effect, lamstock UTS is adjusted from 2 ft. to the length of the load span using Eq X1.7. For example, if the load span being modeled is 6 ft., the lamstock UTS is reduced from the original 2 ft. length to that for a 6 ft. length. This accounts for the random distribution of strength-reducing defects (on the tension side of the beam) over the length of beam under the maximum moment. To account for width effects, the UTS probability distribution function (PDF) used represents in-grade test data for the width of the beam being studied. The UTS is further adjusted to account for finger joints as shown in the following section.

X1.3.3 After failure of the first wood lamination in tension above the FRP reinforcement, the UTS of the remaining laminations are adjusted a 2 ft. length. This assumes that the first tensile failure of a wood lamination occurs in the area of maximum moment, and that subsequent tensile failures of the remaining wood laminations occur in the immediate vicinity of the first lamination failure in tension above the FRP. Therefore,

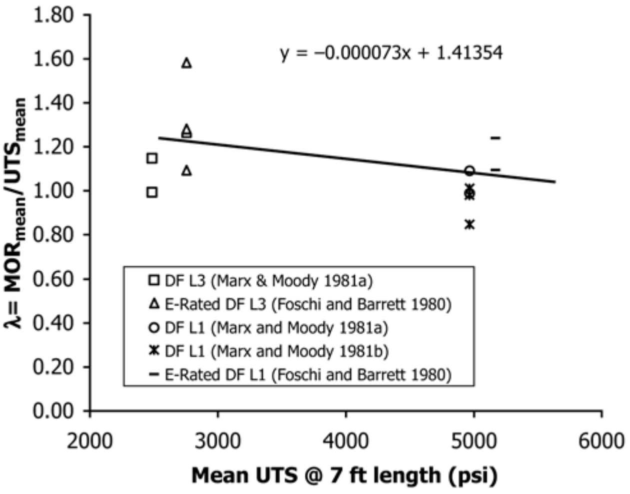

FIG. X1.3 λ as a Function of Mean UTS (8 ft. length) while this analysis is performed at a single cross-section, it also accounts for the lengthwise variability, and thus the length effect, in lamstock UTS. No length adjustment is used for lamstock UCS, following the recommendation by Practice D1990.

X1.4 *Finger Joints*:

X1.4.1 In this example, finger-joint location in the tension region of the cross-section is determined by generating random lengths of lumber, and assembling the simulated beam while noting the locations of the end joints. When end joints in the simulated beam occur in the region of maximum moment (between the load-heads in four-point bending), finger joint UTS (UTS(FJ)) is generated based on finger-joint test data provided by the laminator. This is the same general procedure used by Govindarajoo (1989) and Hernandez *et al.* (1992). UTS(FJ) is treated as an independent random variable with a normal distribution.

X1.5 *The Laminating Effect*:

X1.5.1 The laminating effect may be developed using finite element modeling, by stochastically generating defects that correspond to those present in various laminating grades (Serrano, 2001). This approach is numerically very intensive and not practical for the kinds of models envisioned to be developed under this standard. Another approach is to develop an empirical laminating effect using laboratory test data, then to use the factor in the mechanics model. This is the approach employed in the following example.

X1.5.2 One definition of the laminating effect (λ) is "...a strength increase of lamination lumber as a result of being bonded into a glulam beam." (Falk and Colling, 1995, p. 1857). Falk and Colling (1995) use the following general equation to describe λ in unreinforced beams:

$$\lambda_k = \frac{MOR_k}{UTS_k} \qquad (X1.8)$$

X1.5.3 Where MOR_k and UTS_k are, respectively, characteristic values of beam MOR and lamstock UTS. Falk and Colling (1995) demonstrated that when evaluated at the mean, λ_k increases with decreasing lamstock UTS. Therefore, the laminating effect is estimated by multiplying the distribution of lumber UTS by the factor λ, which is a function of the mean UTS at standard length (7 ft.). The function λ was developed using beam and lamstock test data from Foschi and Barrett (1980), and Marx and Moody (1981a and 1981b). Only beams consisting of L1 and L3 grade laminations were considered, as higher grades of lamstock did not exhibit a laminating effect (Falk and Colling, 1995). All tested beam MORs were adjusted to standard size (5⅛ in. by 12 in. by 21 ft.) using the NDS volume adjustment factor. Two sets of beams from the Marx and Moody study (1981a) were eliminated from the data set because they consisted of only two laminations, and were likely not subject to the full laminating effect. The function λ is (see Fig. X1.3):

$$\lambda = -0.000073 * UTS_{mean} + 1.41 \geq 1.0 \qquad (X1.9)$$

Where UTS_{mean} is the mean UTS at 8 ft. length for the particular species and grade in lb/in.^{2}.

X1.5.4 In this example, pseudo-random UTS observations are generated for each lamination, and then multiplied by λ. It is important to note that the data set shown in Fig. X1.3 could be expanded to improve on the prediction of λ. The objective here is to illustrate one possible methodology to obtain and use the laminating factor λ, rather than to recommend particular values for λ.