Designation: D7199 – 20

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 describes procedures for establishing the characteristic values for reinforced structural glued-laminated timber (glulam) beams using mechanics-based models and validated by full-scale beam tests. Glulam beams shall be manufactured in accordance with applicable provisions of ANSI A190.1.

1.2 This practice also describes a minimum set of performance-based durability test requirements for reinforced glulam beams, 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 practice.

1.3 This practice is limited to procedures for establishing flexural properties (modulus of rupture, MOR, and modulus of elasticity, MOE) about the x-x axis of horizontally-laminated reinforced glulam beams.

1.4 The establishment of secondary properties, such as bending about the y-y axis, shear parallel to grain, tension parallel to grain, compression parallel to grain, and compression perpendicular to grain, for the reinforced glulam beams are beyond the scope of this practice.

NOTE 1—When the establishment of secondary properties is deemed necessary, testing according to other applicable methods, such as Test Methods D143 and D198 or analysis in accordance with Practice D3737, may be considered.

1.5 Reinforced glulam beams subjected to axial loads are outside the scope of this practice.

1.6 Proper safety, serviceability, and adjustment factors including duration of load, to be used in design are outside the scope of this practice.

1.7 Evaluation of unbonded, prestressed, and shear reinforcement is outside the scope of this practice.

1.8 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. The mechanics-based model shall be permitted to be developed using SI or inch-pound units.

1.9 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.10 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

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

[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.

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-Based Structural Materials
D5124 Practice for Testing and Use of a Random Number Generator in Lumber and Wood Products Simulation

2.2 *Other Standard:*
ANSI 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*—reinforcing material that is continuously attached to a glulam beam through adhesive bonding.

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

3.2.3 *compressive 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*—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)*—composite material consisting of at least two distinct components: reinforcing fibers and a binder matrix (a polymer).

3.2.6.1 *Discussion*—The reinforcing fibers may be either synthetic (for example, glass), metallic, or natural (for example, wood), and may be long and continuously-oriented, or short and randomly oriented. The binder matrix may be either thermoplastic (for example, polypropylene or nylon) or thermosetting (for example, epoxy or vinyl-ester).

3.2.7 *laminating effect*—apparent increase of lumber lamination tensile strength because it is bonded to adjacent laminations within a glulam beam.

3.2.7.1 *Discussion*—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 glulam.

3.2.9 *reinforcement*—lamination or material that is not a conventional wood lamstock and having a mean longitudinal ultimate tensile and compressive strength greater than 20 ksi (138 MPa) and a mean tension and compression MOE greater than 3000 ksi (20.7 GPa).

3.2.9.1 *Discussion*—Examples of acceptable reinforcing materials include fiber-reinforced polymer (FRP) plates and bars, metallic plates and bars, FRP-reinforced laminated veneer lumber (LVL), and FRP-reinforced parallel strand lumber (PSL).

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

3.3 *Symbols:*

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

b = beam width

C = total internal compressive force within the beam cross-section (see Fig. A2.2)

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. A2.1)

F_b = allowable bending stress parallel to grain

F_x = internal horizontal force on the beam cross-section (see Eq A2.2)

GFRP = Glass fiber-reinforced polymer

LTL = lower tolerance limit 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. A2.1)

N.A. = neutral axis

T = total internal tensile force within the beam cross-section (see Fig. A2.2)

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. A2.2)

y = distance from extreme compression fiber to point of interest on beam cross-section (see Fig. A2.2)

ε_c = strain at extreme compression fiber of beam cross-section (see Fig. A2.2)

ε_{cult} = compressive strain at lamstock failure (see Fig. A2.1)

ε_{cy} = compressive yield strain at lamstock UCS (see Fig. A2.1)

ε_{tult} = tensile strain at lamstock failure (see Fig. A2.1)

$\varepsilon(y)$ = strain distribution through beam depth (see Fig. A2.2)

[3] Available from APA – The Engineered Wood Association, 7011 South 19th Street, Tacoma, WA 98466, http://www.apswood.org.

ρ = tensile reinforcement ratio (%); cross-sectional area of tensile reinforcement divided by cross-sectional area of beam between the center of gravity of tensile reinforcement and the extreme compression fiber

ρ' = compressive reinforcement ratio (%); cross-sectional area of compressive reinforcement divided by cross-sectional area of beam between the center of gravity of compressive reinforcement and the extreme tension fiber

σ(*y*) = stress distribution through beam depth (see Fig. A2.2)

4. Modeling Requirements

4.1 *General:*

4.1.1 *Purpose for Modeling*—Characteristic values for the flexural properties about the x-x axis of horizontally-laminated reinforced glulam beams shall be established through the use of an analytical model. The establishment of flexural properties using full-scale beam tests is outside the scope of this practice.

4.1.2 *Mechanics-Based Models*—Models used to develop new combinations and predict characteristic values shall be able to predict accurately these values for a broad range of combinations and validated by full-scale tests according to Section 5.

4.2 *Minimum Model Inputs*—Any numerical solution methodology shall be permitted for use, so long as it incorporates the nonlinearities in mechanical properties for wood and reinforcement as specified in A2.1 and satisfies the conditions of strain compatibility (A2.2), and equilibrium (A2.3). In addition, the mechanics-based analysis shall account for variability of mechanical properties, volume effects, finger-joint effects, laminating effects, and stress concentrations at termination of reinforcement in beams with partial length reinforcement.

NOTE 2—These analysis input requirements are described in detail in Annex A2.

4.3 *Minimum Model Analyses:*

4.3.1 *Bending Strength*—The model shall predict the lower 5 % tolerance limit (LTL) for modulus of rupture ($MOR_{5\ \%}$) for the reinforced layup being analyzed. The model-predicted bending strength characteristic values $MOR_{5\ \%}$ shall include the volume effect. Beam MOR shall be based on gross (full width and depth) cross-sectional properties.

4.3.2 *Bending Stiffness*—The model shall predict the mean modulus of elasticity (MOE) for the reinforced layup being analyzed. Beam MOE shall be based on gross (full width and depth) cross-sectional properties.

4.3.3 *Bumper Lamination*—If a bumper lamination is to be used, the characteristic bending strength value $MOR_{BL5\ \%}$ corresponding to bumper lamination failure shall also be calculated and reported. In addition, the beam stiffness properties before and after failure of the bumper lamination shall be calculated and reported.

NOTE 3—See Appendix X1 for example calculations.

NOTE 4—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.

4.4 *Secondary Properties:*

4.4.1 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 permitted to be determined following methods described in Practice D3737.

NOTE 5—Analysis has shown that with the level of FRP extreme fiber tensile 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.

5. Model Validation Testing Requirements

5.1 *Test Method*—Tests for flexural strength and modulus of elasticity shall be conducted in accordance with Test Methods D198 or D4761. If Test Methods D4761 is used, the load rate shall be modified to be in accordance with Test Methods D198. Specimens shall be tested under dry-service conditions where the moisture content of the wood, excluding non-wood reinforcement, is 12 ± 3 %. The temperature of the test specimens shall not be less than 50°F (10°C) nor more than 90°F (32°C) at the time of the tests.

5.2 *Sampling Requirements*—Mechanics-based models which satisfy the requirements set forth in this standard shall be validated through physical testing as shown in Tables 1 and 2. The sample size shall be large enough to provide the standard error of the sample less than 10 % of the 5 % LTL of MOR, but not less than 10 beams for each size/reinforcement ratio. Six sample sets shall be tested using a primary wood species (Table 1) equating to a minimum of 60 beams, and two sample sets shall be tested for each additional wood species (Table 2) equating to a minimum of 20 beams.

6. Analysis and Applicability of Test Results

6.1 *Failure Modes*—Each failed specimen shall be inspected to determine the failure mode(s). The location and type (end joint, lumber, shear, tension, compression, etc.) of observed failures shall be documented and compared to the model. Lamination characteristics influencing failure shall be noted.

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

Beam Size	Number of Beam Tests		
	Min[C]	Typical[C]	Max[C]
5⅛ in. by 12 in. by 21 ft (130 mm by 305 mm by 6.40 m)	10	10	10
6¾ in. by 24 in. by 42 ft (171 mm by 610 mm by 12.8 m)	10	10	10

[A] All beams shall use the same layup, species, reinforcement type, and wood lam thickness.

[B] A larger set shall be required if the Standard Error is greater than 0.1 × 5 % LTL. See Practice D2915 for determining the minimum sample size.

[C] See Table 3. The model shall 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	Number of Beam Tests		
	Min[C]	Typical[C]	Max[C]
5⅛ in. by 18 in. by 32 ft (130 mm by 457 mm by 9.75 m)	10	—	10

[A] All beams shall use the same layup, species, reinforcement type, and wood lam thickness.
[B] A larger set shall be required if the Standard Error is greater than 0.1 × 5 % LTL. See Practice D2915 for determining a minimum sample size.
[C] See Table 3. The model shall 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 (GPa)	6 000 (41)	10 000 (69)	20 000 (138)	30 000 (207)
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 shall use any minimum, maximum, or typical value considered appropriate, although the model shall only be valid within the range tested.
[B] Tensile reinforcement ratio (%); cross-sectional area of tensile reinforcement divided by cross-sectional area of beam above center of gravity of tensile reinforcement.

6.2 *Mechanical Properties:*

6.2.1 *Modulus of Rupture*—The predicted 5 % LTL using the mechanics-based model (5 % LTL_{model}) shall be compared with the 5 % LTL calculated from the test results (5 % LTL_{test}) for each of the eight cells in Tables 1 and 2. Conditions of model acceptance are as follows:

$$|(5\,\%\,LTL_{model} - 5\,\%\,LTL_{test})|\,/\,5\,\%LTL_{model} < 0.10$$

for each of the 8 cells in Tables 1 and 2

$$1/8\,\Sigma[(5\,\%\,LTL_{model} - 5\,\%\,LTL_{test})\,/\,5\,\%\,LTL_{model}] < 0.06$$

for all 8 cells in Tables 1 and 2

6.2.2 *Modulus of Elasticity*—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

$$1/8\Sigma[(\text{mean } MOE_{model} - \text{mean } MOE_{test})\,/\,\text{mean } MOE_{model}] < 0.06$$

for all 8 cells in Tables 1 and 2

7. Periodic Evaluation

7.1 *Lumber Properties*—The lumber characteristics used as a basis for establishing grades and as inputs to predictive models shall be maintained through continuous process control. Strength and stiffness properties for each grade shall be evaluated periodically or maintained through continuous process control to ensure that they are maintained over time.

7.2 *Reinforcement Properties*—The reinforcement characteristics used as inputs to predictive models shall be evaluated periodically or maintained through continuous process control to ensure that they are maintained over time.

7.3 *End Joint Strength*—Lamination end joint strengths shall be subject to ongoing process control to maintain the required strengths.

7.4 *Beam Tests*—Full-scale beam tests shall be conducted to verify the continued applicability of the model used for assigning characteristic values when the trend of the lumber properties, reinforcement properties or end joint strengths, evaluated in 7.1 through 7.3, warrants such an evaluation.

8. Report

8.1 The report shall include the following:

8.1.1 Description of the sample(s), including species, lamination properties, layup(s), size(s), conditioning, location of end joints, matched end joint strength, quality control requirements, etc.

8.1.2 Description of the test machine and setup, including method and location of load application, test span or gauge length, etc.

8.1.3 Description of measurement methods for dimensions, load, deflections, moisture content, etc.

8.1.4 Rate of testing and the method of controlling the rate of load application.

8.1.5 Equation(s) used to determine stresses and elastic moduli.

8.1.6 Data for specimens, including: dimensions; maximum load or stress, or both; moisture content; time to failure; description and location of failure; load versus deformation curves, etc.

8.1.7 Description of statistical analyses used to determine characteristic value(s).

8.1.8 Identification and description of any model(s) used or evaluated.

8.1.9 Details of any deviations from the recommended procedures.

9. Keywords

9.1 bending; characteristic value; composites; flexural; flexure; FRP; full-scale; glulam; laminated; layup; modulus; reinforcement; timber

ANNEXES

(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 reinforced beam strength and stiffness retentions can be achieved.

NOTE A1.1—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 shall 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.

A1.2.1 *Wood-to-Wood Bond*—Wood-to-wood bonds shall comply with requirements of ANSI 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 reflect the key characteristics of the manufacturing equipment used in the facility to be qualified and 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 lamination (the wood lamina), 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 %.

A1.2.2.2 *Resistance to Delamination During Accelerated Exposure*—Durability of wood-reinforcement bonds shall be evaluated according to: (*a*) resistance to delamination during accelerated exposure to wetting and drying; and (*b*) resistance to deformation under sustained static load as specified in the Specification D2559 with modifications to the delamination test procedures as follows:

(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).

(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) Acceptable delamination for the wood-to-FRP bond lines shall be 8 % maximum when measured in accordance with the procedures described in Specification D2559.

(4) If preservative-treated wood is to be qualified, the delamination testing shall also be conducted using preservative-treated specimens. The long-term adhesive/reinforcement/preservative interaction is outside the scope of this practice.

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.

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

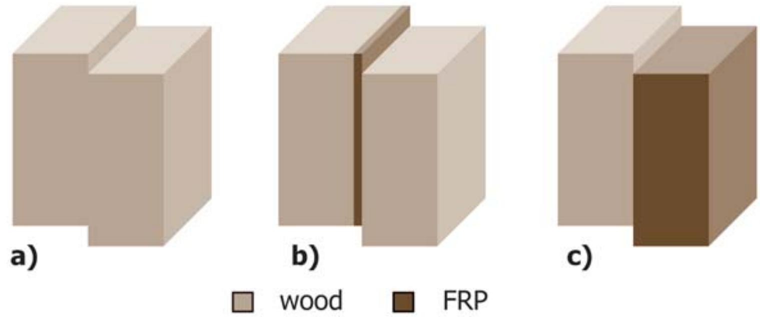

FIG. A1.1 Block Shear Specimens for Modified Specification D2559 Test
(*a*) Regular Wood-Wood Specimen; (*b*) Modified Reinforcement-Wood Specimen—for Thin Reinforcement Sheets; (*c*) Modified Reinforcement-Wood Specimen for Thick Reinforcement Sheets

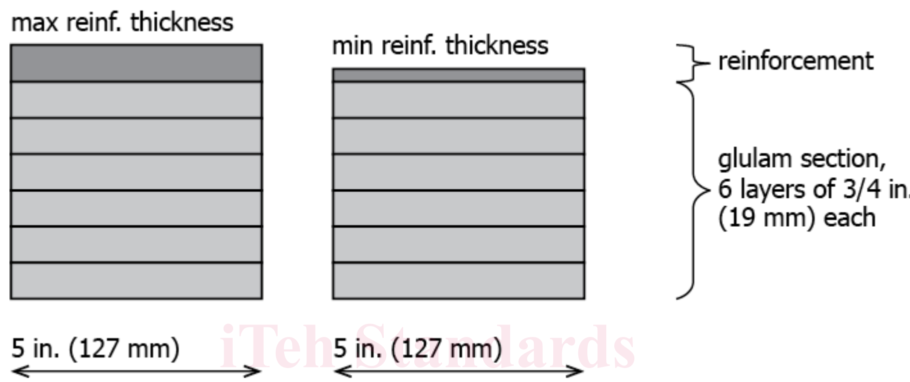

FIG. A1.2 Delamination Specimens for Modified Specification D2559 Test
(*a*) Maximum Thickness of the Reinforcement Layer(s); (*b*) Minimum Thickness of the Reinforcement Layer(s)

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 ensure 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.

NOTE A1.2—Under these conditions, flexural compression, flexural tension, and flexural shear fatigue failures in the wood laminations have been observed in reinforced glulam beams.

A2. REQUIREMENTS FOR MECHANICS-BASED ANALYSIS METHODOLOGY

A2.1 *Stress-Strain Relationships*:

A2.1.1 *Conventional Wood Lamstock:*

A2.1.1.1 The stress-strain relationship shall be established through testing following Test Methods D198, or other established relationships as long as the resulting model meets the criteria established in Section 4. Test lamstock shall be sampled in sufficient quantity, from enough sources to ensure 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.

NOTE A2.1—See Practice D2915 for guidelines on sampling procedures for the investigation of specified populations of wood and wood-based structural products.

A2.1.1.2 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 shall be used throughout this practice (see Fig. A2.1). In the bilinear model both tensile and compressive MOE shall be permitted to be approximated by using the long-span flatwise-bending MOE obtained using Test Methods D4761.

NOTE A2.2—In Fig. A2.1, m*E is the downward slope of the compressive stress-strain curve, defined as the best-fit downward line through the point (UCS, ε_{cy}) on the compressive stress-strain curve. The downward best-fit line may be terminated at the point where the ultimate compressive strain ε_{cult} is approximately 1 %.

A2.1.2 *Reinforcement:*

A2.1.2.1 The stress-strain relationship shall be established through material-level testing in accordance with Test Methods D3039/D3039M and D3410/D3410M.

A2.1.2.2 Nonlinearities in the stress-strain relationship shall be included in the analysis, if present.

NOTE A2.3—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.

A2.2 *Strain Compatibility*—Fig. A2.2 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:

$$\varepsilon(y) = \varepsilon_c - \varepsilon_c * (y/Y) \quad \text{(A2.1)}$$

A2.3 *Equilibrium*:

A2.3.1 In order to maintain equilibrium, the cross-section shall satisfy the conditions of horizontal equilibrium (Eq A2.2), and the internal moment ($M_{internal}$) shall equal the external moment applied to that cross section ($M_{applied}$) (Eq A2.3). See Fig. A2.2 as an example of strain compatibility and equilibrium:

$$\sum F_x = 0 \Rightarrow \int_{depth} \sigma(y)\, dA = 0 \quad \text{(A2.2)}$$

$$M_{applied} = M_{internal} = C(\text{or } T) * Arm = \int_{depth} - y * \sigma(y) * dA \quad \text{(A2.3)}$$

A2.4 *Variability of Mechanical Properties*:

A2.4.1 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*). An example is provided in Appendix X1.

A2.5 *Volume Effects*—The model shall properly account for changes in beam strength properties as affected by beam size.

NOTE A2.4—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 should properly account for this phenomenon. One possible approach to address the volume effect is described in Appendix X1.

A2.6 *Finger-Joint Effects*—The model shall account for the finger joint effects on both the mean and variability of the beam mechanical properties.

NOTE A2.5—One example of how this may be achieved is provided in Appendix X1.

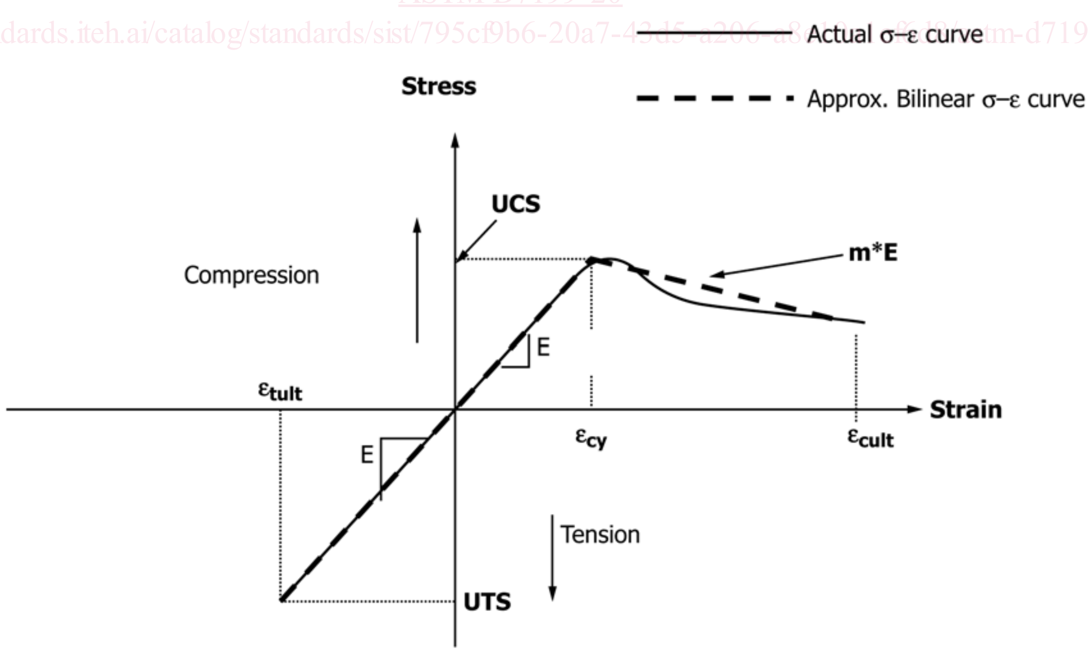

FIG. A2.1 Typical Stress-Strain Relationship for Wood Lamstock, with Bilinear Approximation