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LAMINATING LUMBER AND END JOINT PROPERTIES FOR FRP-REINFORCED GLULAM BEAMS

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Abstract

Glulam beams reinforced with fibre-reinforced-polymer (FRP) are typically manufactured using graded laminating lumber with FRP reinforcement in the tension zone and have been used in numerous construction projects worldwide. Unfortunately, the layup combinations currently used for manufacturing FRP-reinforced glulam are all proprietary even though an FRP glulam standard, ASTM D 7199, *Standard Practice for Establishing Characteristic Values for Reinforced Glued Laminated Timber (Glulam) Beams Using Mechanics-Based Models*, was published in 2007. This standard resulted from years of joint effort by APA – The Engineered Wood Association and the Advanced Engineered Wood Composites Center (AEWC) of the University of Maine.

A mechanics-based computer model, called ReLam, has been developed by the AEWC for predicting the performance of FRP-reinforced glulam beams in accordance with ASTM D 7199. This model can be used to develop a range of layup combinations for FRP-reinforced glulam beams. As the first step toward the development of these glulam layup combinations, mechanical properties of laminating lumber, including the tensile and compressive strength and moduli, and the end joint tensile strength must be obtained. While the lumber properties for these lumber grades have been published in glulam industry standards, such as AITC 407, *Standard for Alternate Lumber Grades for Use in Structural Glued Laminated Timber*, the basis of those data is more than 20 years old and was in need for an update and reaffirmation. While there are end joint tension data generated daily from the quality control records of each glulam plant, those data are considered proprietary and typically unavailable for general use. In addition, the compressive strength and moduli data are not readily available. As a result, APA initiated a comprehensive study to evaluate four Douglas-fir (DF) laminating lumber grades; 302-24 tension lam, L1, L2, and L3, and two grades of end joints, 302-24 tension lam and L1, from a range of glulam plants in 2008 using current production resources in the U.S.

These laminating lumber properties, including end joint data, not only confirm the historical data for these dominant DF lumber grades and end joints used in today's glulam production in the U.S., but also provide the required data for the development of layup combinations using ReLam. This paper presents the laminating lumber and end joint properties. In addition, the likely FRP-reinforced glulam beam layup combinations at characteristic bending strength and modulus of elasticity values of 43.4 N/mm^2 (6,300 psi) and 13800 N/mm^2 (2.0 x 10^6 psi), and 49.2 N/mm^2 (7,140 psi) and 15200 N/mm^2 (2.2 x 10^6 psi), respectively, are also provided. These FRP-reinforced glulam beams are expected to be highly competitive with steel in non-residential construction markets in the U.S.

1. Introduction

Reinforcing structural glued laminated timbers (glulams) with synthetic fibres for enhanced structural performance is not a new concept and there have been a wide range of applications around the world using fibre-reinforced-polymer (FRP) reinforced glulam. Unfortunately, the design methodology for FRP-reinforced glulam has been kept as proprietary information and is not readily available to general design engineers. Moreover, the development of FRP-reinforced glulam layup combinations for commercial production has not been widely understood. These factors have prohibited a wider application of this technology in the otherwise highly competitive commercial construction market with steel and concrete. In the last decade, staff members of APA – The Engineered Wood Association have been working with at least 3 private consortiums in promoting and advancing this FRP-reinforced glulam technology with limited success.

The main-stream FRP-reinforced glulam methodology in North America is based on the development work championed by the Advanced Engineered Wood Composites Center (AEWC, http://www.aewc.umaine.edu/) of the University of Maine. Working with the AEWC and the ASTM D07 Committee on Wood, APA has been able to standardize the fundamental FRP-reinforced glulam design and manufacturing methodologies in ASTM D 7199 [1], *Standard Practice for Establishing Characteristic Values for Reinforced Glued Laminated Timber (Glulam) Beams Using Mechanics-Based Models*, which was published in 2007. This standard resulted from years of joint effort by the APA and AEWC, but has not been put into practical use except for limited research projects.

A mechanics-based computer model, called ReLam, has been developed by the AEWC for predicting the performance of FRP-reinforced glulam beams [2]. This model can be used to develop a range of layup combinations for FRP-reinforced glulam beams. As the first step toward the development of these glulam layup combinations, mechanical properties of laminating lumber, including the tensile and compressive strength and moduli, and the end joint tensile strength must be obtained. While the lumber properties for these lumber grades have been published in glulam industry standards, such as AITC 407 [3], *Standard for Alternate Lumber Grades for Use in Structural Glued Laminated Timber*, the basis of those data is more than 20 years old and was in need of an update and reaffirmation. While there are end joint tension data generated daily from the quality control records of each glulam plant, those data are considered proprietary and typically unavailable for general use. In addition, the compressive strength and moduli are not readily available. As a result, APA initiated a comprehensive study to evaluate four Douglas-fir (DF) laminating lumber grades; 302-24 tension lam, L1, L2, and L3, and two grades of end joints, 302-24 tension lam and L1, from a range of glulam plants in 2008 using current production resources in the U.S.

The main objective of this study was to develop a database on the characteristic tensile and compressive stresses parallel to grain, and long-span E of major grades of DF laminating lumber for use in the modelling of FRP-reinforced glulam in accordance with ASTM D 7199 and the ReLam model. Characteristic finger joint tensile strengths for the highest 2 grades of laminating lumber were also developed.

2. Materials and Test Methods

2.1 Material Description

Thirty pieces of 4267-mm (14-foot) long 2x6 (38 mm x 140 mm or 1-1/2 inches x 5-1/2 inches net dimension) Douglas-fir sawn lumber specimens for each of 4 Douglas-fir laminating lumber grades; 302-24 tension lam, L1, L2, and L3, were sampled by APA quality services division auditors from 3 major glulam plants; Calvert Company Inc., Washougal, Washington, Cascade Structural Laminators, Chehalis, Washington, and

Rosboro, Springfield, Oregon in April 2008. These specimens were shipped to the APA Research Center in Tacoma, Washington where these lumber specimens were regraded and reclassified as on-grade materials meeting the grade requirements specified in the *Grading Handbook for Laminating Lumber* [4]. A non-destructive long-span E test was conducted on each specimen, followed by destructive tension tests in May 2008.

Thirty pieces of 2438-mm (8-foot) long 2x6 Douglas-fir laminations with a finger joint near the center of the specimen for each of the 2 highest laminating lumber grades, 302-24 tension lam and L1, were sampled by APA auditors from regular production runs at the same glulam plants mentioned above in April 2008. The adhesives used in manufacturing the finger joints were previously qualified by the manufacturers in accordance with the *American National Standard for Structural Glued Laminated Timber*, ANSI/AITC A190.1 [5], using melamine-urea formaldehyde from one plant, and phenol-resorcinol-formaldehyde from the other 2 plants. These specimens were also shipped to the APA Research Center for destructive tension tests in May 2008.

From each of the 4267-m (14-foot) long 2x6 lumber specimens designated for the long-span E and tension tests, 2 specimens of 305-mm (12 inches) in length were cut prior to tension tests. These specimens were regraded for excessive knots and slope of grain, and then square-cut to 191-mm (7-1/2 inches) in length for destructive compression test with a slenderness ratio (length to least radius of gyration) of 17.3 in accordance with ASTM D 198 [6], *Standard Methods of Static Tests of Timbers in Structural Sizes*.

2.2 Test Methods

Tension parallel to the grain tests were conducted in accordance with Sections 24 – 29 of ASTM D 4761 [7], *Standard Test Methods for Mechanical Properties of Lumber and Wood-Base Structural Materials*, using an 2438-mm (8-foot) gauge length for laminating lumbers. A 610-mm (2-foot) gauge length was used for finger-jointed tests. For the long-span E tests, a flatwise center-point bending method with an on-center span of 3810-mm (150 inches) (i.e., the span-to-depth ratio = 100:1) was followed in accordance with AITC Test T116 [8], *Modulus of Elasticity of E-Rated Lumber by Static Loading*. All specimens were tested at as-received conditions (the average moisture content of the specimens from each manufacturer was in the range of 10 to 13%). The moisture content and specific gravity of selected specimens were determined using the oven-drying method specified in ASTM D 4442 [9], *Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials*, and D 2395 [10], *Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials*, after the mechanical testing.

Compression tests were conducted following Sections 12 -19 of ASTM D 198 using a gauge length of 130 mm (5-1/8 inches) with a constant loading rate of 0.38 mm (0.015 in.) per minute. Special attention was made to ensure the contact surfaces were plane and parallel to each other and normal to the long axis of the specimen. To accomplish this, the specimen was square-cut at each end. After trimming the ends, but prior to the mechanical testing, the actual cross-sectional dimension of each specimen was measured at the mid-length to the nearest 0.025 mm (0.001 inch). For the measurement of compressive deformation, two LVDTs were attached to the opposite faces of the specimen at a gauge length of 130 mm (5-1/8 inches). No lateral supports were provided during testing. All specimens were tested at as-received conditions (the average moisture content of the specimens from each manufacturer was in the range of 10 to 13%).

The downward slope (m) of the compressive load and deformation curve, which is required by the ReLam model due to the fact that the compression failure is the predominant failure mode for FRP-reinforced glulam at a high percentage of fibre reinforcement ratio, was determined based on Figure 1 using the relationship between two slopes obtained before and after the ultimate failure load, as shown in Section 3 of ASTM D 7199. The slope before failure was determined in the proportional range of load and deformation curve.

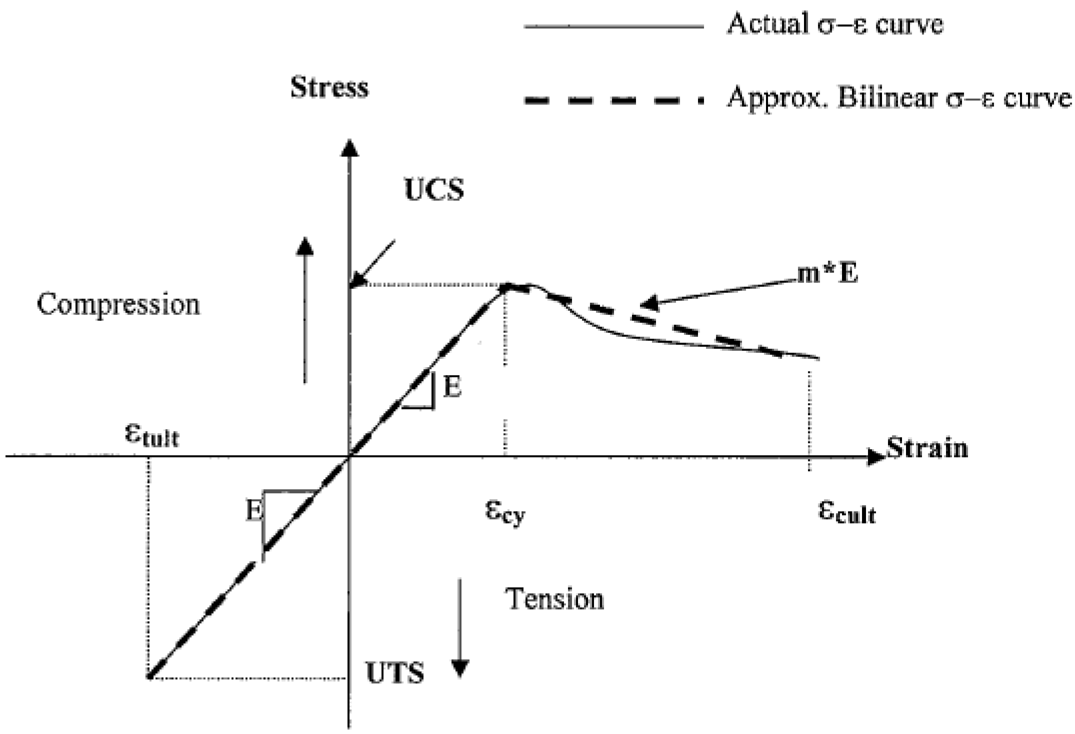

Figure 1. Schematic compressive stress-strain curve (excerpt from ASTM D 7199)

3. Results and Discussions

3.1 Lumber Tension

Test results for lumber tension (2438-mm or 8-foot gauge length) are shown in Table 1. The characteristic tensile strength (5th percentile with 75% confidence) of the lumber, $f_{t,0,l,05}$, of each lumber grade from the combination of 3 glulam plants were determined based on ASTM D 2915 [11], *Standard Practice for Evaluating Allowable Properties for Grades of Structural Lumber*. Figure 2 shows the data distribution of each lumber grade.

Table 1. Summary statistics of lumber tensile strength

Properties	Lumber Tensile Strength			
	302-24	L1	L2	L3
No. of observations	86	90	87	93
$f_{t,0,l,mean}$, N/mm^2 (psi)	48.9 (7093)	30.0 (4354)	20.9 (3026)	14.3 (2073)
Coefficient of variation	0.271	0.293	0.286	0.325
$f_{t,0,l,05}$, N/mm^2 (psi) [(a)]	29.0 (4212)	17.5 (2537)	12.3 (1777)	7.8 (1137)
Published $f_{t,0,l,05}$, N/mm^2 (psi) [(b)]	27.6 (4008)	16.7 (2420)	11.6 (1680)	7.0 (1010)

[(a)] Parametric 5th percentile with 75 percent confidence of laminating lumber (lognormal distribution).
[(b)] Characteristic value of laminating lumber published in AITC 407.

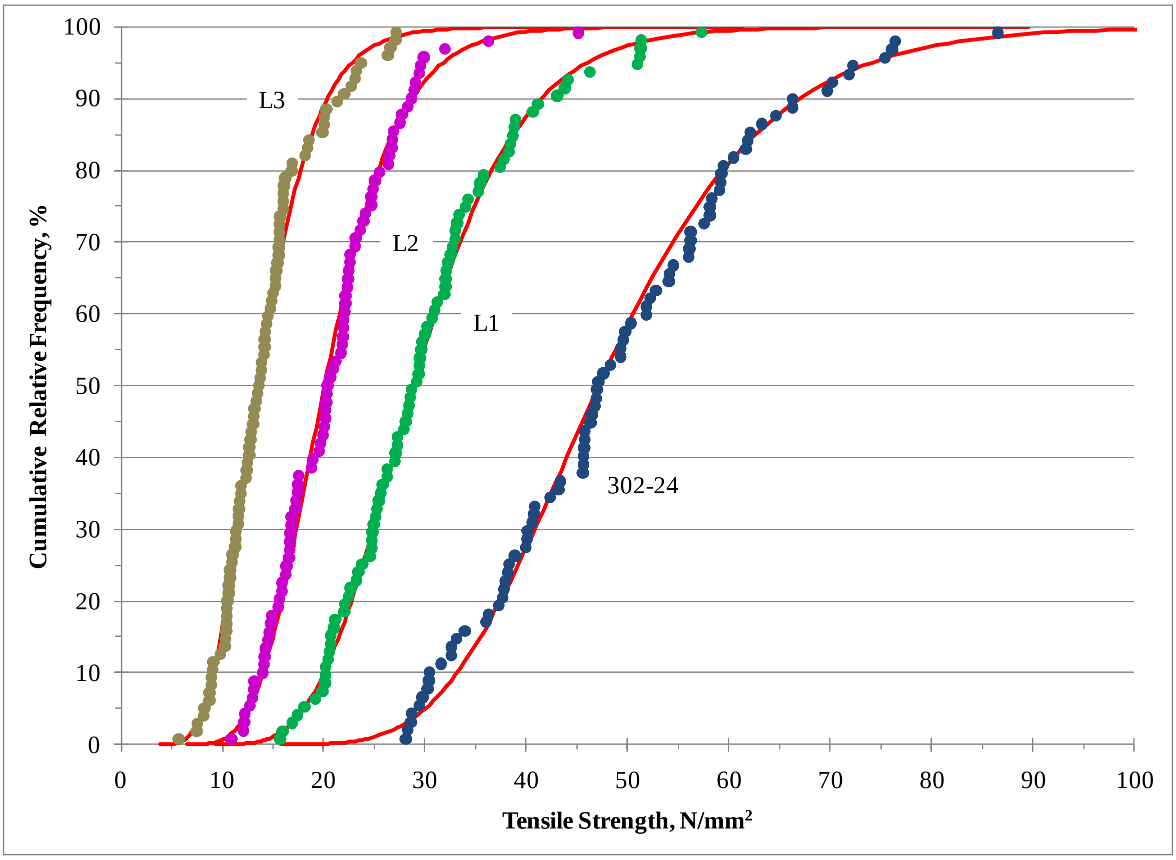

Figure 2. Data distribution of lumber tensile strength based on an assumed log-normal distribution function

As shown in Table 1, the characteristic tensile strength of each lumber grade based on an assumed log-normal distribution meets the currently published characteristic value with a coefficient of variation of between 27 to 33% depending on the relative lumber quality.

3.2 End-Joint Tension

Test results for end joint tension (610-mm or 2-foot gauge length) are shown in Table 2. The characteristic tensile strength (5th percentile with 75% confidence) of the end joints, $f_{t,j,05}$, for each of the two lumber grades from the combination of 3 glulam plants was determined based on ASTM D 2915. The data distribution of end joint tension values for each lumber grade is shown in Figure 3.

Table 2. Summary statistics of end joint tensile strength

Properties	End Joint Tensile Strength	
	302-24	L1
No. of observations	80	88
$f_{t,j,mean}$, N/mm^2 (psi)	35.6 (5165)	30.4 (4416)
Coefficient of variation	0.149	0.183
$f_{t,j,05}$, N/mm^2 (psi)	27.8 (4036) [(a)]	21.5 (3114) [(b)]
$f_{t,0,l,05}$, N/mm^2 (psi) [(c)]	29.0 (4212)	17.5 (2537)
Published $f_{t,0,l,05}$, N/mm^2 (psi) [(d)]	27.6 (4008)	16.7 (2420)
$f_{t,j,05}/f_{t,0,l,05}$	0.96	1.23

(a) Non-parametric 5th percentile with 75 percent confidence of end joints.
(b) Parametric 5th percentile with 75 percent confidence of end joints (lognormal distribution).
(c) Parametric 5th percentile with 75 percent confidence of laminating lumber (from Table 1).
(d) Characteristic value of laminating lumber published in AITC 407.

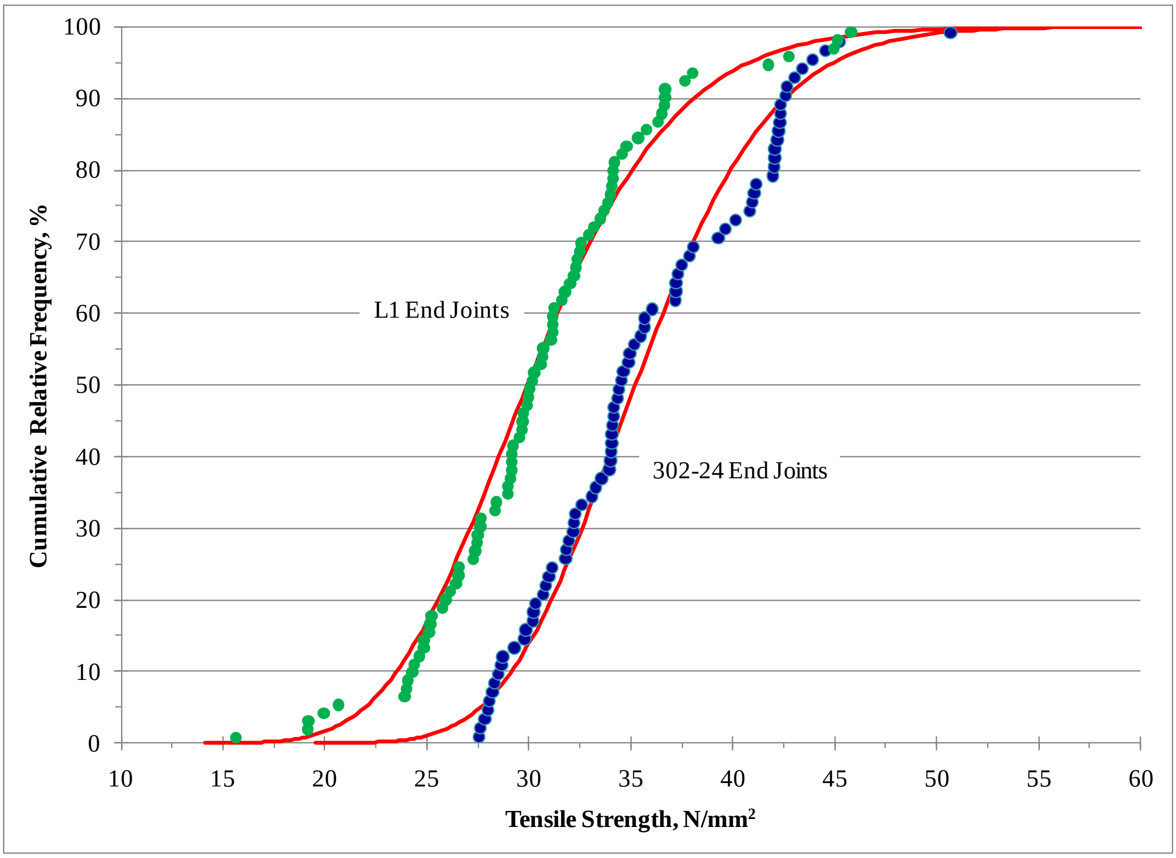

Figure 3. Data distribution of end joint tensile strength based on an assumed log-normal distribution function

As compared to Table 1, Table 2 shows that the end joints have a substantially lower coefficient of variation than the corresponding laminating lumber as is expected. As a result, even though the mean tensile strength of the end joints, $f_{t,j,mean}$, made of high-quality 302-24 tension lams is significantly below the mean tensile strength of the laminating lumber, $f_{t,0,l,mean}$, the characteristic tensile strength of the end joints, $f_{t,j,05}$, remains comparable (within 4%) to the characteristic tensile strength of the laminating lumber, $f_{t,0,l,05}$. On the other hand, for L1 lumber, the mean tensile strength of the end joints is comparable to the mean tensile strength of the laminating lumber. As a result of the reduced coefficient of variation, the characteristic tensile strength of the end joints is substantially higher (23%) than that of the laminating lumber. In all cases, the end joints appear to meet the currently published characteristic value for the laminating lumber.

It is important to note that in the North American glulam standards, the characteristic tensile strength of end joints is required to be only as strong as the characteristic tensile strength of the corresponding lumber. This is different from prEN 14080 [12], *Timber Structures - Glued Laminated Timber and Glued Laminated Solid Timber – Requirements*, which requires the characteristic tensile strength of end joints to be 5 N/mm^2 higher than the characteristic tensile strength of the lumber. While it is entirely possible that some low to medium grades of lumber could have end joints that are 5 N/mm^2 higher than the characteristic tensile strength of the lumber, it is recognized by the North American glulam industry that this requirement is extremely difficult to satisfy for high-quality lumber, such as 302-24 tension laminations and it has been demonstrated through numerous full-scale beam tests to be unnecessary to ensure beam performance.

3.3 Lumber Long-Span E

Table 3 shows test results for lumber long-span E (span-to-depth ratio of 100:1 in flatwise bending). The mean long-span E of the lumber, $LSE_{m,l,mean}$, of each lumber grade can be considered as the shear-free modulus of elasticity. As shown in Table 3, the mean long-span E values of the high-quality 302-24 tension laminations and L2 lumber are substantially higher (15% and 12%, respectively) than the currently published values. The higher long-span E for the 302-24 tension laminations should not be a surprise because the current published long-span E value is assumed to be the same value as the relatively lower quality L1 grade.

Table 3. Summary statistics of lumber long-span E

Properties	Lumber Long-Span E [(a)]			
	302-24	L1	L2	L3
No. of observations	86	90	87	93
$LSE_{m,l,mean}$, kN/mm^2 (10^6 psi)	16.7 (2.42)	14.9 (2.15)	13.1 (1.91)	11.6 (1.69)
Coefficient of variation	0.124	0.154	0.151	0.172
Published $LSE_{m,l,mean}$, kN/mm^2 (10^6 psi) [(b)]	14.5 (2.1)	14.5 (2.1)	11.7 (1.7)	11.0 (1.6)
$LSE_{m,l,mean}$/Published $LSE_{m,l,mean}$	1.15	1.02	1.12	1.06

[(a)] Tested with a span-to-depth ratio of 100:1 in accordance with ASTM D 4761.
[(b)] Mean value published in AITC 407.

3.4 Lumber Compression

Table 4 shows the test results for lumber compression based on short-column tests (a slenderness ratio of 17.3) in accordance with ASTM D 198. The characteristic compressive strength (5th percentile with 75% confidence) of the lumber, $f_{c,0,l,05}$, of each lumber grade from the combination of 3 glulam plants were determined based on ASTM D 2915. The data distribution of each lumber grade is shown in Figure 4. Note that there are no currently published compressive strength values for laminating lumber. However, as compared to results shown in Table 1, the characteristic compressive strength of the laminating lumber is 1.6, 2.5, 3.2, and 4.9 times higher than the characteristic tensile strength values, respectively, for 302-24, L1, L2, and L3 laminations. This trend suggests that the compression-to-tension ratio increases with decreasing lumber quality.

Table 4. Summary statistics of lumber compressive strength

Properties	Lumber Compressive Strength			
	302-24	L1	L2	L3
No. of observations	149	145	89	93
$f_{c,0,l,mean}$, N/mm^2 (psi)	56.9 (8260)	53.6 (7774)	51.7 (7506)	50.7 (7357)
Coefficient of variation	0.098	0.108	0.146	0.146
$f_{c,0,l,05}$, N/mm^2 (psi) [(a)]	47.7 (6926)	44.2 (6406)	38.9 (5639)	38.6 (5592)
$f_{c,0,l,05}/f_{t,0,l,05}$ [(b)]	1.6	2.5	3.2	4.9

[(a)] Parametric 5th percentile with 75 percent confidence of laminating lumber (lognormal distribution).
[(b)] Based on the results reported in Table 1.

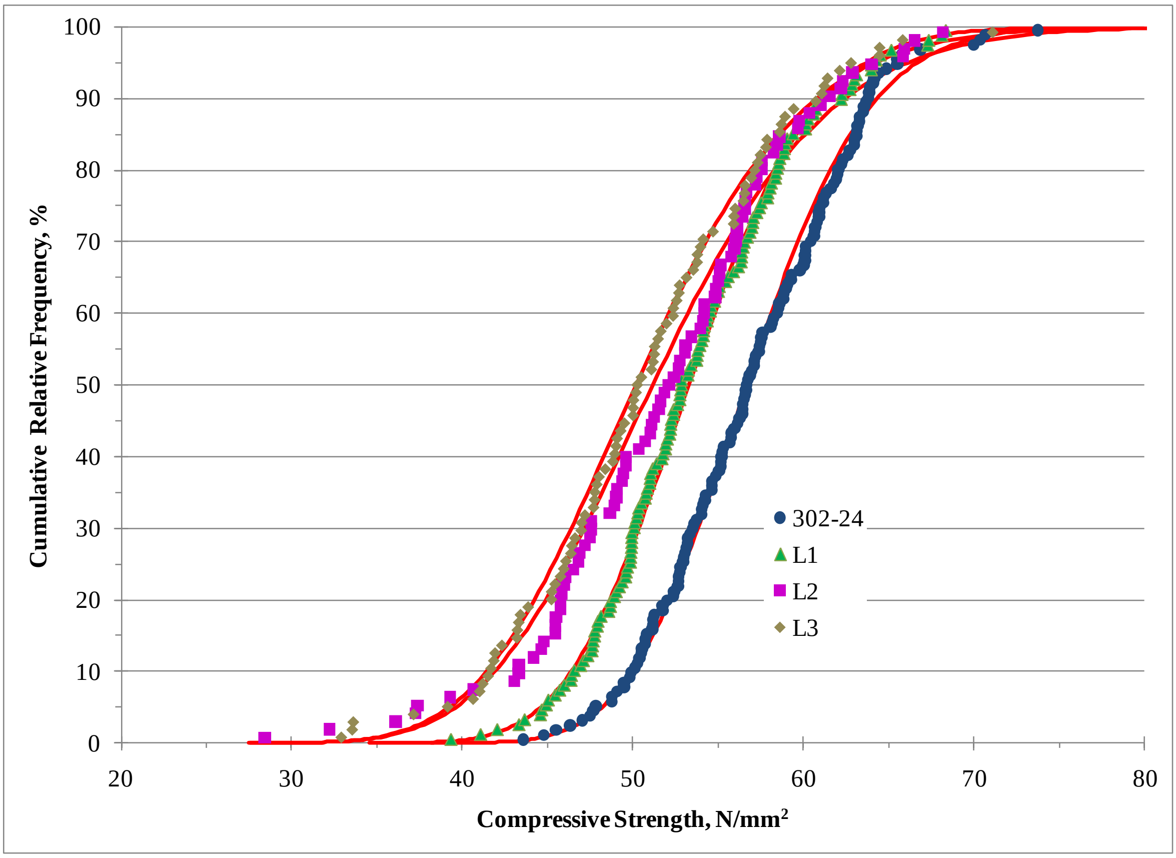

Figure 4. Data distribution of lumber compressive strength based on an assumed log-normal distribution function

The compression moduli and downward slope (m) of the bi-linear compressive stress and strain curve, as shown in Figure 1, are summarized in Table 5. The high coefficient of variation for this property is not a surprise because it is related to the post-failure phenomenon. As a result, the use of this information for computer modelling is highly likely to affect the quality of the simulation. An active investigation is pending for improving the accuracy of the estimate for this property and studying the effect of the coefficient of variation on the quality of the ReLam prediction.

Table 5. Summary statistics of the downward slope of compressive stress and strain curve

Properties	M	
	302-24	L1
No. of observations	47	54
Mean	-0.24	-0.20
Coefficient of variation	0.72	0.55

4. FRP-Reinforced Glulam Layup Combinations

Based on the data obtained from this study, FRP-reinforced glulam layup combinations were generated using the ReLam model. Figure 5 shows two candidate layup combinations with a targeted characteristic bending strength, $f_{m,g,k}$, of 48.3 N/mm^2 (7000 psi) and mean bending modulus of elasticity, $E_{0,g,mean}$, of 14480 N/mm^2 (2.1 x 10^6 psi) based on a reinforcement ratio, ρ (the ratio of the reinforcement to the overall beam volume), of about 3%. These layup combinations are designed to utilize low-grade laminations (mostly L2 and L3) to achieve a bending strength that far exceeds the conventional non reinforced glulam beam.

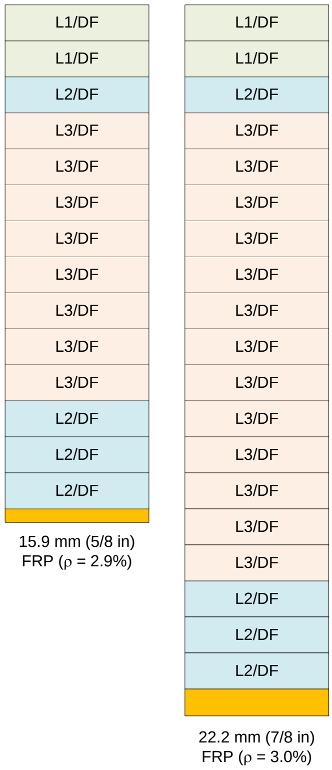

Figure 5. Candidate FRP-reinforced glulam layup combinations at a reinforcement ratio (ρ) of around 3% of the beam depth

The confirmation of the properties for the layup combinations shown in Figure 5 by full-scale beam tests is currently active and will be provided in a separate report when the results become available. Nonetheless, once the ReLam model is confirmed with its methodology and prediction, computer simulations can be conducted to generate FRP-reinforced glulam layup combinations with different reinforcement ratios, wood species, lamination grades, and targeted characteristic beam properties.

5. Conclusions and Recommendations

Results obtained from this study provide the characteristic properties of Douglas-fir laminating lumber that can be used for the modelling of FRP-reinforced glulam in accordance with ASTM D 7199. These data also confirm that the currently published laminating lumber properties are adequate albeit in some cases conservative. For the purpose of the glulam modelling using the bilinear compressive stress and strain curve, further investigation on the accuracy of the estimate for the downward slope after the compression failure will be conducted.

A model analysis was conducted for the development of candidate layup combinations with a targeted characteristic bending strength of 48.3 N/mm^2 (7000 psi) and mean bending modulus of elasticity of 14480 N/mm^2 (2.1 x 10^6 psi) based on a reinforcement ratio of about 3% utilizing low-grade laminations. The confirmation of the properties for these layup combinations is pending the completion of full-scale beam tests.

Once the confirmation of the ReLam model is completed, APA will pursue obtaining a code evaluation report based on ICC-ES AC280 [13], *Acceptance Criteria for Fiber-Reinforced-Polymer Glued Laminated Timber Using Mechanics Based Models*, on behalf of its manufacturing members. This will allow APA members to be listed on the code evaluation report and significantly expand the use of FRP-reinforced glulam in the U.S.

6. References

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