In-Grade Evaluation of U.S. Glulam Beams, End Joints, and Tension Laminations

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1 Introduction

Structural glued laminated timber (glulam) has been in commercial production in the U.S. since 1934 [Rhude, 1996]. There are about 30 glulam plants in the U.S., producing a total volume of 606000 m^3 (257 million board feet) of glulam in 2016 for a variety of construction applications [APA, 2016]. Today, the glulam manufacturing in the U.S. has been standardized in ANSI A190.1, *American National Standard for Structural Glued Laminated Timber* [ANSI/APA, 2017]. In the meantime, an analytical methodology, known as the "I_K/I_G" model established in 1954 through extensive research conducted by the U.S. Forest Products Laboratory in Madison, Wisconsin, has also been standardized in ASTM D3737, *Standard Practice for Establishing Allowable Properties for Structural Glued Laminated Timber* [ASTM, 2012]. The ASTM D3737 methodology was previously reviewed in the CIB W18 paper 40-12-4 [Williamson and Yeh, 2007].

ASTM D3737 provides a basis for glulam design properties published in ANSI 117, *American National Standard for Structural Glued Laminated Timber of Softwood Species* [ANSI/APA, 2015] for a variety (86 in total) of glulam layup combinations, including mixed-grade ("combined") and single-grade ("homogeneous") glulams. For hardwood species, the glulam industry generally adopts AITC 119, *Standard Specifications for Structural Glued Laminated Timber of Hardwood Species* [AITC, 1996], which has not been updated since 1996 due in part to the dissolution of American Institute of Timber Construction (AITC) in 2012 and an insignificant production volume for hardwood glulams in the U.S.

As compared to the European practice, ASTM D3737 and ANSI 117 adopt a different assumption in assigning glulam design values, i.e., the end joint strength is assumed to perform at a level that will support the assigned glulam properties and does not reduce the glulam structural performance through in-plant quality assurance on an on-going basis. In other words, the published glulam design values are predicated on the performance of end joints, as defined in ANSI A190.1. Therefore, the quality of end joints remains critical to the glulam beam performance. However, there are no requirements in ANSI A190.1 for full-scale glulam beam tests as part of the quality assurance program on a regular basis. It is assumed that if the glulam components – laminating lumber, adhesive, end joints, and face joints are properly quality-controlled at the plant, the finished glulams will perform well without full-scale glulam beam tests. This practice has apparently stood the test of time as there have been no major glulam performance issues reported in the U.S.

For these reasons, full-scale glulam beam test data are quite limited. However, as other engineered wood products, such as structural composite lumber (SCL) and prefabricated wood I-joists, are regularly tested in full size, it is considered desirable to obtain glulam performance data from “in-grade” productions sampled over multiple years from representative production facilities to re-evaluate or reaffirm the current glulam design values that have been in use for decades in the U.S.

As a result, a 4-year in-grade glulam program was initiated in 2012 by APA – The Engineered Wood Association, which trademarks about 92% of glulam production currently in the U.S. and Canada. With the support of the glulam industry, the in-grade program sampled and tested full-scale glulam beams, and matched end joints and tension laminations from regular productions. This paper provides an analysis of the glulam beam bending strength (MOR) and modulus of elasticity (MOE), the tensile strength of end joints, and the tensile strength and long-span E (LSE) of tension laminations. The results are compared to the published design values based on the ASTM D3737 analytical model for glulams used in the U.S.

2 Objectives

The main objectives of this multiple-year in-grade glulam evaluation program were to determine the overall quality of glulam beams manufactured from multiple manufacturing facilities in the U.S. using regular productions and to re-evaluate or reaffirm the published glulam design values based on the ASTM D3737 analytical model.

3 Materials and Methods

3.1 Materials

Although there are 86 softwood glulam layup combinations that are prescribed in ANSI 117, the vast majority (75% or more) of current glulam productions in the U.S. are manufactured in accordance with 4 primary glulam layup combinations: 24F-V4 Douglas-fir (DF), 24F-V3 Southern Pine (SP), 24F-V8/DF, and 24F-V5/SP. These layup combinations use mostly visually graded lumber except that mechanically graded lumber may be substituted on an equivalent performance basis in accordance with ANSI A190.1 and ANSI 117. This substitution occurs mostly on special tension laminations ("302-24"). The first 2 layup combinations are unbalanced layups for DF and SP, meaning the layups are asymmetrical for the lamination grades used on top and bottom portions of the glulam beam. On the other hand, the latter 2 layup combinations are balanced layups for DF and SP, meaning the layups are symmetrical. In reality, the unbalanced layups are significantly more popular than the balanced layups in the U.S. Therefore, the in-grade program focused on the unbalanced glulam layup combinations of 24F-V4/DF and 24F-V3/SP.

To ensure the tension lamination and its end joints are stressed more like a tension member (vs. a bending member), a beam depth of 12 and 13 laminations, i.e., 457 mm (18 inches) and 454 mm (17-7/8 inches) was chosen for 24F-V4/DF and 24F-V3/SP, respectively, based on the standard lamination thickness of 38 mm (1-1/2 inches) and 35 mm (1-3/8 inches) for DF and SP. The actual glulam beam layups are shown in Table 1.

Table 1. Glulam Layups Used for In-Grade Testing.

Layup Details and Predicted Properties	Lamination #	24F-V4/DF	24F-V3/SP
		Lamination Thickness and Grade[(a)]	
Layup Details	13	—	35-mm N1D10
	12	38-mm L2D	35-mm N1D10
	11	38-mm L2D	35-mm N2D8
	10	38-mm L2	35-mm N2M8
	9	38-mm L3	35-mm N2M8
	8	38-mm L3	35-mm N2M8
	7	38-mm L3	35-mm N2M8
	6	38-mm L3	35-mm N2M8
	5	38-mm L3	35-mm N2M8
	4	38-mm L3	35-mm N2D8
	3	38-mm L2	35-mm N2D8
	2	38-mm L1	35-mm N1D12
	Special Tension Lam	38-mm 302-24	35-mm 302-24
MOR(b), MPa (psi)		34.7 (5040)	34.7 (5040)
MOE(c), MPa (10^6 psi)		12600 (1.83)	12500 (1.82)

(a) Lamination grades are defined in ANSI 117. "302-24" is a special tension lamination grade.

(b) Predicted modulus of rupture (MOR) values are the characteristic values (5th percentile with 75% confidence) adjusted to the standard beam volume of 130 mm x 305 mm x 6400 mm (5-1/8 inches x 12 inches x 21 feet) at the standard moisture content of 12%. The predicted MOR values are limited by the characteristic end joint strength. Without end joints, the predicted MOR value is 35.2 MPa (5109 psi) and 38.5 MPa (5586 psi) for 24F-V4/DF and 24F-V3/SP, respectively.

(c) Predicted modulus of elasticity (MOE) values are the mean apparent MOE values adjusted to the standard moisture content of 12%. The MOE values are assumed to be 95% of the true MOE values in accordance with ASTM D3737.

3.2 Sampling

At least 30 full-size glulam beams of about 130 mm x 457 mm x 10 m (5-1/8 inches x 18 inches x 33 feet) were sampled each year from 3 or more glulam plants (i.e., 10 beams per plant). This sampling continued in 4 consecutive years (2012 through 2015). As the beams were sampled from each glulam plant, at least 30 matched end joints of 38 mm x 140 mm x 2100 mm (1-1/2 inches x 5-1/2 inches x 7 feet) and 30 matched tension laminations of 38 mm x 140 mm x 4000 mm (1-1/2 inches x 5-1/2 inches x 13 feet) were also sampled from the same production so that the component performance could be correlated to the glulam beam performance. Since it is a common practice to combine Coastal and Inland Douglas-fir for the 24F-V4/DF layup combination, efforts were made to sample these 2 sub-wood species separately so as to ensure that the published design values could be evaluated for both. The DF and SP glulam layup combinations have the same published stress class of 24F-1.8E, which has a characteristic bending strength of 34.7 MPa (5040 psi) and mean apparent modulus of elasticity of 12400 MPa (1.8 x 10^6 psi).

At the end of this in-grade program, a total of 130 beams (50 Coastal Douglas-fir, 40 Inland Douglas-fir, and 40 Southern Pine), 397 matched end joints (150 Coastal Douglas-fir, 122 Inland Douglas-fir, and 125 Southern Pine), and 370 matched tension laminations (125 Coastal Douglas-fir, 120 Inland Douglas-fir, and 125 Southern Pine) were sampled from 13 different glulam plants (5 Coastal Douglas-fir, 4 Inland Douglas-fir, and 4 Southern Pine).

3.3 Test Methods

All materials were tested at the APA Research Center in Tacoma, Washington, which has an ISO/IEC 17025-accredited independent test laboratory for the tests covered in this program.

Lamination Tests: The long-span E of tension laminations was tested flatwise in accordance with AITC T116, *Modulus of Elasticity for E-Rated Lumber by Static Loading* [AITC, 2007], using a center-point load method with an on-center span of 3810 mm (150 inches), resulting in a span-to-depth ratio of 100:1. This long-span E is essentially the true E due to minimal shear deflection at this large span-to-depth ratio. The tensile strength of the tension laminations was tested in accordance with AITC T123, *Sampling, Testing and Data Analysis to Determine Tensile Properties of Lumber* [AITC, 2007], using a 2440 mm (8-foot) gauge length, which is a standard in the U.S. for structural lumber tests.

End Joint Tests: The tensile strength of end joints was tested in accordance with AITC T119, *Full Size End Joint Tension Test* [AITC, 2007], using a 610-mm (2-foot) gauge length, which is a standard in the U.S. for structural end joint tests.

Glulam Beam Tests: A two-point load method, as shown in Figure 1, was applied to test each glulam beam using a span-to-depth ratio of approximately 21. The test apparatus, including rocker-type reaction supports, reaction bearing plates and rollers, load bearing block, and load bearing rollers was set up following ASTM D198, *Standard Test Methods of Static Tests of Lumber in Structural Sizes* [ASTM, 2015]. The position of end joints in each beam was random and not specifically excluded from the center one-half (high tensile stress) portion of the glulam beam.

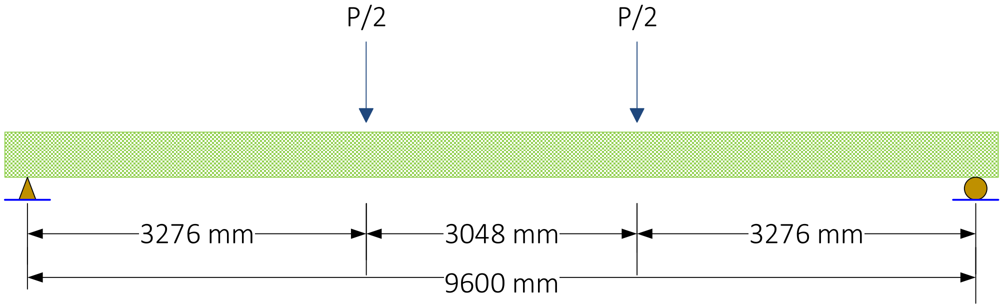

Figure 1. Loading configuration for glulam beam bending tests

For determining the glulam bending strength, the MOR value obtained from bending testing was adjusted by a volume factor, C_v, (Equation 1) based on the 2015 *National Design Specification for Wood Construction,* NDS [ANSI/AWC, 2015].

$$C_v = \left(\frac{130}{b}\right)^{\alpha}\left(\frac{305}{h}\right)^{\alpha}\left(\frac{6400}{\ell}\right)^{\alpha} \qquad (1)$$

where: C_v = volume factor,

α = 1/10 for Douglas-fir glulam and 1/20 for Southern Pine glulam, and

b, h, ℓ = beam width and depth, and test span in mm, respectively.

In addition, the MOR and apparent MOE values were adjusted to the standard 12% moisture content based on ASTM D1990, *Standard Practice for Establishing Allowable Properties for Visually-Graded Dimension Lumber from In-Grade Tests of Full-Size Specimens* [ASTM, 2014].

4 Results and Discussion

4.1 Tension Lamination Properties

Based on the sample of 370 tension laminations (125 Coastal Douglas-fir, 120 Inland Douglas-fir, and 125 Southern Pine) from 13 different glulam plants, results of tension lamination tensile strength and long-span E are summarized in Table 2.

Table 2. Tension lamination properties.

Species	N	Tension Lamination Tensile Strength			Long-Span E	
		Mean, MPa (psi)	COV	Characteristic Value [(a)], MPa (psi)	Mean, MPa (10^6 psi)	COV
Douglas-fir	245[(b)]	49.4 (7164)	0.30	27.7 (4024)	15830 (2.30)	0.13
Southern Pine	125	57.6 (8359)	0.26	35.2 (5103)	14931 (2.17)	0.15
Combined	370	52.2 (7568)	0.29	29.7 (4307)	15525 (2.25)	0.14

[(a)] 5th percentile with 75% confidence based on an assumed lognormal distribution function.

[(b)] For long-span E, the number of observations (N) is 244.

The published characteristic tensile strength for the 302-24 tension laminations regardless of the wood species is 27.6 MPa (4008 psi). As shown in Figure 2 and Table 2, the industry-wide data met the published characteristic tensile strength. At the lower tail of the data distribution, the lognormal distribution fits better than the normal distribution. In reviewing individual test results, there were 14 out of 370 tested tension laminations that were lower than the published tensile strength of 27.6 MPa (4008 psi). This represents about 3.8% of probability, which is within the expected probability in practice.

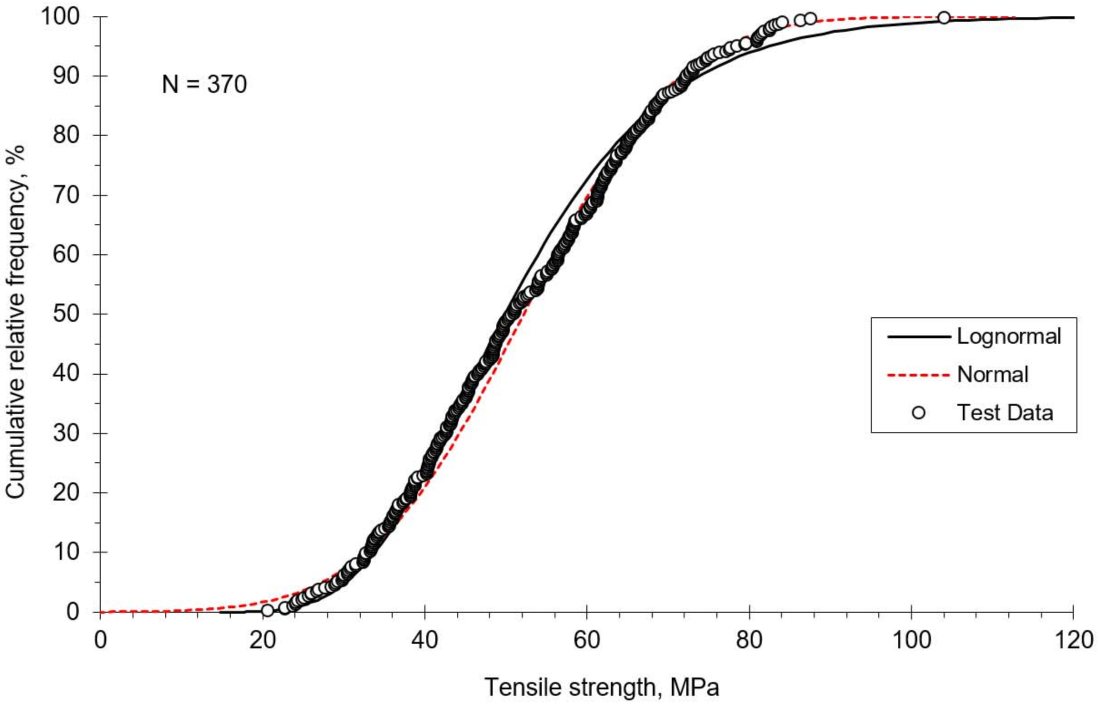

Figure 2. Tensile strength of tension laminations

Table 2 also shows the long-span E for the 302-24 tension laminations. The published LSE is 14500 MPa (2.1 x 10^6 psi) and 13800 MPa (2.0 x 10^6 psi), respectively, for Douglas-fir and Southern Pine 302-24 tension laminations. As shown in Table 2, the tested LSE values exceeded the published LSE values by about 10%.

4.2 End Joint Properties

Based on the sample of 397 end joints (150 Coastal Douglas-fir, 122 Inland Douglas-fir, and 125 Southern Pine) from 13 different glulam plants, results of end joint tensile strength are summarized in Table 3.

Table 3. End joint tensile strength.

Species	N	End Joint Tensile Strength		
		Mean, MPa (psi)	COV	Characteristic Value [(a)], MPa (psi)
Douglas-fir	272	39.6 (5740)	0.18	27.9 (4042)
Southern Pine	125	40.5 (5873)	0.16	30.2 (4376)
Combined	397	39.9 (5782)	0.17	28.6 (4153)

[(a)] 5th percentile with 75% confidence based on an assumed lognormal distribution function.

As previously mentioned, end joints are required to be quality-controlled in accordance with ANSI A190.1 based on the glulam performance level. Since end joints are required to be tested in full-scale tension (instead of bending), for glulam bending members, the end joint must be quality-controlled at 80% of the characteristic bending strength of the glulam beam by taking into account the difference between tensile and bending strengths. As a result, since the characteristic bending strength of 24F glulam beams is at least 34.7 MPa (5040 psi), the end joints must be quality-controlled at the characteristic tensile strength of 27.6 MPa (4008 psi) in accordance with ANSI A190.1.

As shown in Figure 3 and Table 3, the characteristic end joint tensile strengths met the required value of 27.6 MPa (4008 psi) for 24F glulam beams. It should be noted that the coefficient of variation (COV) for the tensile strength of end joints is significantly lower than that of tension laminations shown in Table 2. In reviewing individual test results, there were 11 out of 397 tested end joints that were lower than 27.6 MPa (4008 psi). This represents about 2.8% of probability. While this level of probability is considered acceptable in practice, the use of an in-line proof loader in production (note that not all end joints tested in this program were proof-loaded, which reflects the current industry practice) may help to eliminate the low performer in production.

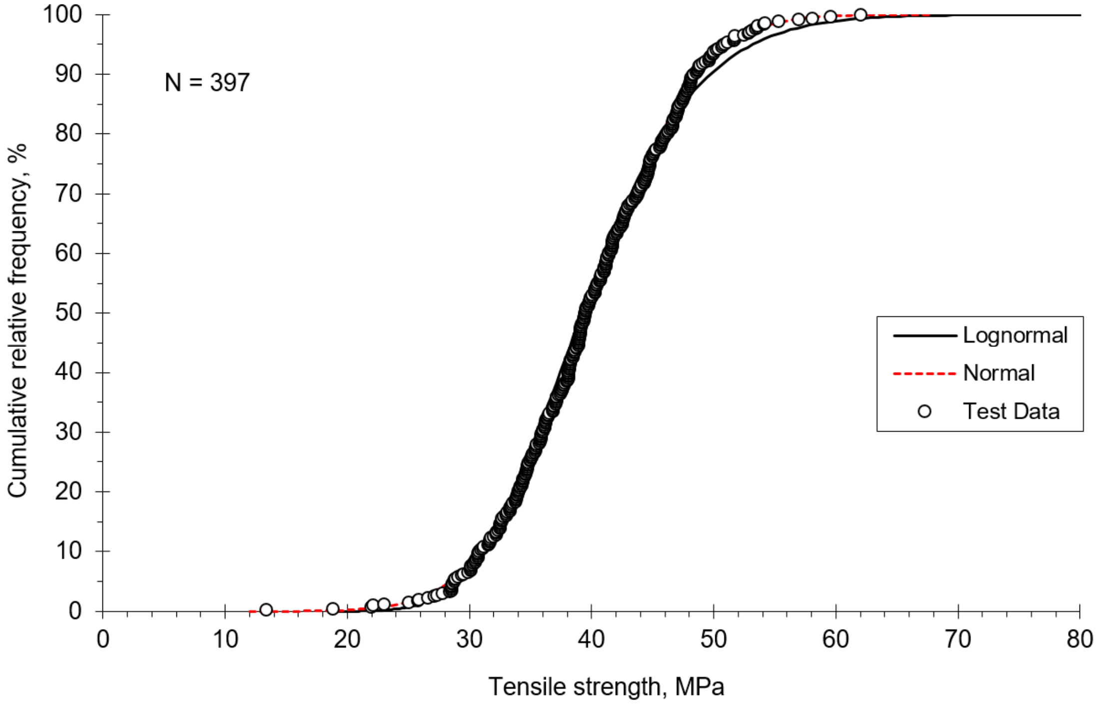

Figure 3. Tensile strength of end joints

4.3 Glulam Beam Performance

Based on the sample of 130 glulam beams (50 Coastal Douglas-fir, 40 Inland Douglas-fir, and 40 Southern Pine) from 13 different glulam plants, results of glulam beam bending properties are summarized in Table 4. As previously noted, the bending strength values have been adjusted for the volume effect. In addition, both MOR and MOE values have been adjusted for the standard moisture content of 12%.

Table 4. Glulam beam bending properties.

Species	N	Glulam Beam Bending Strength (MOR)			Glulam Beam Modulus of Elasticity (MOE)	
		Mean, MPa (psi)	COV	Characteristic Value [(a)], MPa (psi)	Mean, MPa (10^6 psi)	COV
Douglas-fir	90	46.7 (6767)	0.16	34.2 (4965)	14055 (2.04)	0.10
Southern Pine	40	50.4 (7307)	0.17	36.6 (5312)	14179 (2.06)	0.07
Combined	130	47.8 (6933)	0.17	35.0 (5078)	14093 (2.04)	0.09

[(a)] 5th percentile with 75% confidence based on an assumed lognormal distribution function.

Most glulam beams failed in bending due to finger joint tension failure at the ultimate load, while there were some beams failed as a result of tension lamination failure due to edge knots or slope of grain, as shown in Figure 4. Note that the edge knot shown in Figure 4 was noticed to be off-grade for the 302-24 tension laminations, which is limited to 1/6 of the lamination width. Since this was uncommon in occurrence, its test results were not removed from the database reported in Table 4 for added conservatism.

Figure 4. Glulam beam failure modes

The published MOR for 24F glulams, as predicted by the ASTM D3737 analytical model (see Table 1) is 34.7 MPa (5040 psi), which is governed by the end joint strength. Based on the characteristic tensile strengths of tension laminations (Table 2) and end joints (Table 3), a combination of tension lamination and end joint tension failures are to be expected for these tested glulam beams. As noted from Table 4, the characteristic glulam MOR is 35.0 MPa (5078 psi) based on the combined test data, which matches well with the predicted MOR of 34.7 MPa (5040 psi). While the characteristic glulam MOR for Douglas-fir glulam beams is about 1.5% below the targeted value, it is within the standard rounding tolerance (2%) for the design bending value of 24F glulam beams. Figure 5 shows the bending strength (MOR) data distribution for all glulam beams tested in this program.

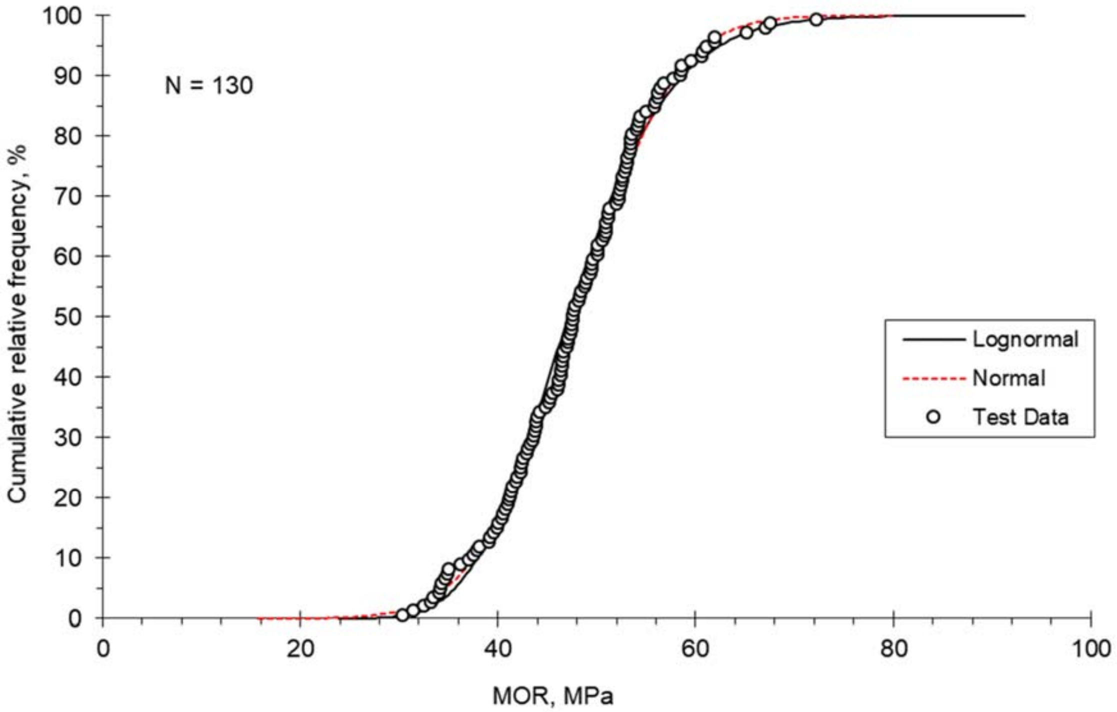

Figure 5. Bending strength (MOR) of glulam beams

In reviewing individual test results, there were 5 out of 130 beams with an MOR that was lower than the expected MOR for 24F glulam beams. This represents about 3.8% of probability, which correlates well with the 3.8% and 2.8% probabilities reported above for tension laminations and end joints, respectively. While this level of probability is considered acceptable in practice, the continuing attention to lumber grading and end joint quality control techniques should be helpful to the improvement of glulam beam performance.

When comparing the characteristic end joint tensile strength shown in Table 3 and the glulam beam bending strength shown in Table 4, the ratio of end joint tensile strength and glulam beam bending strength is 4042 psi/4965 psi or 0.814 for Douglas-fir glulams, 4376 psi/5312 psi or 0.824 for Southern Pine glulams, and 4153 psi/5078 psi or 0.818 for the combined data. These results are similar and confirm the aforementioned ratio of 0.80 that has been adopted by the U.S. glulam industry in the last 30 years.

The data distribution for the combined glulam beam MOE results is shown in Figure 6. Table 4 also shows the mean glulam beam MOE values, which are significantly (about 13%) higher than the predicted value of 12600 MPa (1.83 x 10^6 psi) for 24F-V4

Douglas-fir glulams and 12500 MPa (1.82 x 10^6 psi) for 24F-V3 Southern Pine glulams. This should not be a surprise based on the 10% higher LSE values from the tension laminations, as shown in Table 2. As the ASTM D3737 analytical model adopts the transformed-section method in predicting the glulam beam MOE, the glulam beam MOE is directly affected by the lamination LSE. In fact, when the lamination LSE values are increased by 10%, the predicted beam MOE would be 13860 MPa (2.01 x 10^6 psi) for the 457 mm (18 inches) deep 24F-V4 Douglas-fir beams and 13790 MPa (2.00 x 10^6 psi) for the 454 mm (17-7/8 inches) deep 24F-V3 Southern Pine beams. These predicted glulam MOE values are within 3% of the tested glulam MOE values shown in Table 4. This confirms that the transformed section method is a reasonable model for predicting glulam beam MOE. Therefore, a continuing quality control of the lamination LSE should be adequate to ensure the glulam stiffness performance.

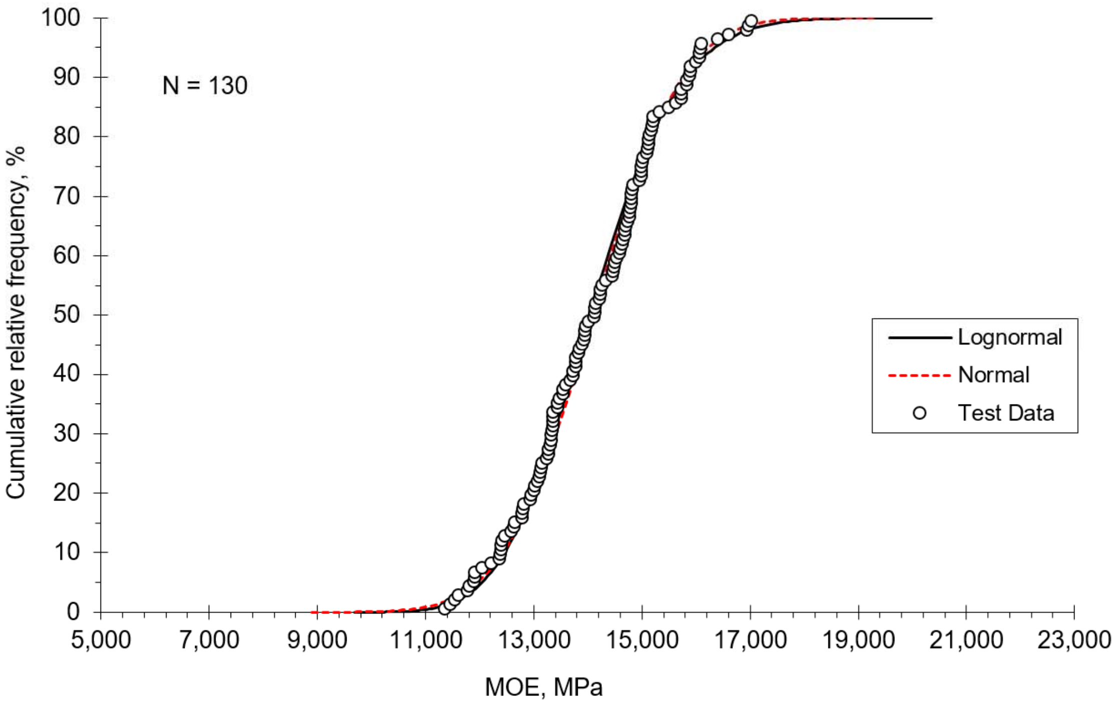

Figure 6. Bending modulus of elasticity (MOE) of glulam beams

The relatively high glulam beam MOE obtained from this in-grade program, as compared to the currently published glulam MOE, was discussed by glulam manufacturers for a possible revision to the current design values. However, due to a concern over consistent supplies of high quality lumber laminations in the long run, a conscious decision was made by the glulam industry to not pursue this option at this point. The industry will continue to monitor the lamination LSE.

5 Conclusions

Results obtained from this 4-year in-grade program, which included the tensile strength of end joints, tensile strength and long-span E of tension laminations, and bending strength and modulus of elasticity of glulam beams, are representative of the state of glulam production quality in the U.S. Overall, a total of 130 glulam beams, 370 tension laminations, and 397 end joints were evaluated.

Overall, the following conclusions can be drawn based on the results obtained from this program:

1. The tensile strength of tension laminations met the published value. On the other hand, the long-span E of tension laminations exceeded the published value by about 10%. This has a positive and direct impact to the glulam beam MOE. Since the tension lamination performance is critical to the glulam beam performance, the lumber grading for laminations in glulam production should continue to be a priority for glulam manufacturers.
2. The tensile strength of end joints met the value established by the glulam standard, ANSI A190.1, for the 24F glulam beams. Since the end joint performance is critical to the glulam beam performance, the daily quality control of end joints in glulam production should remain vigilant by glulam manufacturers.
3. The ratio of 0.8 for the characteristic tensile strength of end joints and the characteristic bending strength of glulam beams, as established by ANSI A190.1 is confirmed by the results of this program.
4. The bending strength of glulam beams met the design value published in the glulam design specification, ANSI 117, while the bending modulus of elasticity exceeded the published value by about 13%, which is attributed in part by the higher LSE of tension laminations.
5. The ASTM D3737 analytical model remains adequate for predicting glulam design values and no immediate revisions to the model are suggested by the results obtained from this program.

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