Tensile strength of AITC 302-24 grade tension laminations

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Abstract

Distributional characteristics of tensile strength for laminating grades of lumber in the United States are necessary for the reliability-based design of glued-laminated timbers (glulam). The most important of the laminating grades is the American Institute of Timber Construction visually graded tension lamination grade called 302-24. This study was conducted to provide tensile strength distributional characteristics of 302-24 tension laminations, which can be used as input for reliability-based design models and as baseline criteria for alternate grades and products that might serve as substitutes for the 302-24 grade. A total of 691 "on-grade" 2 by 6's, 12 feet long, were tested in tension parallel to grain. Included were 362 Douglas-fir - larch, 219 southern pine, and 110 hem-fir specimens. No end joints were used. Testing followed standard procedures with the exception that the specimens were tested to failure in an average time of 2 minutes. Three-parameter Weibull distributional estimates are reported because they fit quite well the tensile strength and modulus of elasticity for all the species. There were no significant differences between "on-grade" and "as-graded" samples. The resulting tensile strength of the Douglas-fir - larch specimens was in the range expected, but the tensile strengths of the southern pine and hem-fir specimens were higher than expected; at those high lumber strengths, the strength of end joints could become the controlling factor. The current near-minimum level of 4,000 pounds per square inch used as a criterion for the acceptance of proposed alternate tension lamination grades or products was substantiated.

Current deterministic design procedures for glued-laminated timbers (glulam) require only the characterization of near-minimum properties. However, this information will not be sufficient for newer reliability-based design procedures, which will require distributional data for the strength properties of glulam.

Computer simulation models are the most promising method of predicting distributional properties for a large number of laminating combinations. Several computer models for predicting the strength and stiffness distributions of glulam timbers have already been developed; one such model was developed by Foschi and Barrett (5).

Accurate and reliable tensile strength distributional characteristics for laminating grades of lumber are needed to provide input into these models, and to provide a baseline for determining the acceptance of alternate tension lamination grades and products. The purpose of this study was to evaluate tensile strength distributional properties for the most important grade of laminating lumber in the United States, the current American Institute of Timber Construction (AITC) visually graded tension lamination grade called 302-24.

Under the current I_K/I_G deterministic design concept, which has been used in the United States to establish design stresses in bending for glulam beams, several special tension lamination grades have evolved since 1967. The current 302-24 tension lamination grade is the most important grade in terms of controlling beam strength for a large portion of glulam timbers. It is required on beams greater than 15 inches in depth with a design stress of 2,400 pounds per square inch (psi). Details on the grading criteria for the 302-24 grade are given in Appendix A.

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Only small samples of tensile strength data are available from several studies of visually graded 302-24 tension lamination material or material similar in quality (8,9,10,11,12,13) Although the data base from those studies was useful in planning the work reported here, it was inadequate to meet the present need for accurate characterization of tensile strength distributions. Thus, it was important to collect and evaluate a large sample of 302-24 quality material.

Experimental design

The specimen collection program was designed to provide a representative sample of the type of material used over a period of time as tension laminations in glulam beams in the United States. Specimens were collected from 26 laminating plants represented by AITC, which account for almost all of the structural glulam timber produced in the United States. Douglas-fir - larch, southern pine, and hem-fir were the three species sampled. Douglas-fir - larch was sampled the most extensively because it accounts for more than one-half of the total production.

The number of specimens collected from each plant was based on its relative production. All of the plants were visited at least once, and the larger plants were visited up to a maximum of six times. A limit of 10 specimens per plant per visit was chosen. The actual sample sizes for tensile strength were:

Species	No. of plants	No. of visits	No. of specimens
Douglas-fir - larch	20	50	362
Southern pine	9	22	219
Hem-fir	3	6	110

A major modification to the planned sample size occurred for Douglas-fir - larch. A total of 530 specimens of that species was collected. However, 166 of the specimens were lost to this study when a parallel study of rate-of-loading effects on tensile strength (using a subsample of the 530 Douglas-fir - larch specimens) found a significant rate-of-loading effect (7). Thus, only specimens tested at the rate used for this study could still be used to evaluate tensile strength. When measurements such as knot size were recorded before the testing of tensile strength, however, the Douglas-fir - larch sample size was about 530.

Nominal 2 by 6 lumber, 12 feet long, was sampled. To reflect actual production practices, the selected southern pine specimens were resurfaced at each plant to a thickness of 1-3/8 inches, but the Douglas-fir - larch and hem-fir specimens were left at their original 1-1/2-inch thickness.

Sampling procedures

In general, the test specimens were selected systematically from each laminating plant's inventory. The procedure used depended upon the total number of 2 by 6 pieces in stock that were graded as 302-24 tension laminations. For larger plants with sufficient inventory, the test specimens were systematically selected from bundles of lumber that were also systematically selected according to early, middle, or late placement into inventory. For other plants that had little inventory and tended to grade as they laminated, it was necessary to have at least 30 pieces graded and set aside to be sampled later. Most of the specimens were collected between April and November 1980.

On-grade and as-graded samples

This study was designed to collect two samples of lumber: one was graded 302-24 by the plant graders but may have actually contained some misgraded pieces (as-graded); the other was certified as actually meeting the 302-24 grade by the AITC inspectors (on-grade). For each misgraded piece encountered in the sampling process and identified as a part of the as-graded sample, an extra piece meeting the 302-24 grade was randomly selected and identified as part of the on-grade sample. Pieces that met the 302-24 grade and were initially encountered in the sampling process were considered part of both the as-graded and on-grade samples. Only the on-grade results are presented in the tables and discussed in the main text. The as-graded results are discussed in Appendix B.

Research methods

Test procedures

Testing followed ASTM D 198 (3) tension parallel-to-grain procedures with the exception of the rate of loading. The rate of loading was chosen so that the specimens failed in an average time of 2 minutes, which is faster than the standard ASTM rate. This faster time was needed in order to test the large amount of material in a reasonable timeframe. Based on the results of Gerhards et al. (7), some material tested at the standard rate and some at 25 times the standard rate had to be eliminated.

The specimens were tested in the tension machine at the Forest Products Laboratory. The grips for that machine each take up about 2.5 feet. Thus, when 12-foot lumber is tested, the result is a 7-foot test span. The grips were fixed to prevent rotation in an effort to partially simulate the restraint the lumber will experience as part of a glulam timber.

Data obtained

Moisture content values were determined using a resistance meter. Specific gravity (SG) values were calculated based on dry weight and test volume. Modulus of elasticity (MOE) values were determined from a flatwise bending vibration test spanning the full length of the lumber.

Statistical analysis

The data analysis consisted of descriptive statistics (means, standard deviations, histograms, etc.) for each measured variable. In addition, an analysis of variance was performed for tensile strength, MOE, and SG to test for the significance of plant-to-plant variation as well as visit-to-visit variation within a plant.

The analysis of these results also included the determination of lower tail properties such as fifth percentile point estimates, confidence intervals, and tolerance limits. Several procedures for estimating lower tail properties were used including nonparametric estimates, and estimates based on the normal distribution, the two-parameter lognormal distribution,

and the three-parameter Weibull distribution. All methods used are consistent with those used in the U.S. In-Grade Testing Program (6).

Results

Physical properties

Table 1 summarizes the physical properties of moisture content, width and thickness dimensions, and SG. Moisture content values averaged between 10 and 11 percent. Width and thickness measurements averaged within 0.02 inch of the expected sizes. SG values were considerably above the species average.

Mechanical properties

Average tensile strength and MOE values are given in Table 2 with the standard deviation, coefficient of variation (COV), and the range of test values.

Table 3 summarizes estimates of the tensile strength and MOE data by several statistical distributions. Included are nonparametric estimates as well as estimates using the normal, two-parameter lognormal, and three-parameter Weibull statistical distributions. The 5th percentile for tensile strength and the 50th percentile for MOE are currently the levels important for design.

Statistical analysis

Analysis of variance. —Tensile strength, MOE, and SG properties were studied to see if they varied significantly from plant to plant, visit to visit, or by size of plant.

Tensile strength, the most important property, did not vary significantly by either plant, visit, or size of plant at the $\alpha = 0.05$ level for Douglas-fir - larch. MOE varied significantly by both plant and visit, but not size of plant. SG varied significantly only by visit.

For the southern pine tensile strength data, there was an indication of a possible visit effect ($p = 0.0807$)

TABLE 1 — *Summary of physical properties*

Species	Sample size	Moisture content[a] Mean	Moisture content[a] Standard deviation	Width Mean	Width Standard deviation	Thickness Mean	Thickness Standard deviation	Specific gravity[b] Mean	Specific gravity[b] Standard deviation
		(%)		(in.)					
Douglas-fir — larch	362	10 9	1 6	5 49	0 06	1 50	0 02	0 57	0 05
Southern pine	219	10 2	1 7	5 49	08	1 3 9	03	65	06
Hem-fir	110	10 3	1 6	5 48	06	1 5 1	02	49	04

[a]By resistance moisture meter
[b]Based on calculated dry weight and on test volume

TABLE 2 - *Summary of average mechanical properties*

Species	Sample size	Tensile strength Range	Tensile strength Mean	Tensile strength Standard deviation	Tensile strength Coefficient of variation	Modulus of elasticity" Range	Modulus of elasticity" Mean	Modulus of elasticity" Standard deviation	Modulus of elasticity" Coefficient of variation
		(psi)			(%)	(million psi)			(%)
Douglas-fir – larch	362	2,180-14,690	7,590	2,260	29.8	136-359	243	0.41	17.0
Southern pine	219	4,460-16,060	10,160	2,250	22.2	152-329	238	38	15.9
Hem-fir	110	3,550-13,440	8,160	1,840	22.6	134-295	203	32	15.6

'Dynamic modulus of elasticity from E-computer.

TABLE 3. - *Summary of distribution estimates of mechanical properties.*

Sample size	Statistical distribution	Tensile strength 50th percentile	Tensile strength Standard deviation	Tensile strength 5th percentile	Tensile strength 75% tolerance limit, 5th percentile	Tensile strength 95% confidence interval, 5th percentile Lower	Tensile strength 95% confidence interval, 5th percentile Upper	Modulus of elasticity 50th percentile	Modulus of elasticity Standard deviation	Modulus of elasticity 95% confidence interval, 50th percentile Lower	Modulus of elasticity 95% confidence interval, 50th percentile Upper
		(psi)						(million psi)			
					DOUGLAS-FIR - LARCH						
362	Weibull	7,480	–	4,020	3,930	3,780	4,250	2.44	–	2.39	2.49
	Nonparametric	7,330	–	4,370	4,210	3,720	4,680	2.43	–	2.39	2.49
	Lognormal	7.260	–	4.390	4.310	4.180	4.610	2.40	–	2.35	2.45
	Normal	7,590	2,260	3,870	3,740	3,510	4,240	2.43	0.41	2.39	2 48
					SOUTHERN PINE						
219	Weibull	10,240	–	6,330	6,150	5,820	6,840	2.38	–	2.32	2.44
	Nonparametric	10,320	–	6,020	5,670	5,100	6,710	2.38	–	2.33	2.43
	Lognormal	9,880	–	6,620	6,500	6,290	6,960	2.35	–	2.29	2.40
	Normal	10,160	2,250	6,440	6,280	5,980	6,910	2.38	.38	2.32	2.43
					HEM-FIR						
110	Weibull	8,140	–	5,130	4,970	4,680	5,580	2.02	–	1.95	2.09
	Nonparametric	8,250	–	5,390	4,970	3,550	5,610	2.02	–	1.93	2.10
	Lognormal	7,950	–	5,370	5,230	5,010	5,750	2.00	–	1.94	2.07
	Normal	8,160	1,840	5,130	4,930	4,590	5,660	2.03	.32	1.96	2.09

that seemed to be related to variation due to size of plant. Both MOE and SG varied significantly by plant. The size of plant, however, did not produce any consistent results for MOE and SG, and can be ignored.

Neither the hem-fir tensile strength or SG data varied significantly by plant, visit, or size of plant. However, there was an indication of a possible visit effect on SG ($p = 0.0730$). MOE only varied significantly by visit, but that was a highly significant visit effect ($p = 0.0001$).

As these analysis-of-variance results show, there is some indication of a fair amount of variation from visit to visit and plant to plant, but no real variation due to size of plant. Therefore, it would probably be best to use several plants and several visits for the collection of samples in future studies.

Regression analysis. – Correlations between tensile strength and MOE, tensile strength and SG, and tensile strength and both MOE and SG were found to be low, with r^2 values generally less than 0.20. This does not mean, however, that there is a lack of overall correlation between those values. Rather, these low correlations are probably due to the relatively narrow ranges of MOE, SG, and tensile strength because of the high quality of the test specimens. MOE and modulus of rupture (MOR) relationships used in establishing machine stress rated (MSR) grades were determined from a range of grades and, therefore, have a much wider range of MOE values.

Distributional values

Estimates of distributional properties for tensile strength and MOE are given in Table 3. Four different methods of estimation were explored. Estimates, where a distributional form is assumed, were produced using the normal, two-parameter lognormal, and three-parameter Weibull distributions. In addition, nonparametric estimates that do not assume a distributional form of the data were produced.

Table 3 lists results of the four methods in decreasing order concerning visual goodness of fit for tensile strength. The Weibull and nonparametric estimates appear to be the best for the tensile strength data; the Weibull estimates generally fit the data well, while the non-parametric estimates were less affected by some of the data peculiarities such as outliers or bimodal data sets. The lognormal distribution fit only the tensile strength distribution for the on-grade Douglas-fir - larch data well because it was the only right-skewed data set. The normal distribution did not fit any of the tensile strength distributions well because none of them were symmetric.

If one distributional form had to be chosen as the best, it would probably be the Weibull distribution. In addition to generally fitting the tensile strength distributions well or being slightly conservative, the Weibull distribution provides information on the whole distribution. The Weibull distribution was also visually found to be a good fit for all of the MOE distributions. For these reasons, three-parameter Weibull estimates for the tensile strength and MOE distributions are given in Table 4 and should prove useful to future research. Figure 1 shows the resulting Weibull distribution overlaid on the histogram generated from the Douglas-fir - larch tensile strength data. The figure shows that the estimated Weibull distribution has a good overall fit with the actual data. Similar fits were found for the Douglas-fir - larch MOE data as well as for the southern pine and hem-fir tensile strength and MOE data.

Comparisons

Species. – Figure 2 compares the tensile strength three-parameter Weibull distributions fitted for the Douglas-fir – larch, southern pine, and hem-fir on-grade samples. Figure 3 compares their actual cumulative distribution functions for tensile strength. Both Figures 2 and 3 show that the three species have significantly different tensile strength distributions. As will be discussed in more detail later, both the southern pine and hem-fir specimens were of high quality compared to the Douglas-fir - larch specimens, even though it was judged that the majority of specimens for all three species were of a quality similar to that actually being used in the manufacture of glulam beams.

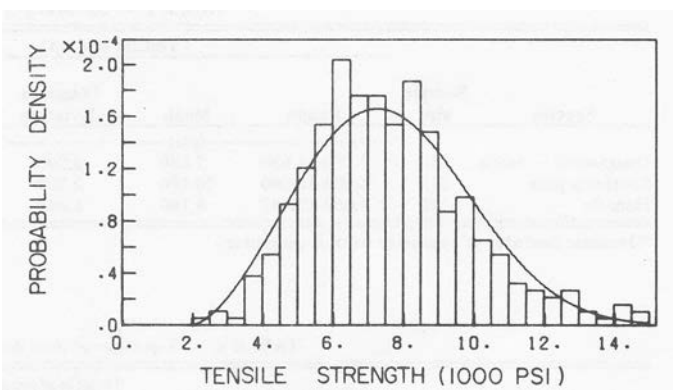

Figure 1. – The fitted three-parameter Weibull distribution is shown over the histogram of the on-grade Douglas-fir – larch tensile strength data.

TABLE 4. — *Three-parameter Weibull estimates of mechanical properties.*

Species	Sample size	Tensile strength			Modulus of elasticity		
		Shape	Scale	Location	Shape	Scale	Location
			(psi)			(million psi)	
Douglas-fir - larch	362	2.654	6,353	1,942	3.781	1.554	1.029
Southern pine	219	4.411	9,536	1,464	3.598	1.339	1.172
Hem-fir	110	3.286	6,159	2,635	2.908	.939	1.188

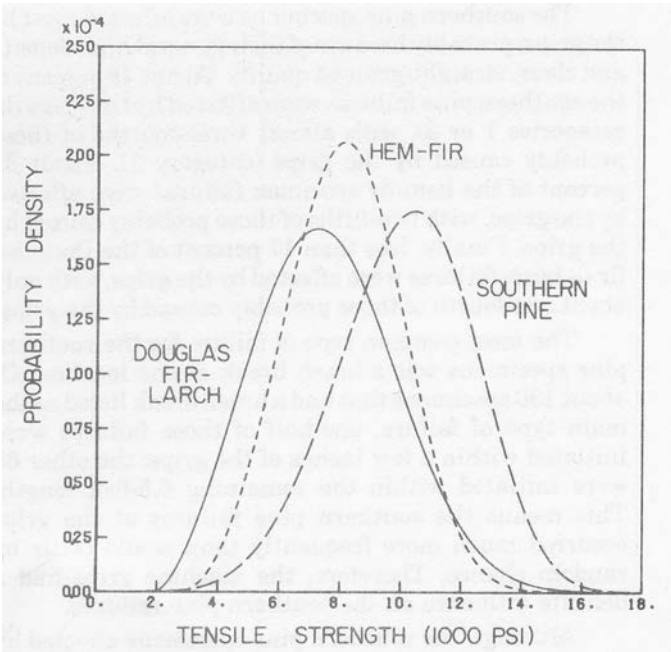

Figure 2. – Comparison of the tensile strength of the on-grade Douglas-fir – larch, southern pine, and hem-fir samples using the fitted three-parameter Weibull distributions.

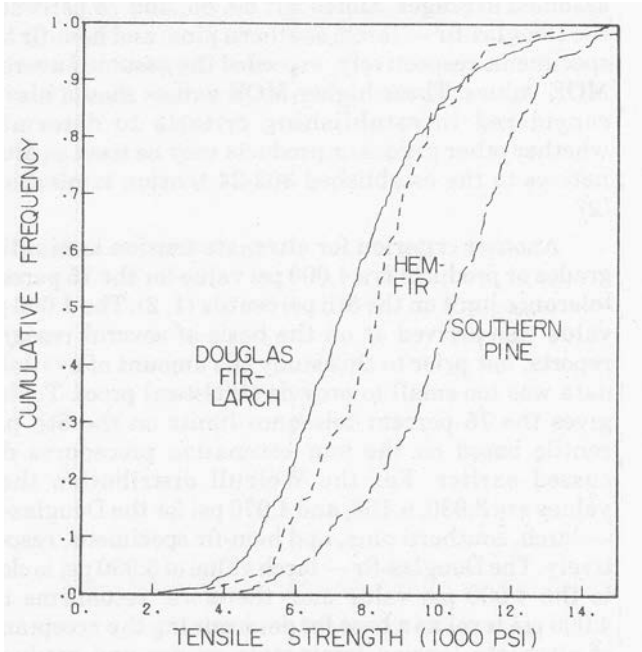

Figure 3. – Comparison of the tensile strength cumulative distribution functions of the on-grade Douglas-fir – larch, southern pine, and hem-fir samples.

Figure 4 compares the actual MOE cumulative distribution functions for Douglas-fir - larch, southern pine, and hem-fir on-grade samples; Douglas-fir - larch and southern pine specimens were approximately the same for the entire distribution and noticeably above the hem-fir specimens.

Duncan's multiple range test (α = 0.05) was used to test for differences between the mean tensile strength, MOE, and SG values of the three species. The tests revealed significant differences between all three species for tensile strength and SG. The Douglas-fir - larch and southern pine MOEs, however, were not shown to be significantly different.

End-joint strengths. – It should be remembered that these tests were done on unjointed lumber. In reality, most material used in glulam beams needs to be end jointed to provide longer laminations. The average strength of well-made end joints in relatively clear, dense material is about 6,000 psi.[1] The cumulative distribution functions in Figure 3 show that 75, 95, and 85 percent of the on-grade Douglas-fir – larch, southern pine, and hem-fir specimens, respectively, exceeded the 6,000 psi average value. This implies that if the material used in this study were end jointed and then tested, the end joints instead of the test material would be the cause of failure in the majority of instances.

Previously assumed values. – The MOE of tension laminations for the species tested in this study are assumed to be the same as for L1 Douglas-fir – larch, No. 1D southern pine, and L1D hem-fir when using the

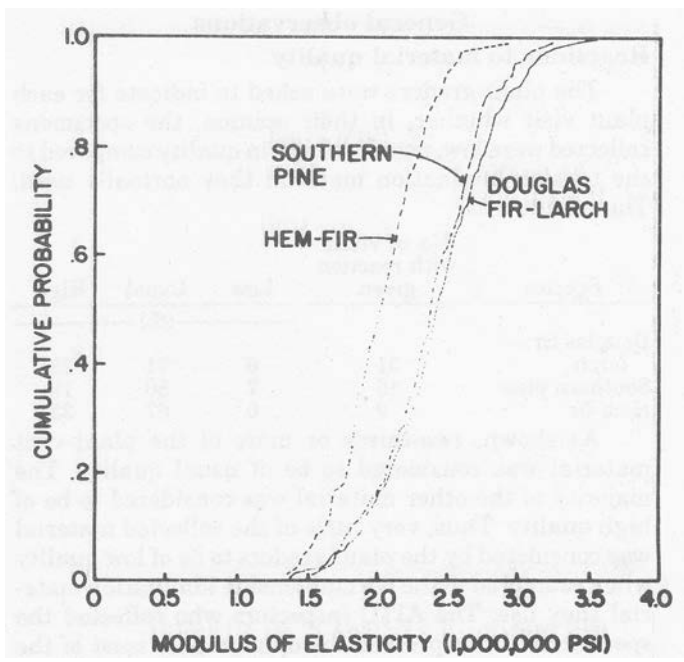

Figure 4. - Comparison of the modulus of elasticity cumulative distribution functions of on-grade Douglas-fir - larch, southern pine, and hem-fir samples.

I_K/I_G concept to predict bending design stresses. Those assumed average MOE values are 2.1, 2.0, and 1.8 million psi, respectively. The test MOE averages (Table 2) were between 13 and 19 percent higher than those

[1]Jack Minneci, AITC, private communication.

assumed averages. Moreover, 80, 85, and 75 percent of the Douglas-fir – larch, southern pine, and hem-fir test specimens, respectively, exceeded the assumed average MOE values. These higher MOE values should also be considered in establishing criteria to determine whether other grades or products may be used as alternatives to the established 302-24 tension laminations (2).

Another criterion for alternate tension lamination grades or products is a 4,000 psi value for the 75 percent tolerance limit on the 5th percentile (1, 2). The 4,000 psi value was arrived at on the basis of several research reports, but prior to this study the amount of available data was too small to provide statistical proof. Table 3 gives the 75 percent tolerance limits on the 5th percentile based on the four estimation procedures discussed earlier. For the Weibull distribution these values are 3,930, 6,150, and 4,970 psi for the Douglas-fir - larch, southern pine, and hem-fir specimens, respectively. The Douglas-fir - larch value of 3,930 psi is close to the 4,000 psi value and, therefore, reconfirms the 4,000 psi level as a base for determining the acceptance of alternate tension lamination grades and products. The southern pine and hem-fir values of 6,150 and 4,970 psi, respectively, are significantly above the 4,000 psi value. However, it may not be possible to actually obtain those higher values once the strength of end joints is considered.

General observations

Reactions to material quality

The plant graders were asked to indicate for each plant visit whether, in their opinion, the specimens collected were low, usual, or high in quality compared to the tension lamination material they normally used. The results are:

Species	No. of visits with reaction given	Low	Usual	High
		----------(%)----------		
Douglas-fir – larch	31	6	71	23
Southern pine	15	7	80	13
Hem-fir	9	0	67	33

As shown, two-thirds or more of the plant-visit material was considered to be of usual quality. The majority of the other material was considered to be of high quality. Thus, very little of the collected material was considered by the plant graders to be of low quality when compared to the normal tension lamination material they use. The AITC inspectors who collected the specimens also expressed the opinion that most of the material collected was of a quality typically used for the manufacture of glulam beams.

Grips

The tension-machine grips were observed to affect a significant number of the specimen failures. In an attempt to quantify the number of specimen failures affected by the grips, failures for the on-grade specimens were classified into one of three categories: 1) the grips probably caused failure, 2) the grips may have influenced or caused failure, and 3) the grips had no effect on the failure.

The southern pine specimens were affected most by the grips, probably because of their general high density and clear, straight-grained quality. About 42 percent of the southern pine failures were affected by the grips (in categories 1 or 2), with almost three-fourths of those probably caused by the grips (category 1). About 32 percent of the hem-fir specimen failures were affected by the grips, with two-fifths of those probably caused by the grips. Finally, less than 17 percent of the Douglas-fir – larch failures were affected by the grips, with only about one-fourth of those probably caused by the grips.

The most common type of failure for the southern pine specimens was a brash break at one location. Of about 130 specimens that had a brash break listed as the main type of failure, one-half of those failures were initiated within a few inches of the grips: the other 65 were initiated within the remaining 6.5-foot length. This means the southern pine failures at the grips occurred much more frequently than would occur by random chance. Therefore, the machine grips had a definite influence on the southern pine failures.

Although the southern pine specimens affected by the grips were scattered throughout the tensile strength distribution, there were more at the higher strengths. It is not known how much of an adverse effect the grips had on the southern pine tensile strength distribution. Grips have also been cited as a problem in other tensile strength studies of high-quality southern pine specimens tested with different machines (e.g., 11, 12).

Conclusions

This report evaluates tensile strength data of AITC 302-24 grade tension laminations. The results provide some of the most important information necessary for input into existing computer simulation models predicting strength and stiffness distributions of glulam timbers. The results will also be useful in providing a baseline for the determination of acceptable alternate tension lamination grades and products. The data substantiated the near-minimum value of 4,000 psi currently used as one baseline criterion.

The resulting tensile strength distribution of the Douglas-fir - larch data was in the range expected, but the tensile strength distributions for the southern pine and hem-fir data were higher than expected. At those high lumber strengths, the strengths of end joints could become the controlling factor. The average MOE values obtained were significantly higher than those currently assumed in designing glulam combinations.

The sampling plans in future studies should include several plants and visits, if possible.

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Appendix A - 302-24 grading requirements

In addition to the basic requirements of the grades tabulated in AITC 117, the following criteria apply to 302-24 tension laminations (1):

1. A 1-foot length of a lamination is considered as a cross section.

2. Knots are limited to one-fifth (20%) of a cross section.

3. Each cross section must have at least two-thirds clear wood free of strength-reducing characteristics such as knots and/or grain deviation with a slope of grain steeper than 1:16.

4. Maximum-size single strength-reducing characteristics must be at least 2 feet apart measured center-to-center when they are not in the same horizontal projection.

5. The general slope of grain can not exceed 1:16; however, more restrictive slope of grain may be required for some laminating combinations.

6. The tension laminations must have near average or above average specific gravity for the species; in addition, Douglas-fir - larch and southern pine tension laminations are required to be visually dense for the full length of the piece.

7. Wide-ringed or lightweight pith-associated wood at the ends of the piece cannot exceed one-eighth of the cross section.

Appendix B - "As-graded" samples

The "on-grade" samples consisted of all the test specimens except those marked as misgraded. The "as-graded samples consisted of all the test specimens except those marked as the extra on-grade specimens. Thus, the as-graded samples represented the specimens that were first selected from the available plant 302-24 inventories. It should be noted that the vast majority of pieces in both the on-grade and as-graded samples are the same.

Judgment of specimen quality

Information on specimens that were misgraded and reasons why they were misgraded were obtained when the specimens were collected. Of the 530 Douglas-fir – larch specimens originally planned for this study, about 20 percent were judged to be misgraded. The misgrading reason was recorded for 90 of those 112 specimens. Of those 90 specimens, 40 percent were misgraded because they did not meet the 302-24 weight and/or visual density requirements. An additional 25 percent of those 90 pieces were misgraded because of excessive knot(s) and/or grain deviation, while the remaining misgraded Douglas-fir – larch specimens had excessive slope of grain, or were misgraded for miscellaneous reasons such as wormholes or white speck.

By contrast, only 5 percent or less of the 220 southern pine specimens or the 110 hem-fir specimens were judged to be misgraded. Of those, none were misgraded because they were nondense. Instead, 50 percent of those southern pine pieces and 75 percent of those hem-fir pieces were misgraded because of excessive knot(s) and/or grain deviation.

Thus, more of the Douglas-fir – larch specimens were misgraded due to being nondense, while more of the southern pine and hem-fir specimens were misgraded due to excessive knots and/or grain deviation.

Lower tail specimens

Of 35 as-graded Douglas-fir – larch specimens with tensile strength values below 4,400 psi, 15 (43%) of them had been marked as misgraded. Thus, current visual-grading criteria can be effective in identifying material that will have tensile strength values in the lower tail of the overall distribution. A reason for the misgrading was recorded for 13 of the 15 specimens marked as misgraded. Of those 13 specimens, over one-half had excessive knot or knot-plus-grain deviation size given as the reason for the misgrading. This seems to imply that knot and grain deviation size is more important than density because the number of Douglas-fir – larch specimens misgraded for density exceeded those for any other reason as just discussed. However, it must be remembered that only unjointed material was tested in this study, and density may have a greater effect on end-joint strength. None of 10 southern pine specimens below 6,000 psi were marked as misgraded, and only 1 of 8 hem-fir specimens below 5,500 psi was marked as misgraded.

Comparison of on-grade and as-graded samples

There were virtually no differences between the on-grade and as-graded samples for southern pine and hem-fir because few misgraded pieces were encountered in the sampling process. Although there was a difference between the on-grade and as-graded Douglas-fir – larch samples because of the greater percentage of misgraded specimens, that difference was not statistically significant. This does not imply that misgraded pieces have the same strength as on-grade pieces.

Summary

These as-graded results suggest that it would probably not be worthwhile in future studies to continue collecting both the misgraded specimens as well as the extra on-grade specimens. Instead, it would probably be better to collect only on-grade specimens, but to also keep track of the number and quality of the misgraded pieces encountered in the sampling process.