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Yellow Poplar Glulam Timber Beam Performance

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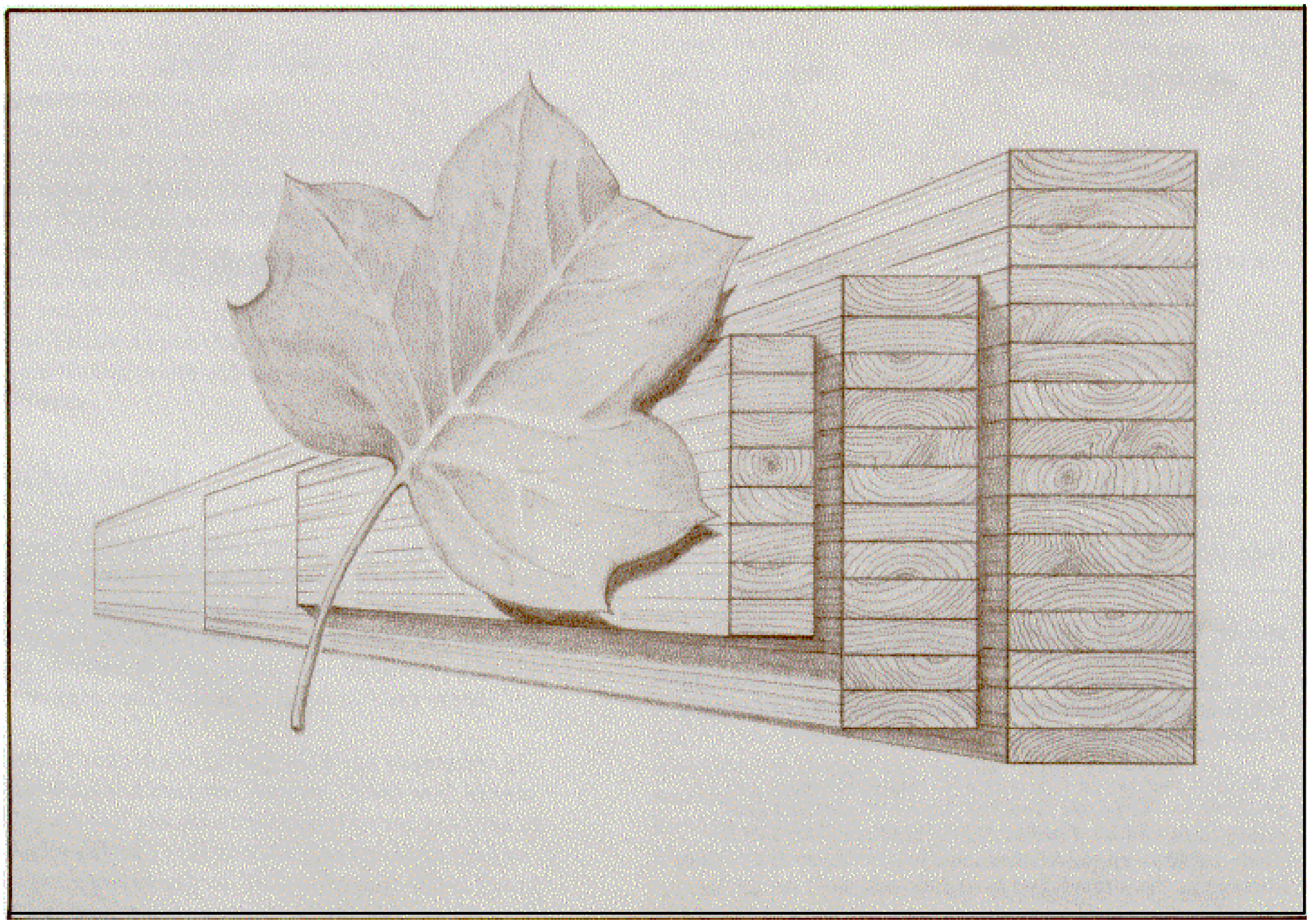

Abstract

Yellow Poplar is currently not used in structural glued-laminated (glulam) timber construction, but its properties suggest that it may be feasible for this purpose. Using Yellow Poplar, we designed glulam beam combinations to target bending stresses of 2,400 lb/in^2 and modulus of elasticity of 1.8 × 10^6 lb/in^2. The glulam combinations were designed with E-rated lumber grades in 25 percent of the outer laminations (top and bottom) and No. 2 grade lumber in 50 percent of the center laminations. In addition to evaluating 45 full-sized beams, more than 200 end-jointed lumber specimens were tested in tension to compare individual specimen performance to full-size beam performance. Results for the Yellow Poplar glulam beams met the target design levels, indicating that this species is a feasible candidate for structural glulam construction.

Keywords: Laminated wood, hardwood, glulam, E-rated, Yellow Poplar, modeling

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Introduction

The economical and efficient use of timber in engineered structures, such as long-span roofs and bridges, is practical with structural glued-laminated (glulam) timber. Long-span glulam beams are needed for timber bridges of conventional deck-and-stringer design and stress-laminated systems consisting of T- and box-section design (Ritter 1990). Douglas Fir and Southern Pine lumber are primarily used for glulam timber; however, using an underutilized hardwood species, such as Yellow Poplar, would be advantageous. Yellow Poplar is abundant in areas of Virginia and West Virginia. These areas also have a need for several bridges in the span ranges obtainable with glulam timber. Thus, the use of Yellow Poplar for a value-added product such as glulam timber could enhance industrial development in these areas.

Table 1—SI conversion factors

English unit	Conversion factor	SI unit
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
board foot	0.002	cubic meter (m^3)
pound per cubic foot (lb/ft^3) (weight)	1.60	kilogram per cubic meter (kg/m^3)
ton (metric)	1,000	kilogram (kg)
pound per square inch (lb/in^2) (stress)	6.895	kilopascal (kPa)
pound-force (lbf)	4.448	newton (N)
degree Fahrenheit (°F)	$t_{°C} = \frac{t_{°F} - 32}{1.8}$	Celsius (°C)

Background

The use of Yellow Poplar veneer for manufacturing small laminated beams was investigated by researchers in Pennsylvania during World War II (Norton 1943, Nearn and Norton 1952). As expected, the mechanical properties of these laminated veneer lumber (LVL) beams were comparable to those of clear wood.

Several studies have investigated the properties of Yellow Poplar structural lumber. Koch and Rousis (1977) studied the effectiveness of using modulus of elasticity (MOE) and specific gravity as predictors of the bending strength of Yellow Poplar. They found that for clear wood samples, MOE and specific gravity exhibited good correlation with strength properties; however, the strength properties of clear wood samples were not useful for predicting the strength of lumber containing defects, such as knots, checks, and shakes. Based on the experimental work performed by Maeglin (1978), Gerhards (1983) studied the effect of high-temperature drying on the bending strength of nominal 2- by 4-m. (2 by 4) Yellow Poplar. (See Table 1 for metric conversions.) Gerhard's study showed that 2 by 4's processed with high-temperature drying have negligibly lower bending strength than lumber produced by conventional sawing and drying. Also, he found that machine grading could be applicable to Yellow Poplar because of the high correlation between MOE and modulus of rupture (MOR). Stern and Dunmire (1972) conducted an extensive study on strength properties of Yellow Poplar. They observed that strength properties increased with increases in specific gravity and decreased with rapid rates of growth.

Green and Evans (1987) evaluated Yellow Poplar as part of the In-Grade Lumber Testing Program. Table 2 gives a comparison of the bending and tensile strength properties of visually graded Yellow Poplar and Southern Pine lumber from that study. Table 2 also compares bending and tensile design properties from the National Design Specification (NDS) for the same grades and species of lumber (NFPA 1991). Bending strength of Select Structural Yellow Poplar lumber was up to 15 percent lower than that of Southern Pine lumber, whereas tensile strength was comparable for the same grade. However, No. 2 Yellow Poplar was comparable in bending strength and significantly greater in tensile strength than was the same grade of Southern Pine. These data are not consistent with design property information from NDS in which Yellow Poplar is assigned much lower design stresses in both bending and tension, either about 50 percent (Select Structural) or 70 percent (No. 2) of Southern Pine.

Table 3 compares the MOE of Yellow Poplar and Southern Pine lumber. Test results and the NDS agree that the Select Structural Yellow Poplar/Southern Pine ratio is 0.83. The MOE ratio from tests on No. 2 Yellow Poplar/Southern Pine is about 0.89 and 0.95, but NDS gives a lower ratio of 0.81.

Data in Tables 2 and 3 suggest that NDS procedures used to develop the design properties of Yellow Poplar may be quite conservative and that much of the material would be underutilized using present design values, particularly the No. 2 grade lumber. The current approach to developing design values for Yellow Poplar is understandable, because the sample size of Yellow Poplar lumber (Green and Evans 1987) was less than that for Southern Pine and there has been little experience with Yellow Poplar in engineered structural applications.

Freas and Selbo (1954) published basic property information for Yellow Poplar from which design properties for glulam timber could be developed. The property information was based on clear wood data without actual tests of Yellow Poplar glulam timber beams. Since then, Yellow Poplar has been included in various specifications for hardwood glulam timber, most recently in AITC 119 (1985). In AITC 119, design stresses in bending are limited to 1,600 lb/in^2 for beams made from high-grade lumber, and MOE for these beams is limited to 1.5×10^6 lb/in^2.

Test data are not available on the strength of glulam timber beams made of Yellow Poplar lumber. The literature on mechanical properties of visually graded Yellow Poplar suggests that it may be underrated in strength and stiffness properties. The potential use of Yellow Poplar in glulam timber needs careful

Table 2—Average bending and tensile strength properties of Yellow Poplar and Southern Pine lumber (adjusted to 15 percent moisture content)

		Strength (lb/in^2)		Yellow Poplar/ Southern Pine ratio
Property and grade	Size (in.)	Yellow Poplar	Southern Pine	
Bending [a]				
Select Structural	2 by 4	9,180	10,920	0.84
No. 2		8,030	7,540	1.06
Select Structural	2 by 8	8,040	8,720	0.92
No. 2		6,310	6,220	1.01
Tensile [a]				
Select Structural	2 by 4	6,760	6,560	1.03
No. 2		4,950	3,380	1.46
Design bending [b]				
Select Structural	2 by 4	1,500	2,850	0.53
No. 2		1,050	1,500	0.70
Select Structural	2 by 8	1,200	2,300	0.52
No. 2		840	1,200	0.70
Design tensile [b]				
Select Structural	2 by 4	863	1,600	0.54
No. 2		600	825	0.73
Select Structural	2 by 8	690	1,300	0.53
No. 2		480	675	0.71

[a] Green and Evans 1987.
[b] NFPA 1991.

Table 3—Average MOE of Yellow Poplar and Southern Pine lumber (adjusted to 15 percent moisture content)

		Strength (lb/in^2)		Yellow Poplar/ Southern Pine ratio
Property and grade	Size (in.)	Yellow Poplar	Southern Pine	
MOE [a]				
Select Structural	2 by 4	1.50	1.82	0.82
No. 2	2 by 4	1.45	1.53	0.95
Select Structural	2 by 8	1.58	1.89	0.84
No. 2	2 by 8	1.43	1.60	0.89
Design MOE [b]				
Select Structural	All	1.50	1.80	0.83
No. 2	All	1.30	1.60	0.81

[a] Green and Evans 1987.
[b] NFPA 1991.

evaluation, particularly with an alternative grading method such as E-rating that could improve the grading efficiency.

Objective and Scope

The objectives of this study were to develop and verify a basis for a specification for Yellow Poplar glulam timber. A total of 45 glulam timber beams were manufactured and evaluated. In addition, more than 200 end-jointed lumber specimens were tested in tension to compare individual specimen performance to full-size beam performance.

Experimental Design

Prior to procuring materials and manufacturing the glulam beam combinations for this study, it was necessary to determine the following factors for designing the targeted glulam combinations: minimum strength ratios, bending stress indices, knot properties, MOE levels of E-rated grades of lumber, potential yields of Yellow Poplar, and end-joint qualification levels.

To design the glulam beam combinations using present procedures, several assumptions were made to establish the minimum strength ratio, bending stress indices (clear wood stress), and knot properties. Minimum strength ratios of the candidate grades of Yellow Poplar were estimated from similar species of lumber listed in AITC 117 (1979). Bending stress indices for the proposed E-rated grades were those recommended by ASTM D3737 (1992a). Knot properties for each of the proposed grades of Yellow Poplar lumber were estimated using actual knot measurements obtained from a study on red maple lumber (Manbeck and others 1993).

In addition to strength ratios and knot information, ASTM D3737 procedures require using the average long-span static bending MOE values for each grade of lumber. This study used E-rated lumber in the beam layup. Thus, it was necessary to determine if the current resource of Yellow Poplar structural lumber would provide adequate yields of the desired E-rated grades. Previously noted studies on Yellow Poplar structural lumber were reviewed to determine potential yields. The issue of end-joint performance also needed to be addressed. Information on Yellow Poplar end-jointed lumber did not exist; therefore, it was necessary to determine its performance level.

Based on information from past research of Yellow Poplar lumber, it was estimated that a target glulam design bending stress of 2,000 lb/in^2 and MOE of 1.6 × 10^6 lb/in^2 could be achieved. However, after evaluating the stiffness of the lumber that was purchased for beam manufacture, we determined that the sample of lumber possessed significantly greater MOE levels than expected. Therefore, the target glulam design bending stress was increased to 2,400 lb/in^2 and the target MOE level increased to 1.8 × 10^6 lb/in^2. The lumber properties in Table 4 were used to develop a new glulam beam combination.

Table 4—Assumed properties of Yellow Poplar lumber grades for ASTM D3737 procedures

Grade	MOE (×10^6 lb/in^2)	Average knot (%)	Maximum knot (%)	Bending stress index (lb/in^2)
2.0-1/6	2.0	3.0	27.0	3,250
2.0-1/3	2.0	5.0	30.0	3,250
1.8-1/3	1.8	5.0	30.0	2,850
No. 2	1.5	8.0	42.0	1,910

To determine if Yellow Poplar end joints would meet ANSI A190.1 (1992) criteria for design bending stresses of 2,400 lb/in^2, samples of 2 by 4 and 2- by 6-in. (2 by 6) lumber were gathered for tension tests. The end joints were manufactured from clear Yellow Poplar lumber at the laminating plant selected for beam manufacture. Although all end-joint specimens were clear, some did not meet tension lamination criteria as a result of slope-of-grain limitations. Most failures exhibited high overall wood failure, and apparent problems were not observed with the glue bonds. On several specimens showing a high percentage of wood failure, we observed that the mineral-stained characteristics of the Yellow Poplar lumber were involved in the failure. The results in Table 5 show that both 2 by 4 and 2 by 6 end joints would meet ANSI A190.1 tensile strength requirements, even with the slope-of-grain material included in the analysis. Therefore, the targeted design levels of 2,400 lb/in^2 bending stress and 1.8 × 10^6 lb/in^2 MOE appeared to be reasonable.

Three beam combinations were designed to represent critical beam sizes with small, medium, and large dimensions (Fig. 1). The smallest had 8 laminations with dimensions of 3 in. wide by 11 in. deep by 20 ft long; the medium had 12 laminations with dimensions of 5 in. wide by 16.5 in. deep by 30 ft long; the largest had 17 laminations with dimensions of 6.75 in. wide by 23.375 in. deep by 40 ft long. The three beam sizes were manufactured using nominal 2 by 4, 2 by 6, and 2- by 8-in. (2 by 8) lumber, respectively.

These glulam combinations were designed with E-rated lumber in the outer and adjacent inner zones and visually graded lumber in the core. Specifically, the beams

Table 5—Results of tension tests on independent sample of Yellow Poplar end joints [a]

Property	2 by 4	2 by 6
Sample size	23	26
Moisture content (%)	11.1	12.0
Specific gravity	0.47	0.45
Lognormal distribution		
Average tensile strength (TS) (lb/in^2)	7,020	7,080
Coefficient of variation of TS (%)	19.3	13.4
$TS_{0.05}$ at 75% tolerance	4,680	5,390

[a] Failures not associated with the end joints were not included in the analysis.

contained 2.0E material in the outer zones, 1.8E material in the adjacent inner zones, and No. 2 material in the core laminations. Lumber used for the two zones on the compression side of the beams and for the next inner zone on the tension side had a knot limitation of one-third the cross section along the edge. Consequently, the 2.0E material (on the compression side) was designated as 2.0-1/3, and the 1.8E material was designated as 1.8-1/3. These two grades represent No. 2 or better lumber. Lumber in the outer tension zone had an edge knot limitation of one-sixth the cross section. This material was designated as 2.0-l/6. Special grades were developed for the outer 5 percent of the tension laminations following ASTM D3737, and criteria for these grades are given in Table 6.

For each beam size, a sample size of 15 beams was selected based on the criterion to be able to detect about a 10-percent significant difference in strength properties for each beam size with a 90-percent confidence level. Thus, a total of 45 beams were manufactured.

Materials and Methods

This section discusses procurement, sawing, yield, grading, and properties of Yellow Poplar lumber as well as fabrication of end joints and full-size beams.

Procurement

Logs were obtained from the southwestern part of West Virginia. The trees that were selected for cutting ranged in diameter from 12 to 24 in. at breast height. The trees varied from 25 years to more than 50 years old. The majority of the trees exhibited crook characteristics approximately 24 to 30 ft above the ground that were caused by inclement conditions such as snowfall and wind. Trees with these defects were a major component of those selected because procurement of a sufficient low-grade material was a major concern in this study.

Cant sawing was used to obtain the maximum possible yield from the available logs. Cant sawing is widely used for softwoods and structurally graded hardwoods. The objective of using this sawing method was to have the midsurface of each piece coincide with a line bisecting the log. It was observed that the 2 by 8's were less likely to warp than were the 2 by 4's and 2 by 6's.

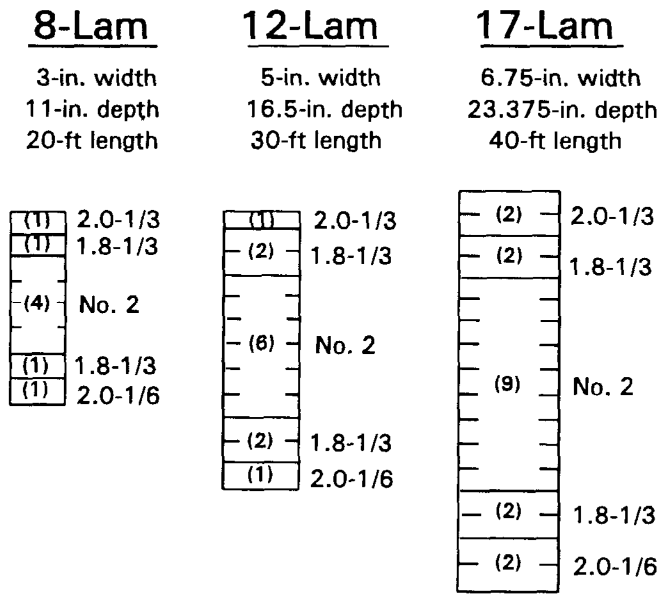


Figure 1--Yellow Poplar glulam combinations showing placement of lumber grades for the 8-. 12-. and 17-lamination beams.

Table 6—Tension lamination criteria required by ASTM [a]

Criterion	Beam group 8-Lam	Beam group 12-Lam	Beam group 17-Lam
Edge knot plus grain deviation	0.45	0.30	0.30
Center knot plus grain deviation	0.50	0.40	0.35
Slope of grain	1:14	1:16	1:16

[a] Knots plus grain deviations given in decimal parts of cross section (ASTM 1992a).

Table 7—Quantity of Yellow Poplar lumber in various grades and sizes

Nominal size (in.)	Board length (ft)	Lumber yield (board feet)									
		Select Structural		No. 1		No. 2		No. 3		Total	
		Sawn	Graded	Sawn	Graded	Sawn	Graded	Sawn	Graded	Sawn	Graded
2 by 4	16	1,056	963	528	510	1,108	1,038	327	298	3,019	2,809
	14	27	23	(a)	(a)	37	18	37	37	101	78
	12	126	124	221	203	380	332	95	89	846	748
	10	6	6	20	19	13	10	6	6	46	41
	8	137	130	195	185	153	143	73	66	570	528
2 by 6	16	2,032	1,924	1,568	1,518	2,768	2,584	562	536	6,930	6,562
	14	200	240	70	66	252	236	56	54	244	226
	12	540	518	660	640	1,980	1,820	360	340	3,408	3,196
	8	328	316	312	292	880	832	272	248	1,392	1,292
2 by 8	16	5,681	5,327	1,350	1,294	4,738	4,536	407	394	12,176	11,551
	14	337	311	93	85	581	557	168	150	1181	1,103
	12	1,993	1,902	675	651	3,762	3,589	1,013	925	7,445	7,131
	8	1,232	1,203	675	650	1,500	1,417	525	495	4,137	3,969

[a] No 14-ft-long specimens.

The total yield from logs was 46,500 board feet, each log ranging in length from 8 to 16 ft. The total volume of sawn lumber obtained from the logs was 41,495 board feet, a yield of 89.5 percent. The total volume of graded lumber obtained after trimming was 39,234 board feet, a yield of 94.6 percent. Quantities of sawn lumber for the various sizes and grades are summarized in Table 7.

Lumber Grades and Properties

The sawn lumber at the mill was visually graded into Select Structural, No. 1, No. 2, and No. 3 using nationally recognized grading rules (NELMA 1991).

Special care was taken to evaluate and control the lumber properties used in the beams. This was so that the final results of the beam tests would be meaningful when establishing a specification on Yellow Poplar glulam beams.

The grades listed in Table 4 needed to meet both the MOE criteria in AITC 117–Manufacturing (AITC 1988) and the edge-knot criteria established in lumber grading standards for E-rated grades. Therefore, during the testing for MOE, each piece of lumber was inspected and graded as a candidate for one of the four visually graded categories: tension lamination, 1/6 edge knot, 1/3 edge knot, and No. 2.

The MOE was determined using commercially available equipment, utilizing transverse vibration nondestructive techniques (Ross and others 1991). Long-span static bending deflection readings were taken at random throughout the testing to ensure that the transverse vibration equipment was properly calibrated. Figure 2 illustrates the relationship between static and dynamic MOE measurements. Because the difference between static and dynamic MOE was small, the actual dynamic MOE values were used, and data adjustments were not made. Dimensions of the lumber were measured using a standard tape measure, and moisture content levels were measured using a resistance-type moisture meter. Identification numbers were stamped on the narrow edge of each piece of lumber, such that the lumber specimens could easily be located following beam fabrication. In addition, measured MOE values were written on the ends of the lumber for later use when sorting. The sorting scheme used to achieve the target MOE distributions is described in Table 8.

To accurately analyze the beams for bending strength using ASTM D3737 procedures, knot sizes were measured for each grade of lumber after the lumber was sorted by MOE. Knot sizes were measured by estimating the diameter of an equivalent “straight-through” knot; this was done for all tension lamination material and for representative samples of the remaining grades of lumber. Analysis of the knot data was conducted using a program that followed the principles in Freas and Selbo (1954).

The results of lumber sorting to achieve the target MOE values are presented in Table 9. Only those lumber specimens that appeared in the fabricated beams are included in the averages. The results in

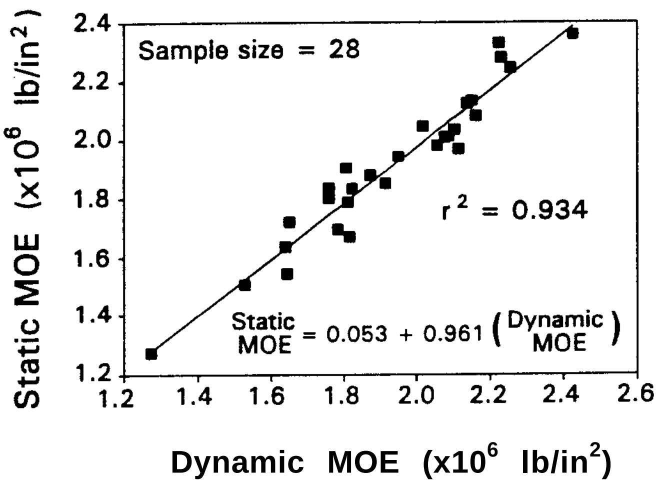


Figure 2—Relationship between dynamic MOE and static MOE.

Table 9 show that the target MOE level for each grade of lumber was generally achieved; an exception was the 1.8-1/3 grade for the 2 by 8's. The sorting of this grade resulted in a MOE level of 1.69 × 10^6 lb/in^2. Therefore, the static bending MOE results of the 17-lamination beams were expected to be slightly less than those of the 8- and 12-lamination beams.

The knot measurement information was transferred from prepared data sheets to a spreadsheet for subsequent analysis. Table 10 lists the results of the knot size calculations based on measurements from more than 6,000 lineal ft of lumber. These data were required as input for ASTM D3737 (1992a).

In addition to the three manufactured beam configurations (Fig. 1), specimens were prepared for end-jointed lumber tests. The location of each lumber piece within each beam was recorded on maps so that the lumber properties could later be related to beam performance. In addition, the quality of the critical tension laminations was assessed, in relation to the allowable knot and slope-of-grain properties, to determine the relative qualities of the beams.

Fabrication

The Yellow Poplar lumber was end-jointed using a melamine adhesive and cured in a radio-frequency tunnel at 200°F. The full-length laminations were then cut to length and stacked according to the designated beam layups. At this point, the location of each piece of lumber was recorded (using the numbers that were stamped on the narrow edge) on prepared beam maps. The beams were then visually inspected to ensure conformance to ANSI A190.1 and determine the relative qualities of the tension laminations in the midlength region that would be subjected to 85 percent or more of the maximum moment during testing. Using the tension lamination criteria listed in Table 6, a relative rating system was developed to categorically assign a quality to the tension lamination. Table 11 lists the allowable percentages of lumber cross-sectional areas that can be occupied by knots, the slope-of-grain limitations, and the MOE restrictions for a classification of low, medium, or high quality.

Table 8—Target MOE values and details of sorting scheme

Grade	Sorting and grading criteria
2.0–1/6	Average MOE of 2.0 to 2.1 × 10^6 lb/in^2 No MOE value <1.60 × 10^6 lb/in^2 5th percentile at 1.67 × 10^6 lb/in^2 No MOE value >2.4 × 10^6 lb/in^2 Edge-knot limitation, 1/6
2.0–1/3	MOE restrictions are the same as above; edge-knot limitation, 1/3
1.8–1/3	Average MOE of 1.8 to 1.9 × 10^6 lb/in^2 No MOE value <1.40 × 10^6 lb/in^2 5th percentile at 1.45 × 10^6 lb/in^2 No MOE value >2.2 × 10^6 lb/in^2 Edge-knot limitation, 1/3
No. 2	No MOE restrictions

Table 9—Results of testing and sorting scheme for MOE

Size and grade	Sample size	Average (×10^6 lb/in^2)	COV[a] (%)
2 by 4			
Tension lamination	23	2.01	7.8
2.0–1/3	24	1.99	7.6
1.8–1/3	65	1.80	9.5
No. 2	69	1.83	8.1
2 by 6			
Tension lamination	38	2.07	7.3
2.0–1/6	58	1.96	9.8
2.0–1/3	87	2.03	8.4
1.8–1/3	100	1.84	12.1
No. 2	185	1.88	10.7
2 by 8			
Tension lamination	54	2.02	9.4
2.0–1/6	53	2.01	8.8
2.0–1/3	106	2.02	9.1
1.8–1/3	225	1.69	11.8
No. 2	340	1.85	14.5

[a]COV = coefficient of variation.

Table 10—Knot properties of laminating lumber

Size and grade	Total length (ft)	$\bar{x}^a$ (%)	$\bar{x} + h^b$ (%)
2 by 4			
Tension lamination	404	0.8	20.6
2.0–1/3	294	0.3	13.5
1.8–1/3	630	1.5	32.4
All 1/3 edge knot	924	1.1	28.3
No. 2	441	3.0	49.5
2 by 6			
Tension lamination	501	0.5	12.6
2.0–1/6	463	2.2	29.1
2.0–1/3	168	5.0	45.6
1.8–1/3	191	4.1	33.0
All 1/3 edge knot	359	4.5	41.1
No. 2	178	6.6	42.5
2 by 8			
Tension lamination	691	1.1	25.9
2.0–1/6	451	1.9	21.0
2.0–1/3	492	4.0	42.4
1.8–1/3	615	5.3	40.3
All 1/3 edge knot	1,107	4.7	41.8
No. 2	574	6.6	45.4

[a] $\bar{x}$ = average of sum of all knot sizes within each 1-ft length, taken at 2-in. intervals (ASTM 1992a).
[b] $\bar{x} + h$ = 99.5 percentile knot size (ASTM 1992a).

The full-length laminations were then face-planed to a uniform thickness of 1.375 in. and laminated with a phenol–resorcinol adhesive. The full-sized beams were clamped at a pressure of 150 lb/in^2 and cured overnight at approximately 90°F. The cured beams were then edge-planed to uniform widths of 3, 5, and 6.75 in. for the 8-, 12-, and 17-lamination beams, respectively.

Another requirement in the development of a new glulam combination is the assurance that the end joints meet certain tensile strength levels. In this study, additional end-joint specimens from each lumber grade were gathered for subsequent tension tests. For both the 2 by 4's and 2 by 8's, end-jointed specimens were obtained during manufacture of the respective grades of lumber for the beams. A slightly different procedure was used for the 2 by 6 end-jointed specimens, as described in the following paragraph. The information obtained from these laboratory tests will aid in the performance comparison of the end-jointed specimens to the full-sized beams.

As stated, 2 by 6 end-jointed specimens were obtained differently than were the 2 by 4 and 2 by 8 end-jointed specimens. A matching group of tension lamination quality material was needed for a subsequent research study regarding preservative treatment of Yellow Poplar. The intent of this subsequent study was to obtain a test group treated and untreated of solid-sawn and end-jointed 2 by 6 lumber specimens. To obtain "matching" groups of solid-sawn lumber, the specimens were equally sorted by MOE into two matching groups: one group treated with preservatives and the other group untreated (control). Thirty specimens were gathered in each group such that the distribution of MOE for each was identical. To obtain "matching" groups of end-jointed specimens, two full-length boards were used to fabricate two end-jointed specimens by cutting one board in half (cross-cut) and joining the two halves to each end of the second full-length pieces. To obtain a range in quality in each test group, a range of MOE lumber pairs was used on each side of the end joint. For example, a low MOE board was end jointed to a high MOE board. Thirty end-jointed specimens were gathered for each test group such that identical distributions of MOE pairs were obtained.

Forty-five Yellow Poplar timber beams were manufactured and inspected to meet the requirements of AITC (1992). The percentages of beams that were categorized as having low-, medium-, or high-quality tension laminations are shown in Table 12. Additional details on the qualities of the individual tension laminations are provided in Appendix A.

End-jointed lumber samples obtained for the tension lamination grade are listed in Table 13, and the remaining grades are listed in Appendix A. A total of 254 specimens were gathered for all grades and widths.

Beam and End-Jointed Lumber

Testing equipment and procedures for evaluating the glulam beams and the end-jointed lumber specimens followed criteria in ASTM D198 (ASTM 1992b).

Beams

The loading configuration used to test the full-sized beams is illustrated in Figure 3. Physical properties (moisture content, weight, and dimension), stiffness properties (full-span deflection), and failure load were measured for each beam. Moisture content levels were measured with a resistance-type moisture meter at the central midspan of all laminations after failure of the beam. The weight of each beam was measured with a scale supported by a 10-t crane. Dimensions were measured at each load point.

Table 11—Relative rating system for tension lamination quality[a]

Beam group and criteria	Permitted values	Quality		
		Low	Medium	High
8-Lam				
EK + GD (%)	45	>30	15 to 30	<15
CK + GD (%)	50	>35	20 to 35	<20
Slope of grain	1:14	>1:16	1:16 to 1:18	>1:18
MOE ($\times 10^6$ lb/in^2)	2.0E (Avg)	<1.7E with characteristic	<1.7E and clear	
12-Lam				
EK + GD (%)	30	>20	10 to 20	<10
CK + GD (%)	40	>30	15 to 30	<15
Slope of grain	1:16	>1:18	1:18 to 1:20	>1:20
MOE ($\times 10^6$ lb/in^2)	2.0E (Avg)	<1.7E with characteristic	<1.7E and clear	
17-Lam				
EK + GD (%)	30	>20	10 to 20	<10
CK + GD (%)	35	>20	10 to 20	<10
Slope of grain	1:16	>1:18	1:18 to 1:20	>1:20
MOE ($\times 10^6$ lb/in^2)	2.0E (Avg)	<1.7E with characteristic	<1.7E and clear	

[a] EK = edge knot; CK = center knot; GD = grain deviation.

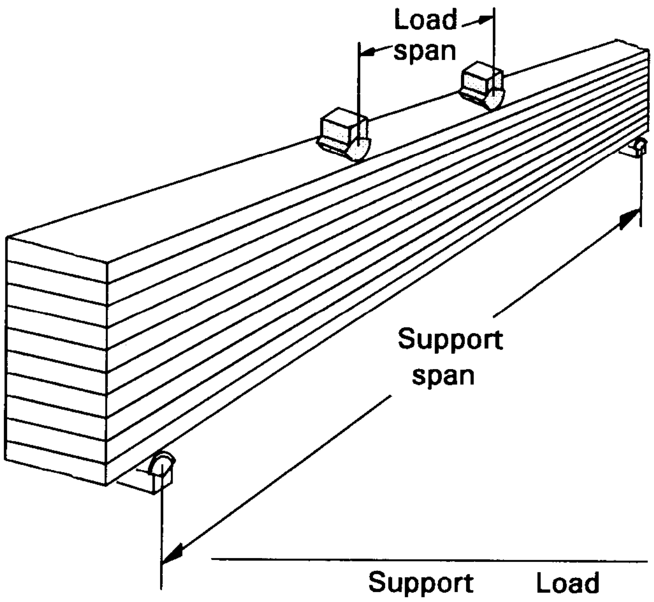
Table 12—Relative quality of tension laminations in midlength region of beams

Beam group[a]	Quality (%) Low	Medium	High
8-Lam	40	33	27
12-Lam	27	20	53
17-Lam	40	27	33

[a] 15 beams in each group.

Table 13—Results of tension tests on end-jointed Yellow Poplar tension lamination material (lognormal distribution)

Property	2 by 4	2 by 6	2 by 8	Combined
Sample size	29	30	30	89
Specific gravity	0.49	0.47	0.46	0.47
Moisture content (%)	8.8	9.9	9.1	9.3
Average tensile strength (lb/in^2)	6,770	7,050	5,220	6,160
COV tensile strength (%)	22.7	31.2	12.2	25.4
$X_{0.05}$ at 75% tolerance	4,230	3,640	4,100	3,840



	Support span (ft)	Load span (ft)
8-Lam	19	4
12-Lam	28.5	6
17-Lam	38	8

Figure 3—Loading configuration for full-size beam bending tests.

During application of load, beam deflections were measured using a precision ruler (0.02 in.) that was attached to the beam. Deflections were recorded at mid-depth with respect to a string line attached over each support. Preliminary tests were conducted by loading the beams within the design level to check for consistency in the rate of loading and deflection measurements. The readings were taken at specified load increments with the use of a surveyor's scope; this allowed the recorder to take readings to the nearest 0.01 in.

After the beams failed, detailed descriptions of the failure propagations were recorded, along with an assessment of the cause of failure (e.g., end joint, knot). Each beam failure was photographed for future reference. The MOR and MOE values were calculated using standard flexural formulas. Dead load stress was included in the MOR calculations. The MOE values were calculated based on the slope of the load-deflection curve determined by a regression of the readings up to design load.

End Joints

End-jointed lumber specimens from each grade and size were also evaluated. The test specimens were about 8 ft long with the end joint located near midspan. Prior to testing, specimens were face- and edge-planed to the same dimensions of the laminating lumber used

Table 14—Results of bending tests on glulam beams

Property	Laminations 8	12	17
Sample size	15	15	15
Moisture content (%)	8.2	7.5	8.0
Normal distribution			
Average MOR (1b/in^2)	8,050	7,560	6,560
COV of MOR (%)	16.8	15.9	17.8
$MOR_{0.05}$ 75th percentile	5,360	5,170	4,242
Average MOE ($\times 10^6$ lb/in^2)	1.89	1.94	1.79
COV of MOE (%)	4.45	3.25	3.35
Lognormal distribution			
Average MOR (lb/in^2)	8,060	7,560	6,570
COV of MOR (%)	17.3	16.1	18.0
$MOR_{0.05}$ 75th percentile	5,640	5,440	4,530

in the glulam beams and stored in a conditioning room. The specimens were stored for approximately 30 days in temperature and humidity conditions that equilibrated the moisture content level of the lumber to about 12 percent. The loading configuration for the end-jointed lumber tension tests was that specified by AITC T119 (1992); however, the time-to-failure was targeted at 5 to 10 min.

The specimens were tested to failure in tension according to the procedures in ASTM D198 (1992b), which specify a time-to-failure of approximately 5 to 10 min. Quality control practices for testing end joints would normally follow AITC 119 (1992), which specify a time-to-failure of 2 min. The end joints in this research project were tested according to ASTM D198 to correspond to the failure times of the full-sized beams. The unrestrained distance between the grips of the tension machine was 30 in., the minimum span of the machine. These data provided information to relate the performance of the individual end joints to that in the beams.

Strength and Stiffness

Bending test results on the beams are summarized in Table 14; individual end-joint results are given in Appendix B. Figure 4 compares the cumulative distribution function (CDF) of MOR for the 8-, 12-, and 17-lamination beams.

Beams

Most beam failures were catastrophic; localized failures emitted cracking sounds as the ultimate load was approached. Several beams exhibited compression wrinkling at or between the load points prior to

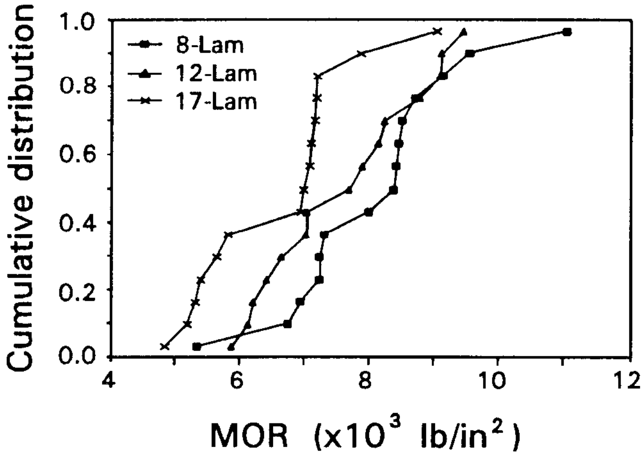


Figure 4—Empirical cumulative distribution function of MOR for Yellow Poplar glulam beams.

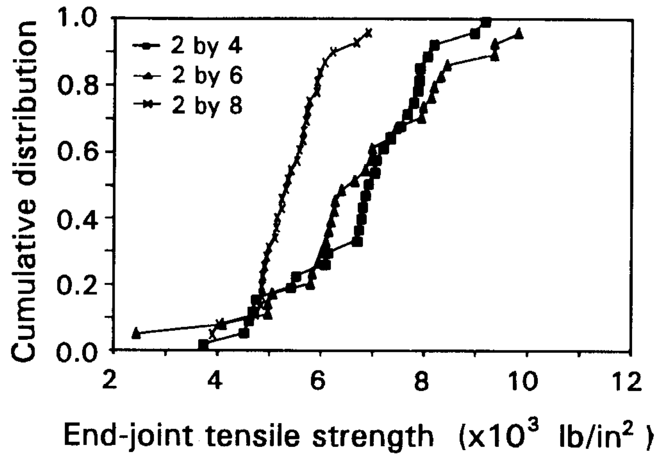


Figure 5—Empirical cumulative distribution function of tensile strength for end-jointed tension lamination lumber.

Table 15—Estimated initial cause of glulam beam failure

	Number of beam laminations		
Failure type	8	12	17
Compression followed by tension	1	3	3
Tension in strength-reducing characteristic	3	6	3
Tension in clear lumber	0	0	2
Tension in end joint	11	6	7

maximum load. All beams ruptured throughout the tension zone near or within the constant moment region. Although it was not possible to positively identify the initial point of failure for all beams, estimates were made of the triggering mechanism of the initial cause of failure. These results are summarized in Table 15. Detailed descriptions of beam failures are provided in Appendix B.

As expected, most beams failed through either an end joint or a strength-reducing characteristic (knot or grain deviation) in the highly stressed regions of the beams, and subsequently propagated through the slope-of-grain characteristics in the lumber. An abrupt or brash failure of the lumber was observed on some occasions in lumber possessing mineral-stain characteristics. This type of mineral stain failure was not associated with a marked weakness in either the beams or lumber. The failure of several beams propagated near gluelines with shallow failure, but this was not necessarily associated with low-strength beams and was not believed to be a cause of failure.

End Joints

Results of tension tests on the end-jointed tension lamination material are given in Table 13 and shown in Figure 5. Test results on the remaining grades of end joints (2.0–1/6, 2.0–1/3, 1.8–1/3, and No. 2) are in Appendix A.

Although a high percentage (>50 percent) of beam failures reported in Table 15 were due to end joints, this does not indicate that the end-joint quality was poor. The only requirement for end-joint performance is that the 5th percentile of tensile strength (75 percent tolerance) be at a qualification level that is 1.67 times the target design of the glulam beams (ANSI 1992). The desired qualification level for the end joints in this study was 1.67 × 2,400 lb/in^2, which is approximately 4,010 lb/in^2. The results in Table 13 show that the 2 by 4 and 2 by 8 end-jointed lumber met this criterion (4,230 and 4,100 lb/in^2, respectively), and the 2 by 6 results were slightly less than the target level (3,640 lb/in^2). Note that the variability of the 2 by 6 end-joint strength results (Table 13) was nearly twice that observed for the 2 by 4 and 2 by 8 results; this higher variability resulted in a lower calculated 5th percentile. Also, the average end-joint strength of the 2 by 6's was slightly greater than that of the 2 by 4's, which indicates that the 2 by 6 end joints performed at a level nearly equal to that of the 2 by 4 end joints (except for variability). It is suspected that the procedures used in manufacturing the 2 by 6 group to obtain "matched" sets with a range of qualities significantly influenced the variability of the test results. When all end-joint tensile strength results were combined, the qualification level equaled 3,840 lb/in^2, which was slightly less than the target of 4,010 lb/in^2, again being influenced by the variability of the 2 by 6 group. However, combining only the 2 by 4 and 2 by 8 groups gave a qualification level of 3,940 lb/in^2.

Analysis

Values of the 5th percentiles given in Tables 13 and 14 were calculated assuming both the normal and lognormal distributions. However, to conduct an analysis of the data, ASTM D3737 (1992a) recommends that a lognormal distribution be used. Therefore, the analysis conducted in this section assumes a lognormal distribution.

Beam Size

By evaluating three beam sizes, it was possible to study the effect of volume on the strength of Yellow Poplar glulam beams. Results indicated that the calculated bending strength values decreased as the beam volume increased (Table 14).

The following relationship has been used to account for the effect of varying beam size on strength for other species (Moody and others 1988):

$$(5.125/b)^{x}(12/d)^{y}(21/\ell)^{z} = C_{v} \qquad (1)$$

where

b = beam width (in.)

d = beam depth (in.)

ℓ = beam length (ft)

C_v = volume effect factor

and x, y, and z are exponents that determine the relative adjustments for width, depth, and length, respectively.

When width, depth, and length are combined to obtain volume, the following relationship is used in place of Equation (1) (assuming x = y = z).

$$(V_0/V)^{k} = C_{v} \qquad (2)$$

where

V_0 = standard volume (5.125 in. by 12 in. by 21 ft)

V = volume of actual beam (b by d by ℓ)

k = exponent that represents x = y = z

Results have shown that exponents of about x = y = z = 1/10 adequately explain the variation in strength for Douglas Fir glulam beams (Moody and others 1990). For red maple glulam beams (Manbeck and others 1993), an exponent of 0.071 was found. A volume effect equation by ASTM D07 adopted x = y = z = 1/10. In contrast, AITC adopted x = y = z = 1/10 for all species of glulam except Southern Pine, for which AITC adopted x = y = z = 1/20 (AITC 1991).

In our study, to determine the most appropriate method of accounting for variation in beam strength as a result of beam size, a confidence interval on the ratio of the beam sizes was conducted. First, the ratio between the volume effect factors of each beam size was determined using both 1/10 and 1/20. Next, the ratio between the averages of the various paired groupings of beams was determined along with a confidence interval using the procedures described by Wolfe and Moody (1978). Table 16 lists the results of this analysis. These results indicate that neither exponent can be rejected because predicted results using both exponents were within the confidence interval. When comparing the 17-lamination beams with the 8- and 12-lamination beams, the predicted results with 1/20 were at the edge of the confidence interval, whereas those with 1/10 were near the middle of the confidence interval.

Next, a regression analysis was conducted to determine the exponent that best fit all data. This exponent was 0.088 (1/11.4) and is shown with the bending strength data in Figure 6. This result agrees closely with the value of 0.071 (1/14.1) reported for red maple glulam timber (Manbeck and others 1993). In all further analysis, the exponent 0.088 was used to adjust data to a common size.

Design Levels

The strength level of all beams was adjusted to a standard beam size of 5-1/8 by 12 in. by 21 ft, using the best fit volume effect relationship (0.088 exponent). Then, results were pooled and analyzed to determine the appropriate design level using ASTM D2915 (1992c). A lognormal distribution was assumed, and the tolerance limit (75 percent confidence in 5th percentile) was adjusted by dividing by 2.1 to obtain the design level. Figure 7 shows that the data closely fit the assumed lognormal distribution. Results in Table 17 indicate that the calculated design level of 2,650 lb/in^2 exceeded the target level of 2,400 lb/in^2. Calculating each beam group individually, the resulting design level values were 2,520, 2,730, and 2,470 lb/in^2 for the 8-, 12-, and 17-lamination beams, respectively (also Table 18).

Table 14 shows that the average MOE of the 8- and 12-lamination beams exceeded the target level of 1.8×10^6 lb/in^2 (1.89 and 1.94×10^6 lb/in^2, respectively). Also, the 17-lamination beams averaged slightly less (1.79×10^6 lb/in^2) as a result of the low stiffness of the 1.8-1/3 grade (1.69×10^6 lb/in^2 (Table 9). However, all three beam sizes rounded to at least the target MOE level of 1.8×10^6 lb/in^2. As expected with

Table 16—Analysis of volume effect factor

Lamination comparison	Volume effect exponent		Mean MOR ratio
	x = y = z = 0.1	x = y = z = 0.05	Actual (90% confidence interval)
12 to 8	0.876	0.935	0.939 (0.841, 1.037)
17 to 8	0.798	0.893	0.815 (0.725, 0.905)
17 to 12	0.911	0.955	0.868 (0.772, 0.964)

Table 17—Glulam beam bending strength results adjusted to standard dimensions of 5-1/8 in. wide by 12 in. deep by 21 ft long

Beam group	Sample size	Average MOR (lb/in^2)	COV (%)	5th percentile (75% tolerance limit)	Adjusted 5% tolerance limit
8-Lam	15	8,060	17.3	5,640	2,520
12-Lam	15	7,560	16.1	5,440	2,730
17-Lam	15	6,560	18.0	4,530	2,470
All	45	7,680	18.0	5,570	2,650

the use of E-rated lumber in glulam, the variability of beam MOE was quite low (Table 14).

Comparison With Predicted Values

Strength

The actual lumber MOE values from Table 9, the actual knot properties from Table 10, and the tension lamination criteria from Table 6 were used to reanalyze the three glulam combinations shown in Figure 1 with ASTM D3737 (1992a) procedures. The reanalysis of the 8-, 12-, and 17-lamination combinations gave allowable design bending values for the glulam beams of 3,000, 2,600, and 2,600 lb/in^2, respectively, when compared to the allowable design bending values calculated from the actual beam tests of 2,520, 2,730, and 2,470 lb/in^2, respectively.

An additional comparison was made of the tensile strength performance of the tension lamination quality end joints. The 5th percentile results of each end-joint group (Table 13) were divided by the 1.67 qualification factor from ANSI A190.1 (1992) to determine the design level for each group. The results indicated that the joints would meet levels of 2,530, 2,180, and 2,460 lb/in^2 for the 2 by 4, 2 by 6, and 2 by 8 end-jointed lumber specimens, respectively. This analysis, in addition to the observations from Table 15, indicates that the beam performance levels were controlled by end-joint strength. Although the tensile strength of the 2 by 6 end joints did not meet the targeted 2,400 lb/in^2 (primarily as a result of high variability of the results, Table 13), the performance of the 12-lamination beams met a design level of 2,700 lb/in^2. Also, as previously discussed, the average performance of the 2 by 6 end joints was similar to that of the 2 by 4 end joints. Therefore, an argument could be made that the 2,150 lb/in^2 end-joint design qualification level for the 2 by 6 end joints would have been considerably greater if a variability problem had not been present. As previously discussed, the cause of the increased variability of the 2 by 6 tension lamination quality end-joint group was probably the method in which this group was gathered. It could also be argued that this sample group was not representative, but still within grade limitations, of the end joints used in the beams.

The analysis discussed in this section was compiled (Table 18) to closely inspect the relationship between actual and predicted beam performance and end-joint performance. Table 18 shows that for the 8- and 17-lamination beam groups, end-joint performance was the controlling factor of the predicted beam design levels. Also, the actual performance of these two beam groups was at the levels expected, equivalent to the design levels of the end joints. In contrast, for the 12-lamination group, ASTM D3737 predictions were slightly less

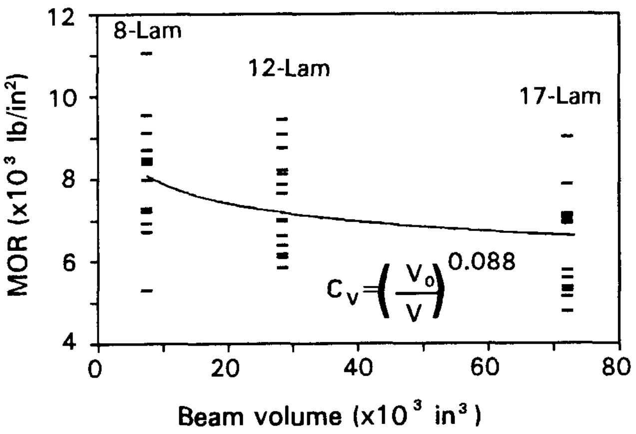


Figure 6—Variation in beam MOR with beam volume showing a line approximating an exponent of 0.088 for Equation (1).

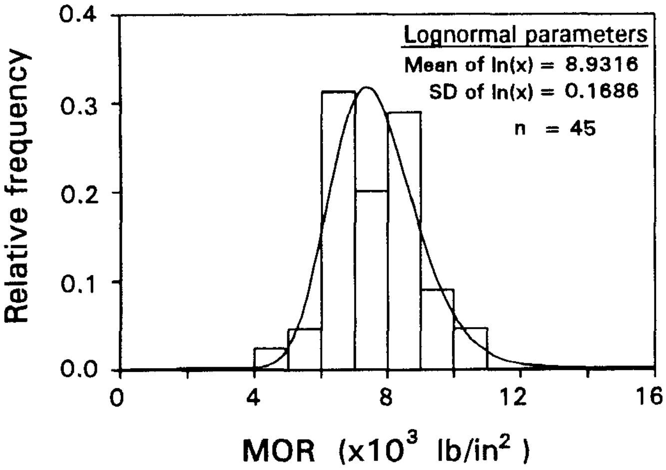


Figure 7—Histogram of MOR values adjusted to a standard beam size and compared to a fitted lognormal distribution.

(conservative) than the actual beam performance. The question remains as to the variability of the tested end joints. However, note that the mean tensile strength value of the 2 by 6 end joints was 7,050 lb/in^2, which was greater than the 6,770 lb/in^2 strength of the 2 by 4 end joints. If the 2 by 6 end-joint group had a coefficient of variation of 18 percent, keeping both the same sample size and mean, the resulting end-joint qualification level would be 2,800 lb/in^2, which is close

Table 18—Results of calculated design levels of full-sized glulam beams and end-jointed lumber

	Design level (lb/in^2)		
Beam group	Predicted[a]	End-joint qualification	Calculated[b]
8-Lam	3,000	2,530	2,520
12-Lam	2,600	2,180	2,730
17-Lam	2,600	2,460	2,470

[a] Using ASTM D3737.
[b] From actual tests.

to the beam performance of 2,730 lb/in^2. Although a firm conclusion cannot be made based on this hypothetical situation, this observation of the 2 by 6 end-joint group did not contradict expected results. Based on the reanalysis using actual lumber properties and the beam test results, it appears that ASTM D3737 and ANSI A190.1 procedures adequately established the performance of the Yellow Poplar glulam beams and end joints. Thus, both analyses justify a design bending stress of more than 2,400 lb/in^2.

Stiffness

Beam stiffness can be predicted by using the actual MOE values from the lumber used in beam manufacture and the transformed section method of ASTM D3737. The MOE values were predicted for each beam, and the results are shown in Figure 8. The 1:1 ratio line is included to show that the actual beam MOE values slightly exceeded the predicted values, and the horizontal line shows that the majority of the actual beam MOE values exceeded the targeted MOE level of 1.8×10^6 lb/in^2. In addition to analyzing beam MOE performance individually, the actual to predicted MOE ratios were calculated for each beam group (Table 19). The results from Figure 8 and Table 19 indicate that the proposed beam combinations (Fig. 1) will meet or exceed the target MOE level of 1.8×10^6 lb/in^2 and that ASTM D3737 procedures adequately predict Yellow Poplar glulam MOE.

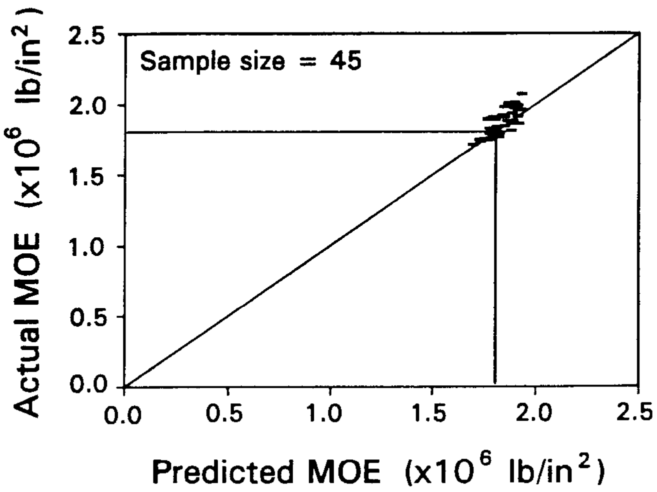


Figure 8—Relationship between actual MOE determined by tests and predicted MOE calculated *from lumber properties.*

Table 19—Comparison of actual and predicted MOE values based on actual lumber properties

	MOE ($\times$ 10^6 lb/in^2)			
Beam group	Actual (A)	Predicted (P)	A/P	A/P difference (%)
8-Lam	1.89	1.83	1.03	3.2
12-Lam	1.94	1.88	1.03	3.1
17-Lam	1.79	1.80	0.99	0.1

Conclusions

Based on the evaluation and analysis of 45 Yellow Poplar glulam beams, a bending stress of 2,400 lb/in^2 and design MOE of 1.8 $\times$ 10^6 lb/in^2 are obtainable and make this species a feasible candidate for structural glulam construction, providing the following criteria are met.

- The outer 10 percent of the laminations (top and bottom) are E-rated to have an MOE of 2.0 $\times$ 10^6 lb/in^2.
- The next inner 10 percent of the laminations (top and bottom) are E-rated to have an MOE of 1.8 $\times$ 10^6 lb/in^2.
- The bottom (tension) 2.0E laminations are visually sorted for a maximum allowable edge knot of one-sixth the cross section.
- The top (compression) 2.0E laminations are visually sorted for a maximum allowable edge knot of one-third the cross section.
- All 1.8E laminations (top and bottom) are visually sorted for a maximum allowable edge knot of one-third the cross section.
- The end-joint qualifications follow procedures recommended in ANSI A190.1.
- Tension lamination grading criteria in Table 6 are used.

In addition, we conclude that ASTM D3737 adequately predicts the strength and stiffness performance of Yellow Poplar glulam timber, given the actual properties of the constituent lumber.

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Appendix A-Tension Test Results

Appendix A contains the following:

- Properties and quality of tension laminations following the relative rating system in Table 11.
- Results of tension tests on end-jointed lumber for the 2.0-1/6, the combined 1/3 edge knot, and the No. 2 grades of lumber.

Table 20—Properties and quality of 2 by 4's used in tension lamination

Beam number	MC (%)	MOE ($x10^6$ lb/in^2)	Characteristic[a]	Relative quality of midlength region
YP4-1	9	2.01	Clear	Low
	9	1.92	45% GD	
YP4-2	8	2.06	30% center GD	Medium
YP4-3	8	2.08	45% GD and 1:12 SOG	Low
	8	1.92	50% EK + GD (both sides), and 15% GD (one side)	
YP4-4	9	2.01	50% CK + GD (one side)	Low
	9	1.78	Clear	
YP4-5	9	2.02	Clear	High
	9	2.06	Clear	
YP4-6	?	2.01	Clear	Low
	9	2.12	40% GD (one side)	
YP4-7	8	1.94	Clear	High
	8	2.17	Clear	
YP4-8	12	1.82	Clear	High
YP4-9	10	2.02	33% GD (both sides)	Medium
	7	2.27	Clear	
YP4-10	8	2.13	1:14 SOG, <15% EK + GD and 50% CK + GD	Low
YP4-11	9	2.31	<15% EK + GD (one side)	High
YP4-12	10	2.00	1:12 SOG	Low
	10	2.01	Clear	
YP4-13	9	1.73	25% EK + GD	Medium
YP4-14	9	2.04	30% GD (one side)	Medium
	7	1.98	Clear	
YP4-15	8	1.86	Clear	Medium
	9	2.12	20% GD (one side)	

[a] CK, center knot; GD, grain deviation; SOG, slope of grain; EK, edge knot.

Table 21—Properties and quality of 2 by 6's used in tension lamination

Beam number	MC (%)	MOE ($x10^6$ lb/in^2)	Characteristics[a]	Relative quality of midlength region
YP6-1	7	2.00	15% CK + GD (one side)	Medium
YP6-2	8	1.88	<15% CK + GD	Medium
	10	2.11	1:18 edge SOG	
YP6-3	8	2.08	<10% CK + GD (one side)	High
YP6-4	7	1.73	<20% CK + GD (one side)	High
	9	2.04	Clear	
YP6-5	8	2.28	<20% CK + GD	High
	7	2.25	Clear	
YP6-6	7	1.88	1:18 SOG	Medium
	7	1.87	Clear	
YP6-7	7	2.19	5% CK + GD, 1:10 SOG	Low
YP6-8	9	2.07	20% GD (both sides)	Low
	7	2.18	1:16 SOG, <10% edge GD	
YP6-9	8	1.90	1:16 SOG (face), and <15% CK + GD (one side)	Low
YP6-10	10	2.11	Clear	High
	8	2.14	10% GD (one side)	
YP6-11	8	1.99	Clear	High
YP6-12	7	1.99	<10% GD	High
YP6-13	10	1.99	<10% CK + GD (one side)	High
YP6-14	8	2.16	Clear	Medium
	9	2.04	20% CK + GD (both sides)	
YP6-15	7	2.01	1:16 edge SOG	Low
	9	1.93	1:16 face SOG	

[a] CK, center knot; GD, grain deviation; SOG, slope of grain; EK, edge knot.

Table 22—Properties and quality of 2 by 8's used in tension lamination

Beam number	MC (%)	MOE ($x10^6$ lb/in^2)	Characteristics[a]	Relative quality of midlength region
YP8-1	6	2.29	20% CK + GD	Low
	9	1.81	35% CK + GD	
YP8-2	8	1.99	Clear	Medium
	8	1.97	20% CK + GD	
YP8-3	7	1.83	Clear	High
	8	1.67	Clear	
YP8-4	8	2.16	25% CK + GD	Low
	9	1.96	20% CK + GD	
YP8-5	9	1.92	Clear	High
	10	2.09	Clear	
	8	2.10	Clear	
YP8-6	8	2.05	20% CK + GD	Low
	9	2.15	30% CK + GD	
YP8-7	9	2.17	Clear	Medium
	7	1.68	Clear + lo MOE	
YP8-8	7	2.15	Clear	High
	10	2.11	Clear	
YP8-9	10	2.31	Clear	High
	7	2.25	Clear	
YP8-10	10	1.80	Clear	Low
	8	1.75	25% CK + GD	
YP8-11	10	1.80	25% CK + GD	Low
	8	1.71	Clear	
	10	1.94	Clear	
YP8-12	8	1.74	20% CK + GD	Medium
YP8-13	8	2.27	Clear	High
	10	1.89	Clear	
	7	2.06	Clear	
YPS-14	10	1.92	Clear	High
	10	1.97	<10% CK + GD	
YP8-15	9	1.81	>20% CK + GD	Low
	8	2.11	Clear	

[a] CK, center knot; GD, grain deviation; SOG, slope of grain; EK, edge knot.

Table 23—Results of subsequent tension tests on Yellow Poplar end-jointed lumber using lognormal distribution

Beam grade and property	Lumber size 2 by 4	2 by 6	2 by 8	All sizes combined
2.0-1/6 grade				
All specimens				
Sample size	53	17	49	119
Average tensile strength (TS) (lb/in^2)	6,630	5,560	5,010	5,870
COV TS (%)	20.3	31.3	24.5	27.8
$TS_{0.05}$ (50%) (lb/in^2)	4,570	3,060	3,170	3,480
$TS_{0.05}$ (75%) (lb/in^2)	4,430	2,780	3,050	3,380
Specific gravity	0.48	0.47	0.46	0.47
Moisture content (%)	8.9	10.2	9.3	9.3
Specimens with EJ failure				
Sample size	45	13	46	104
Average TS (lb/in^2)	6,760	5,830	5,080	5,970
COV TS (%)	14.9	24.8	22.1	24.6
$TS_{0.05}$ (50%) (lb/in^2)	5,180	3,680	3,380	3,780
$TS_{0.05}$ (75%) (1b/in^2)	5,040	3,350	3,260	3,680
1/3 EK grade[a]				
All specimens				
Sample size	5	14	5	24
Average TS (lb/in^2)	5,750	4,740	4,420	4,810
COV TS (%)	54.9	22.2	21.0	29.1
$TS_{0.05}$ (50%) (1b/in^2)	1,900	3,150	3,010	2,780
$TS_{0.05}$ (75%) (lb/in^2)	1,250	2,910	2,540	2,600
Specific gravity	0.47	0.47	0.47	0.47
Moisture content (%)	9.2	10.0	9.8	9.7
1/3 EK grade[a]—con.				
Specimens with EJ failure				
Sample size	4	11	4	19
Average TS (lb/in^2)	5,930	5,000	4,640	5,090
COV TS (%)	32.8	21.1	19.8	23.0
$TS_{0.05}$ (50%) (lb/in^2)	3,160	3,400	3,240	3,330
$TS_{0.05}$ (75%) (lb/in^2)	2,270	3,110	2,640	3,110
No. 2 grade				
All specimens				
Sample size	5	10	7	22
Average TS (lb/in^2)	5,920	4,880	5,200	3,840
COV TS (%)	20.8	28.9	63.4	42.2
$TS_{0.05}$ (50%) (1b/in^2)	4,050	2,830	1,430	1,670
$TS_{0.05}$ (75%) (lb/in^2)	3,420	2,490	1,000	1,500
Specific gravity	0.47	0.49	0.46	0.48
Moisture content (%)	8.9	10.2	9.5	9.6
Specimens with EJ failure				
Sample size	4	7	6	17
Average TS (lb/in^2)	5,610	5,130	5,240	5,350
COV TS (%)	20.0	21.1	69.0	44.2
TSo.05 (50%) (lb/in^2)	3,890	3,480	1,270	2,240
$TS_{0.05}$ (75%) (lb/in^2)	3,170	3,070	830	1,950

[a]Because of the small sample sizes, results for 2.0-1/3 and 1.8-1/3 grades were combined.

Appendix B—Glulam Beam Results and Failure Descriptions

Appendix B contains the following:

- Tables listing the results of the physical properties (dimension, moisture content, and weight), mechanical properties (stiffness and strength), and descriptions of the failures for each beam.
- Beam failure maps.

Table 24—Results of bending tests on 20-ft (19-ft span) Yellow Poplar beams

Beam	Dimension (in.) Width	Dimension (in.) Depth	Time to MC (%)	Load at weight (lb)	Beam failure (min:s)	Beam failure (lb)	EJ in MOR[a] (lb/in²)	Any EJ MOE (lb/in²)	TL[b] (Y/N)	Fail (Y/N)	Comment
YP4-1	3.00	10.88	8	164	4:30	6,900	5,320	1.98	Y	Y	Failed in tension lamination (TL) end joint (EJ) (100%) at 10.5 ft, propagated through 2d lamination.
YP4-2	3.00	10.88	8	164	8:20	11,900	9,120	1.81	N	Y	Failed at TL-EJ (50%) at 14.5 ft, through 30% grain deviation (GD) in TL at 10.7 ft.
YP4-3	3.00	10.88	8	162	5:26	9,500	7,300	1.91	Y	Y	Failed in TL-EJ (100%) at 9.8 ft through EJ in 3d lamination (100%) at 11 ft.
YP4-4	3.00	10.88	8	162	4:57	8,760	6,730	1.84	Y	Y	Failed in TL-EJ 100%) at 13 ft, through EJ in 2d lamination (20%) at 18 ft, through EJ in 3d lamination (25%) at 13.2 ft.
YP4-5	3.00	10.88	7	164	6:47	11,340	8,700	1.89	Y	Y	Failed in TL-EJ (100%) at 10 ft, through EJ in 2d lamination (25%) at 12.7 ft, through 3d lamination.
YP4-6	3.00	10.88	7	164	6:42	10,960	8,410	1.97	Y	Y	Failed through TL-EJ (100%) at 7 ft, through 40% EK + GD at 7.5 ft, through EJ in 2d lamination (80%) at 11.7 ft, through EJ in 3d lamination (25%) at 13.2 ft.
YP4-7	3.00	10.88	7	162	7:31	12,440	9,530	1.96	Y	Y	Failed in TL-EJ (100%) at 11.2 ft, through EJ in 2d lamination (50%) at 4.5 ft.
YP4-8	3.00	10.88	7	164	7:00	11,080	8,500	1.83	N	Y	Failed along 1:20 slope-of-grain (SOG) in TL at 8 ft-12 ft, through EJ in 2d lamination (80%) at 9.4 ft, through EJ in 3d lamination (100%) at 10.5 ft, through EJ in 3d lamination (20%) at 12.5 ft.
YP4-9	3.00	10.80	10	160	4:07	8,900	6,930	2.01	Y	Y	Failed in TL-EJ (100%) at 13 ft, through EJ in 2d lamination (10%) at 15 ft.
YP4-10	3.00	10.88	8	160	5:25	10,900	8,360	1.91	N	Y	Failed in TL through 50% CK + GD at 15 ft, through EJ in 2d lamination (100%) at 15 ft, through EJ in 3d lamination (50%) at 10.7 ft.
YP4-11	3.00	10.88	8	164	8:01	14,400	11,030	1.97	N	N	Compression wrinkling through top three laminations at 11.2 ft, TL sliver from 9 to 13 ft at failure.
YP4-12	3.00	10.88	9	164	7:56	9,400	7,220	1.75	Y	Y	Failed in TL-EJ (75%) at 12 ft, through EJ in 2d lamination (15%) at 14 ft, through glueline between 2d and 3d laminations.
YP4-13	3.00	10.88	8	162	6:50	11,000	8,440	1.75	N	Y	Failed in TL through 25% EK + GD at 11 ft, through EJ in 2d lamination (20%) at 9.5 ft, through EJ in 3d lamination (100%) at 7.2 ft.
YP4-14	3.00	10.88	10	160	5:00	10,400	7,980	1.83	Y	Y	Failed in TL-EJ (100%) at 13 ft, through EJ in 2d lamination (10%) at 9 ft.
YP4-15	3.00	10.88	8	164	5:00	9,400	7,220	1.90	Y	Y	Failed in TL-EJ (100%) at 8.2 ft, through EJ in 2d lamination (25%) at 12 ft, through glueline between 2d and 3d laminations.

[a] MOR calculations include dead load stress.
[b] EJ in the TL within the >85% maximum moment region.

Table 25—Results of bending tests on 30-ft (28.5-ft span) Yellow Poplar beams

Beam	Dimension (in.) Width	Depth	Time to MC (%)	Load at weight (lb)	Beam failure (min:s)	Beam failure (lb)	EJ in MOR[a] (lb/in^2)	Any EJ MOE (lb/in^2)	TL[b] (Y/N)	Fail (Y/N)	Comment
YP6-1	4.94	16.44	7	592	6:32	26,740	8,220	2.02	N	Y	Compression wrinkling through top two laminations at 13.5 ft (EJ—top lamination), failed in TL through 15% CK + GD at 12.8 ft, through EJ in 2d lamination (100%) at 13.5 ft, through EJ in 5th lamination (100%) at 13.5 ft.
YP6-2	4.94	16.44	8	592	6:54	28,520	8,760	1.99	Y	Y	Failed in TL through 12.5% CK + GD at 16 ft, through EJ in 3d lamination (100%) at 12.5 ft.
YP6-3	4.94	16.44	7	586	10:30	29,540	9,060	1.94	N	Y	Compression wrinkling in top lamination at 13 ft, failed through TL to EJ in 2d lamination (30%) at 14.8 ft, through EJ in 5th lamination (100%) at 18 ft, through EJ in 6th lamination (40%) at 15.5 ft.
YP6-4	4.94	16.44	7	592	6:32	22,760	7,010	1.91	Y	Y	Compression wrinkling in top lamination at 18.2 ft, failed through TL-EJ (10%) at 23.3 ft, through EJ in 3d lamination (100%) at 18 ft.
YP6-5	4.94	16.44	8	586	7:20	25,600	7,870	1.98	Y	Y	Failed in TL-EJ (100%) at 14 ft, through EJs in 2d lamination (25% each) at 9.3 ft and 15.7 ft, through EJ in 3d lamination (100%) at 13.7 ft.
YP6-6	4.94	16.44	7	584	5:22	20,760	6,400	1.93	Y	N	Failed through 1:18 SOG in TL at 9 to 13 ft, brash lumber failure in 2d lamination at 9 ft.
YP6-7	4.94	16.44	8	594	6:56	21,490	6,620	2.00	N	Y	Failed through 1:10 SOG in TL at 16 to 18 ft, through EJ in 2d lamination (25%) at 14.8 ft, through glueline between 2d and 3d laminations from 11 ft to 21 ft.
YP6-8	4.94	16.44	7	592	8:11	26,400	8,110	1.87	Y	Y	Failed at both TL-EJs (50% each) at 10 ft and 23.3 ft, through EJ in 2d lamination (100%) at 16.8 ft, through 3d lamination.
YP6-9	4.94	16.44	7	592	5:58	22,730	7,000	1.85	N	Y	Failed in TL through 12.5% CK + GD at 16.5 ft, through EJ in 2d lamination (100%) at 15.5 ft, through glueline between 2d and 3d laminations from 12 to 22 ft.
YP6-10	4.94	16.44	8	592	9:08	30,720	9,420	2.08	Y	Y	Failed in TL-EJ (80% at 9.5 ft, through 2 EJs in 3d lamination (100% each) at 10 and 17 ft.
YP6-11	4.94	16.44	8	588	5:53	20,080	6,190	1.91	N	Y	Failed in TL-EJ (30%) at 8.5 ft, through 2d and 3d laminations.
YP6-12	4.94	16.44	8	596	10:30	29,600	9,080	1.92	N	N	Failed in TL through <10% CK + GD at 19.5 ft, through 5th lamination.
YP6-13	4.94	16.44	8	594	9:14	24,910	7,660	1.89	N	N	Failed in TL through 7.5% CK + GD at 15 ft, through 3d lamination.
YP6-14	4.94	16.44	7	594	6:56	18,950	5,850	1.87	Y	Y	Failed in TL-EJ (100%) at 17 ft, through 2d lamination.
YP6-15	4.94	16.44	7	592	5:30	19,600	6,110	1.97	Y	Y	Failed in TL-EJ (100%) at 14.7 ft, through EJ in 2d lamination (90%) at 15.8 ft, through glueline between 2d and 3d laminations.

[a]MOR calculations include dead load stress.
[b]EJ in the TL within the >85% maximum moment region.

Table 26—Results of bending tests on 40-ft (38-ft span) Yellow Poplar beams

Beam	Dimension (in.) Width	Dimension (in.) Depth	Time to MC (%)	Load at weight (lb)	Beam failure (min:s)	Beam failure (lb)	EJ in MOR[a] (lb/in^2)	Any EJ MOE (lb/in^2)	TL[b] (Y/N)	Fail (Y/N)	Comment
YP8-1	6.75	23.38	8	1,474	9:58	60,780	9,020	1.77	Y	Y	Compression wrinkling in top two laminations at load points (16 ft and 24 ft), failed at TL-EJ (100%) at 13 ft, through EJ in 2d lamination (100%) at 15 ft.
YP8-2	6.75	23.38	8	1.472	5:00	34,480	5,170	1.79	Y	Y	Failed in TL through 20% CK + GD at 27 ft. through EJ in 2d laminat.ion (100%) at 24.5 ft, through EJ in 4th lamination (90%) at 23 ft.
YP8-3	6.75	23.38	9	1,472	5:45	37,580	5,620	1.72	Y	Y	Failed in TL through low MOE board from 15 to 22 ft, through TL-EJ (10%) at 14.8 ft, through EJ in 4th lamination (100%) at 20 ft.
YP8-4	6.75	23.38	9	1,474	7:35	38,780	5,800	1.80	Y	Y	Failed in TL-EJ (15%) at 22.5 ft, through EJ in 3d lamination (35%) at 17 ft, through EJ in 4th lamination (85%) at 19 ft.
YP8-5	6.75	23.38	8	1,474	8:05	47,540	7,080	1.76	Y	Y	Compression wrinkling in top lamination at 19.7 ft, failed in TL-EJ (100%) at 24 ft, through EJ in 2d lamination (50%) at 22.5 ft, through 3d lamination.
YP8-6	6.75	23.38	8	1,468	8:08	48,180	7,170	1.83	Y	Y	Failed in TL through 30% CK + GD at 21.3 ft, through TL-EJ (10%) at 20.5 ft, through EJ in 2d lamination (10%) at 16 ft, through EJ in 6th lamination (40%) at 28.5 ft.
YP8-7	6.75	23.38	8	1,472	8:32	35,940	5,380	1.69	Y	Y	Failed in TL-EJ (80%) at 30.5 ft, through EJ in 2d lamination (70%) at 31 ft, through EJ in 3d lamination (20%) at 30.5 ft, through EJ in 4th lamination (20%) at 25 ft, through EJ in 6th lamination (10%) at 20 ft.
YP8-8	6.75	23.38	9	1,476	8:32	47,900	7,130	1.90	N	Y	Failed in TL-EJ (25%) at 24 ft, through EJ in 3d lamination (25%) at 26 ft.
YP8-9	6.75	23.38	9	1,472	9:05	48,120	7,160	1.92	Y	Y	Failed in 2 TL-EJs (25% at 11 ft) and (10% at 21.2 ft), through EJ in 2d lamination (15%) at 17 ft, through EJ in 8th lamination (20%) at 19 ft.
YP8-10	6.75	23.38	8	1,476	8:15	52,840	7,850	1.82	Y	Y	Compression wrinkling in top lamination at 19.5 ft, failed through clear TL at 23 ft, through EJ in 2d lamination (5%) at 24 ft, through EJ in 3d lamination (100%) at 25 ft, through EJ in 7th lamination (10%) at 22 ft.
YP8-11	6.75	23.38	8	1,470	7:45	46,780	6,970	1.79	Y	Y	Failed in TL-EJ (15%) at 25.5 ft, through EJ in 3d lamination (50%) at 24 ft, through EJ in 6th lamination (50%) at 30 ft.
YP8-12	6.75	23.38	8	1,474	6:08	46,420	6,910	1.78	N	Y	Failed through clear TL at 15 ft, through EJ in 2d lamination (90%) at 17 ft, through EJ in 4th lamination (75%) at 17 ft, through EJ in 6th lamination (50%) at 21 ft.
YP8-13	6.75	23.38	8	1,464	7:35	32,120	4,820	1.76	Y	Y	Failed in TL-EJ (10%) at 26 ft, through 6th lamination.
YP8-14	6.75	23.38	7	1,472	8:50	47,380	7,050	1.77	Y	N	Failed through clear TL at 23 ft and followed 1:20 SOG to 33 ft, through EJ in 6th lamination (50%) at 25 ft.
YP8-15	6.75	23.38	8	1,470	7:35	35,380	5,300	1.77	Y	Y	Failed in TL-EJ (50%) at 22 ft, through 4th lamination.

[a]MOR calculations include dead load stress.
[b]EJ in the TL within the >85% maximum moment region.

Glulam Beam Failure Maps and Lumber Properties

The following applies to all beam failure maps:

- Lumber properties shown on beam maps are in the form X (Y), where

  X = modulus of elasticity ($\times 10^6$ lb/in^2)

  Y = specific gravity

- Critical moment (>85 percent maximum moment) region is defined as the area between 7 and 13 ft for the 8-lamination beams, between 10 and 18 ft for the 12-lamination beams, and between 12 and 28 ft for the 17-lamination beams.
- Lowline strength characteristics are also mapped, where

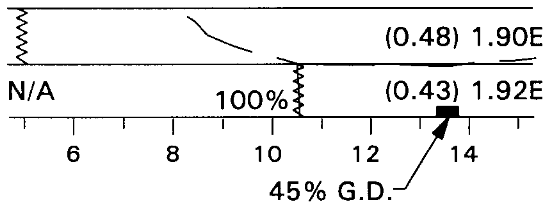
  SOG = slope-of-grain

  CK = center knot

  EK = edge knot

  GD = grain deviation

Beam No. YP4-1



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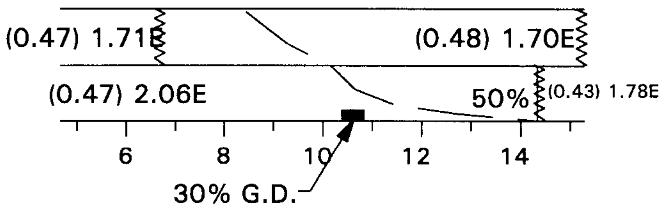

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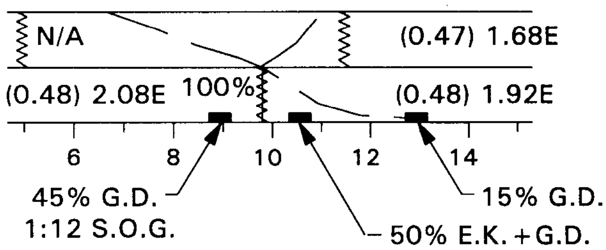

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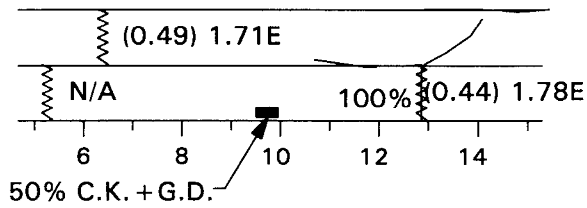

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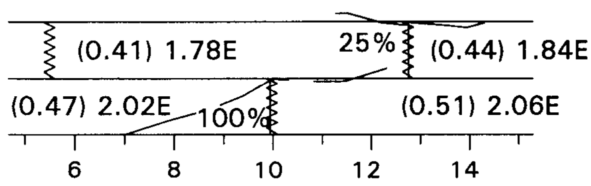

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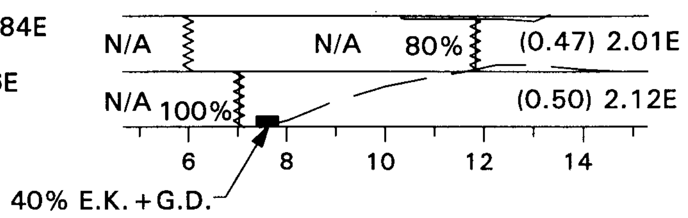

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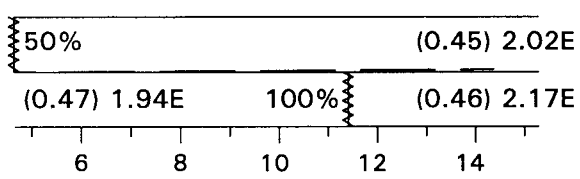

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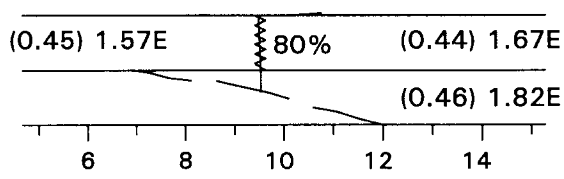

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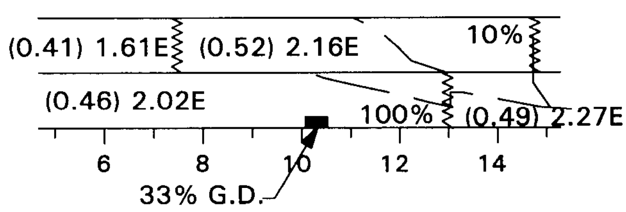

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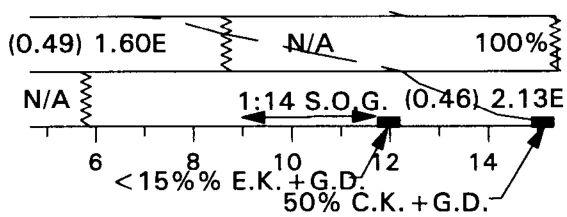

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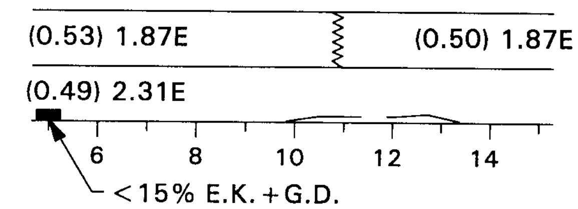

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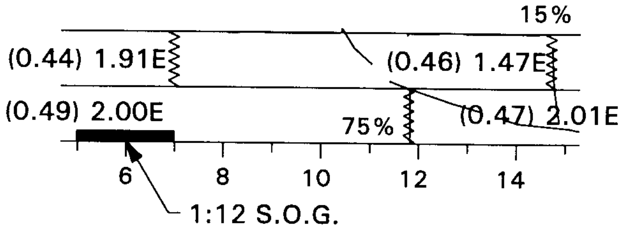

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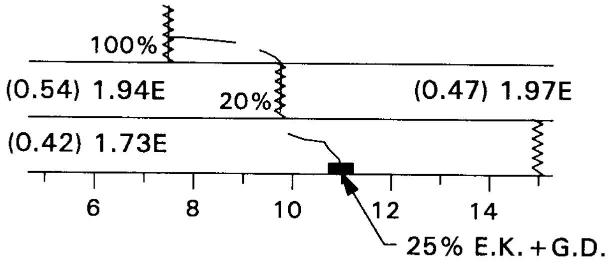

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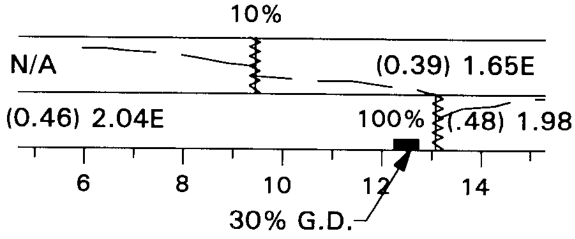

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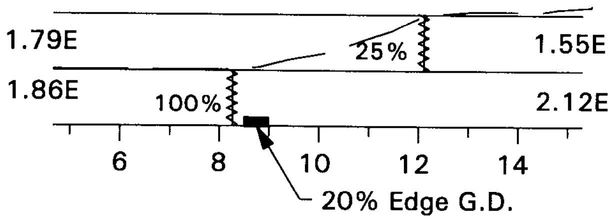
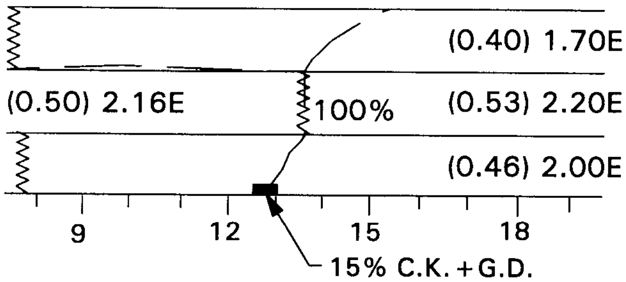


Beam No. YP6-1



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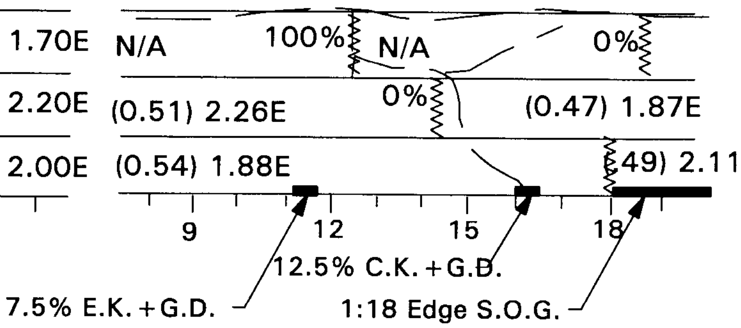

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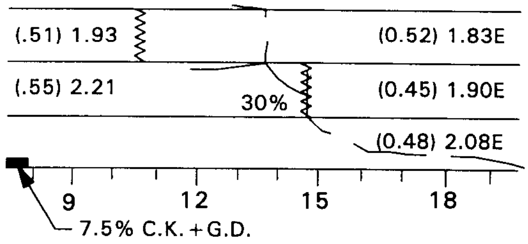

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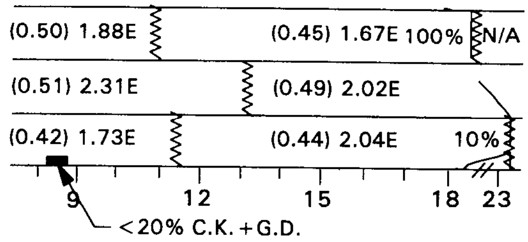

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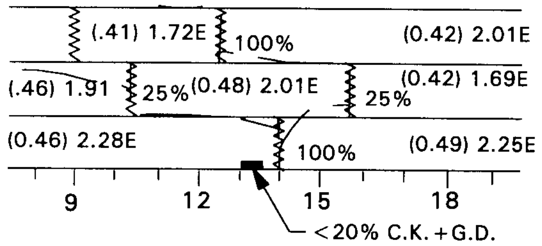

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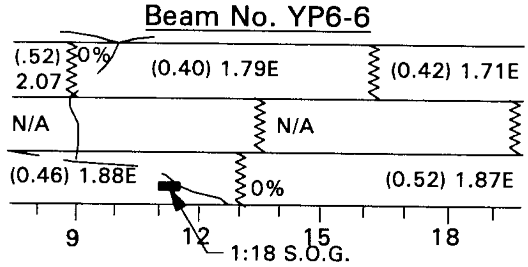

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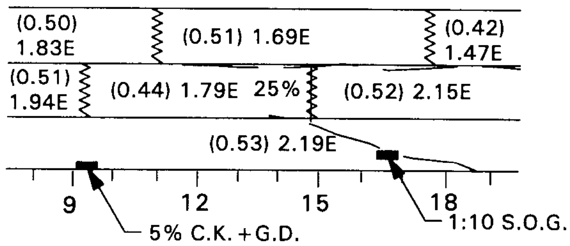

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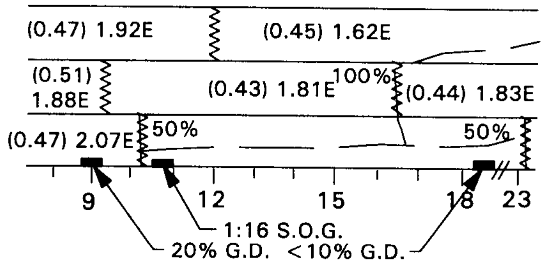

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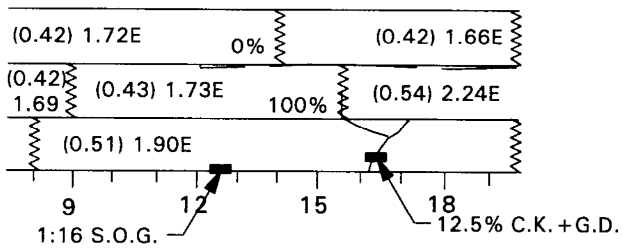

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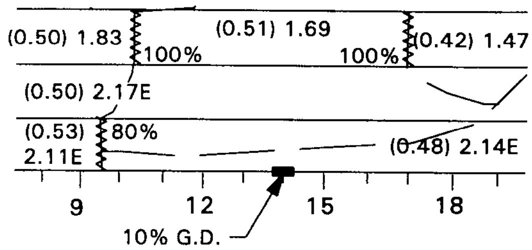

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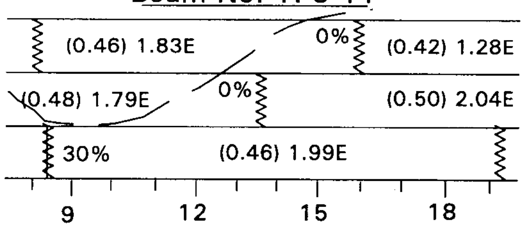

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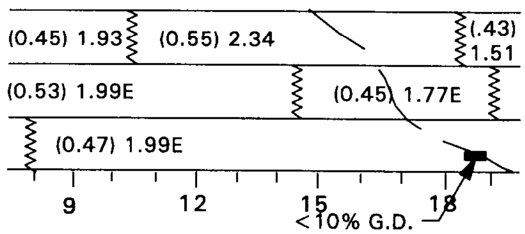

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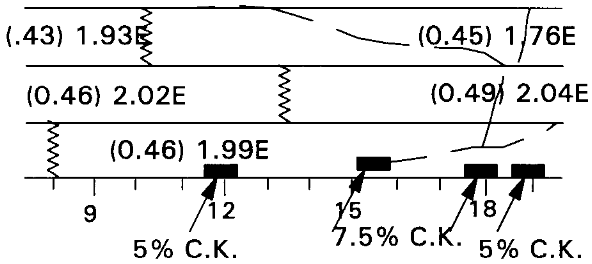

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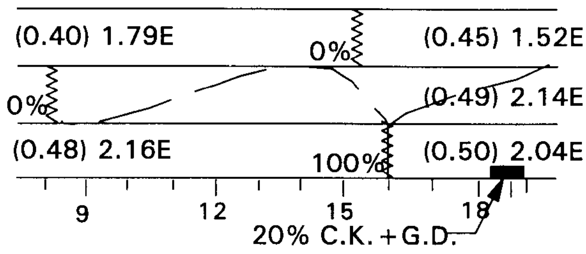

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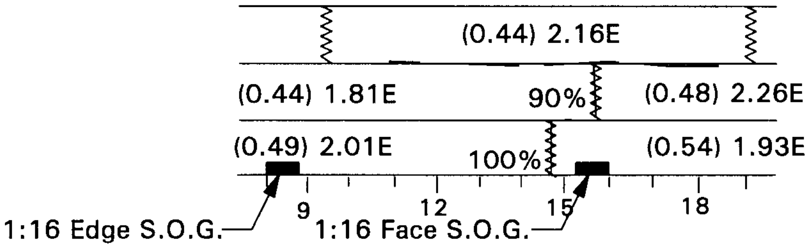

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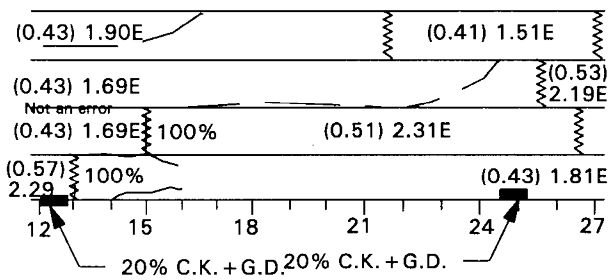

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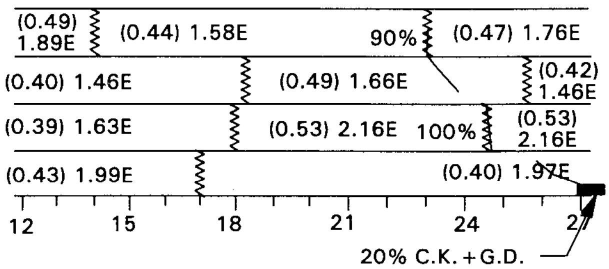

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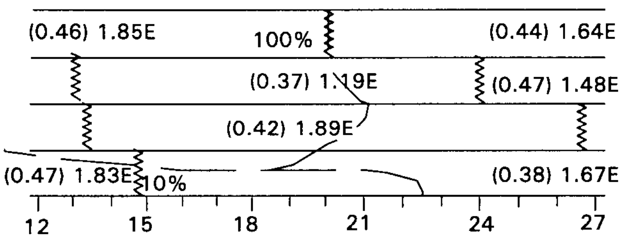

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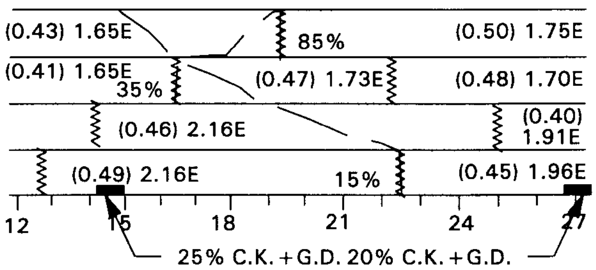

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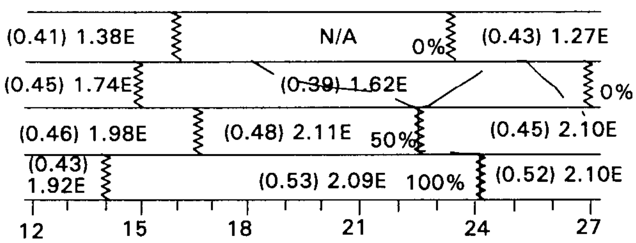

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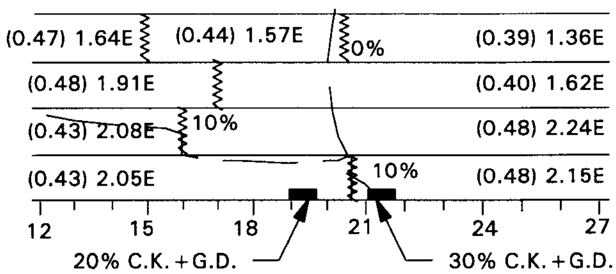

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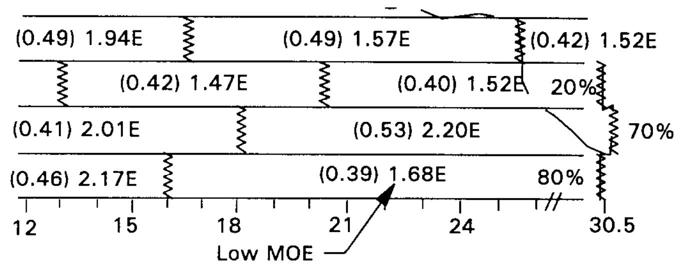

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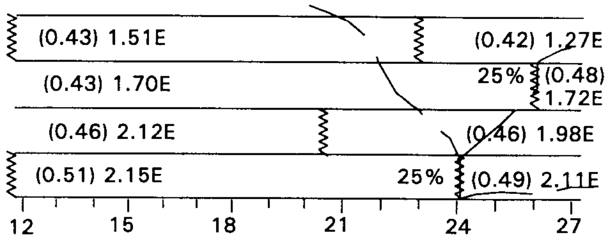

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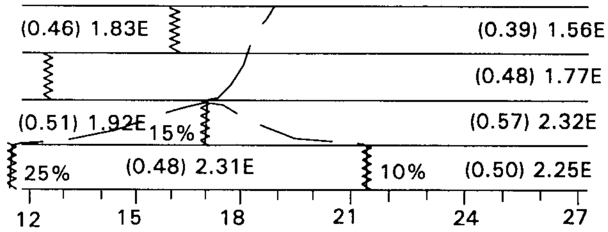

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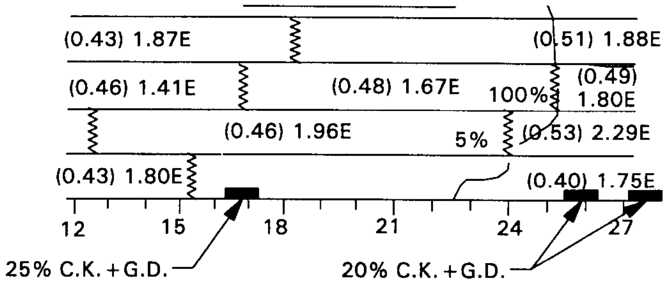

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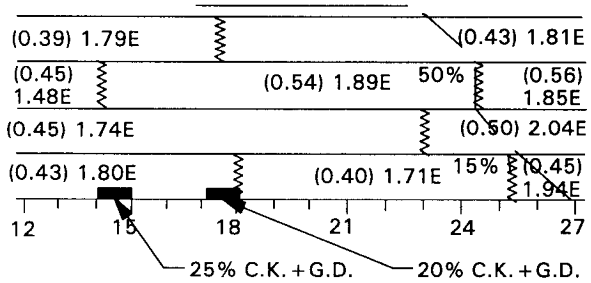

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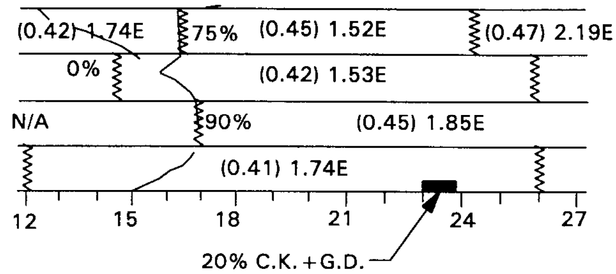

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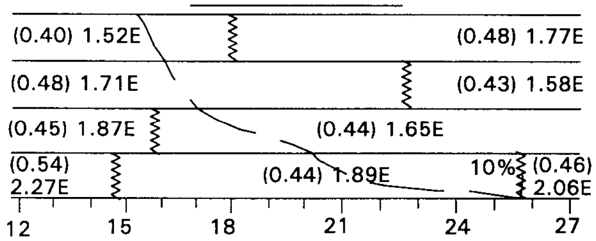

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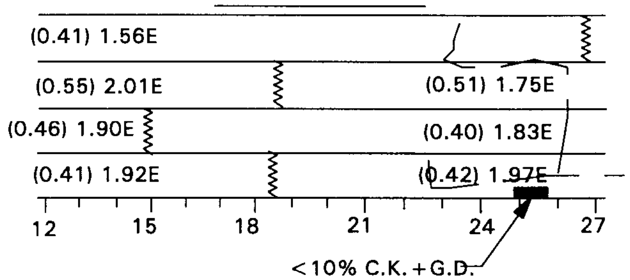

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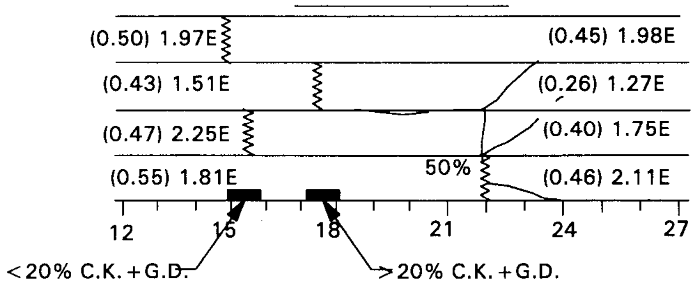

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