EFFICIENT USE OF RED OAK FOR GLUED-LAMINATED BEAMS

J. P. Shedlauskas, H. B. Manbeck, J. J. Janowiak, R. Hernandez,
R. C. Moody, P. Labosky Jr., P.R. Blankenhorn

ABSTRACT. A *red oak glued-laminated beam combination was developed* to *achieve a bending strength of 16.5 MPa (2,400 psi) and a modulus of elasticity of 12.4 GPa (1.8 × 10^6 psi). Thirty beams of two sizes were evaluated to determine the adequacy of ASTM D 3737 (ASTM, 1992a) procedures for prediction of glued-laminated beam design stress and stiffness, and to verify the volume effect equation currently in use. Lumber properties were recorded prior to beam manufacture for use in the ASTM D 3737 analysis. Data were analyzed using both knot data collected for each lamination grade, and for the pooled knot data of combined lamination grades to increase knot data sample size. Beam data were normalized to distinguish the difference in bending strength due to volume effect from the difference in bending strength due to lumber properties. Beam strengths from pooled knot data were not normalized. Beam tests indicate that ASTM D 3737 can be used to satisfactorily predict the strength and stiffness of red oak glued-laminated beams, and that the current volume effect model adequately predicts the behavior of red oak glued-laminated beams.*
Keywords. *Red oak, Glued-laminated beams, Strength, Stiffness, Volume-effect.*

Prior research has determined the volume effect for red maple and yellow poplar glued-laminated beams to be similar to the volume effect for softwoods and also showed that the design strength and stiffness of the red maple and yellow poplar beam were satisfactorily predicted using the procedures outlined in ASTM D 3737 (Manbeck et al., 1993, 1994 Moody et al., 1993). This research, which was conducted between October 1993, and June 1994, was designed to determine if the current volume effect model (eq. 1) can be used for beams manufactured with red oak as well.

$$C_v = k\left(\frac{V_o}{V}\right)^{\frac{1}{x}} \qquad (1)$$

where

V_o = volume of the standard beam, 0.254 m^3 (1291.5 $in.^2$·ft)
V = volume of the beam of interest
x = empirical coefficient (between 10 and 20)
k = loading factor

The current specifications for hardwood glued-laminated timber (AITC, 1985) limits hardwood glued-laminated production to uniform lumber quality characteristics, in terms of maximum knot size, throughout the cross-section. This specification also requires more restrictive slope of grain values (primarily in the core laminations) compared to more conventional lumber grades incorporated into softwood glued-laminated manufacture (AITC, 1993). Application of ASTM D 3737 (ASTM, 1992a) procedures permits more efficient glued-laminated sections to be developed from less restrictive material qualities (i.e., no. 2 or lower grade lumber as core laminations and mechanically sorted lumber for more critical outer beam zones). The recent work with red maple and yellow poplar has shown that the calculation procedures used for softwood glued-laminated design outlined in ASTM D 3737 may possibly be used for all hardwoods. Data on a third hardwood species, such as red oak, will add immeasurably to the hardwood glued-laminated database and help generalize the procedures for designing efficient hardwood glued-laminated beams. This research is needed to continue the development of the design specifications for hardwood glued-laminated timbers by using the available lumber resources in a more efficient and economic manner.

OBJECTIVES

The objectives of this research were to:

- Develop a red oak glued-laminated combination, using a high percentage of no. 2 grade material, with

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The authors are **James P. Shedlauskas,** ***ASAE Member Engineer.*** Graduate Research Assistant, **Harvey B. Manbeck,** ***ASAE Fellow Engineer,*** Professor, Agricultural and Biological Engineering Dept., and **John J. Janowiak,** Associate Professor, School of Forest Resources, Pennsylvania State University. University Park;**Roland Hernandez,** ***ASAE Member Engineer,*** Research General Engineer, and**Russell C. Moody,** Supervising Research General Engineer, USDA-Forest Service, Forest products Lab, Madison, Wisconsin; and **Peter Labosky, Jr..** Professor, and **Paul R. Blankenhorn,** Professor, School of Forest Resources, Pennsylvania State University, University Park. **Corresponding author:** Harvey B. Manbeck, 210 Agricultural Engineering Building, Pennsylvania State University, University Park, PA 16802; e-mail: <hlm@psu.edu>.

a 16.5 MPa (2400 psi) bending design value and is 12.4 GPa (1.8 × 10^6 psi) design stiffness.

- Determine if the volume effect model currently in use for softwoods, yellow poplar. and red maple can be applied 10 red oak glued-laminated beams.
- Determine if ASTM D 3737 procedures satisfactorily predict the bending design stress and modulus of elasticity (MOE) of a red oak glued-laminated beam.

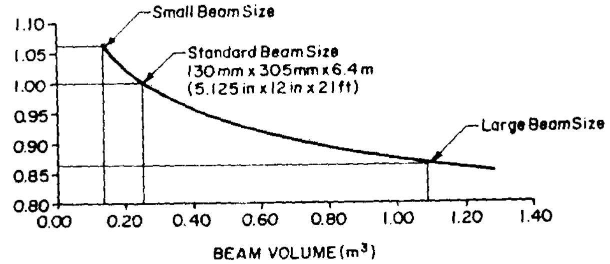

Figure 2–Volume effect factor vs. volume (x = 12.5).

MATERIALS AND METHODS

An overview of the experimental plan and testing procedures follows. Detailed procedures and analysis are presented by Shedlauskas (1994).

The procedures outlined in ASTM D 3737 were used with assumed knot properties to design an 8 lamination (small beam group) and an 18 lamination (large beam group) beam cross-section with target bending design strength and stiffness of 16.5 MPa (2.400 psi) and 12.4 GPa (1.8 × 10^6 psi), respectively (fig. 1). Eighteen beams with dressed dimensions of 76 × 305 mm × 6.1 m (3.0 × 12.0 in. × 20 ft) and 12 beams with dressed dimensions of 130 × 686 mm × 12.2 m (5.125 × 27.0 in. × 40 ft) were planned. These two beam sizes were chosen to provide a predicted strength difference due to volume effect of approximately 15% assuming an exponent of 1/x = 1/12.5 in the volume effect factor (eq. l). The exponent value (1/12.5) is approximately equal to the value found for red maple and yellow poplar (Minbeck et al., 1993: Moody et al., 1993). The relative placement of these beam sizes on the C_v versus beam volume curve is shown in figure 2.

Lumber was graded following NELMA grading rules (NELMA, 1991) to sort no. 2 grade material for fabrication of the core laminations. During this grade sort, no. 2 and better lumber was segregated from the core materials on the optional basis of edge knot characteristics for subsequent usc as outer laminations. No. 2 and better lumber was further divided into two-edge knot categories required for the outer laminations composed of E-rated lumber. The E-rated categories includes lumber limited to one-sixth and one-third edge knot restriction. All lumber was kiln dried to approximately 16% moisture content.

After sorting for maximum permitted edge knots for E-rated lumber requirements, the lumber was evalurated for MOE properties. The beam layups required two outer and inner beam lamination zones with 13.8 GPa (2.0 × 10^6 psi) and 12.4 GPa (1.8 × 10^6 psi) E-rated grades. Lumber was graded using a Metriguard E-computer. A running average was continuously monitored during selection to target a final average MOE value for the lumber to meet the desired stiffness. MOE for the E-rated categories of 13.8 GPa (2.0 × 10^6 psi) and 12.4 GPa (1.8 × 10^6 psi) was limited to property values within an acceptable range (table 1). There is an overlap of the MOE property values between the E-rated lumber grades of each stiffness group designation (table 1). Pieces of lumber which were acceptable for both grades were distributed randomly between the two E-rated grades. Prior to manufacture of the test beams, knot data were collected from samples of each grade.

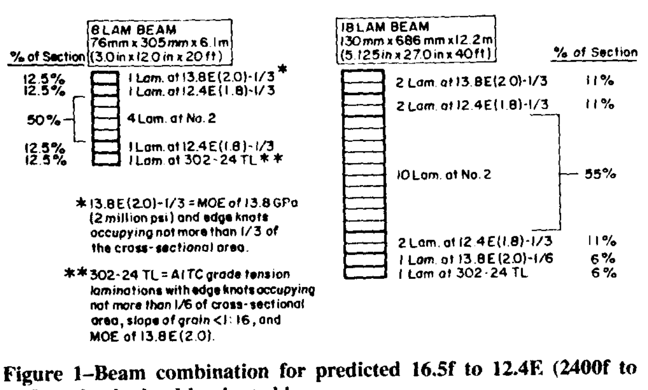

Figure 1–Beam combination for predicted 16.5f to 12.4E (2400f to 1.8E) red oak glued-laminated beams.

All test beams were manufactured in accordance with current AITC standards at an AITC certified laminating plant. At the time of manufacture, the location of each end joint and the MOE (E-rating) of each piece of lumber were recorded on a beam map. The beam map data were used to evaluate the actual MOE values used in each stiffness zone. Due to a planer setup error, the laminations in four of the small beams were planed to a thickness of 33 mm (1.3 in.) rather than the intended 38 mm (1.5 in.) resulting in a beam depth of 267 mm (10.5 in.) rather than 309 mm (12 in.) depth specified. After gluing. the beams were planed to a uniform width of 76 mm (3.0 in.) for the small beams and 130 mm (5.125 in.) for the large beams.

All beams were inspected for compliance with ANSI/AITC A190.1 (ANSI, 1992). Tension laminations were evaluated to classify each beam as having low, medium, or high quality tension laminations. This is not an ANSI/AITC A190.1 (ANSI, 1992) requirement, but was done to achieve a variation in tension lamination quality from those of minimal quality to those which greatly exceed minimum requirements in the test beams. Quality criteria were based on edge knot, center knot, and slope of grain characteristics, and are summarized in table 2.

Beams were tested to failure in accordance with ASTM D 198 (ASTM, 1992b). The weight and dimensions of each beam, as well as the moisture content of each lamination were recorded. After testing, the failure mode and pattern of each beam were recorded. Candidate failure

Table 1. Range of allowable MOE values

Group Designation	Range of Acceptable Values*
13.8 GPa (2.0 × 10^6 psi)	11.0 GPa (1.60 × 10^6 psi) to 16.5 GPa (2.40 × 10^6 psi)
12.4 GPa (1.8 × 10^6 psi)	10.0 GPa (1.45 × 10^6 psi) to 14.8 GPa (2.15 × 10^6 psi)

* Based on AITC 117-93 (AITC, 1993).

Table 2. Tension lamination category quality criteria for ATIC 302-24 grade

Beam Group and Lamination Criteria	Required Value (ASTM D 3737)	Relative Lamination Quality		
		Low	Medium	High
Small				
Edge knot + grain deviation	45%	>30%	15%-30%	<15%
Center knot + grain deviation	55%	>35%	20%-35%	<20%
Slope of grain	1:16	>1:18	1:18-1:20	>1:20
MOE, GPa (10^6 psi)	13.8 (2.0) avg.	<11.7(1.7) w/char*	<11.7(1.7) clear	11.7(1.7) clear
Large				
Edge knot + grain deviation	25%	>20%	20%-10%	<10%
Center knot + grain deviation	30%	>20%	20%-10%	<10%
Slope of grain	1:16	>1:18	1:18-1:20	>1:20
MOE, GPa (10^6 psi)	13.8 (2.0) avg.	<11.7(1.7) w/char*	<11.7(1.7) clear	11.7(1.7) clear

* Indicates lumber with edge knot, center knot, or slope of grain characteristics in addition to the given MOE value.

modes were tension in a strength reducing characteristic, tension in clear wood, tension in an end joint, shear, or compression.

Two approaches were used to analyze beam knot data: (1) knot sizes were evaluated for each grade lumber used in both the small beam and large beam group and (2) knot sizes were "pooled" across lamination grade to increase the knot data sample size. The actual mean modulus of elasticity and knot size values for each grade for each test beam group were determined and used in ASTM D 3737 based calculations to predict the bending strength and stiffness of the test beams. Knot data were analyzed according to USDA Technical Bulletin 1069 (Freas and Selbo, 1954). Load test data were analyzed to characterize the effect of volume on the strength of the beams. Finally, the bending design stress and modulus of elasticity of the test beams were compared to ASTM D 3737 predictions.

The MOE values obtained by using the E-computer for lumber in the beams were recorded on beam maps during manufacture. The MOE values were taken from these maps and adjusted by linear regression. The MOE of a representative sample of each grade was measured using the long span static method with span-to-depth ratio greater than 30 to 1 for all pieces. Test specimen orientation was random with respect to beam layup. The MOE results from the two methods were regressed to obtain a relationship between the static and dynamic MOEs for the small and large beam groups. The regression constants and correlation coefficients for the relationship, MOE (static) = A + B (MOE (Dynamic) are given in table 3.

For each beam group, knot evaluation was required for only three lamination grades—tension laminations, one - third, and no. 2. Tension laminations refer to AITC 302-24 grade with one-sixth edge knot restriction; the 1/3 grade refers to both the 13.8E (2.0)-1/3 and 12.4 (1.8)-1/3 lamination grades. The knot data for these two E-rated grades were combined since both grades are limited to having edge characteristics less than one-third the area of the cross-section of a lamination. The original lumber selection (sorting) based on knot characteristics was independent of the MOE sorting of the lumber.

Table 3. Regression constants for lamination MOE*

Beam Group	A, Mpa (10^6 psi)	B	R^2 (N)†
Small	1.63 (0.237)	0.793	0.89 (60)
Large	2.23 (0.232)	0.788	0.56 (165)

* MOE (static) = A + B · MOE (dynamic).
† Correlation coefficient (sample size).

RESULTS AND DISCUSSION

Results of the analysis of lumber and tension lamination grade characteristics are given in tables 4,5,6, and 7. Knot properties for tension lamination grades differed greatly between the beam groups (table 4). Average knot size (x), expressed as fraction of the cross-section occupied by knots, for tension lamination material of the small beam group was less than one-third the average knot size (x) for tension lamination material of the large beam group (0.006 versus 0.022). Average plus 99.5 percentile knot size (x + h) for the one-third knot grade of the small beam group was approximately half that of average plus 99.5 percentile knot size for the large beam group (0.053 vs. 0.112). The differences are probably due to the limited knot data sample size in these grades. Knot sizes for the no. 2 core material were similar for both beam groups.

Relative quality of the tension laminations are summarized in tables 5 and 6 for both the small and large beam groups. Five, 4, and 9 of the small beam group had low, medium, and high quality, respectively; 5, 5, and 2 of the large beam groups had low, medium, and high quality, respectively. The small beam group outer tension lamination qualities arc skewed toward the high quality end (13 of 18, or 72%, rated as medium or high). The large beam group outer tension lamination qualities arc skewed toward the low quality end (10 of 12, or 83%, rated as medium or low).

The results of the MOE lumber evaluation are listed in table 7. ASTM D 3737 procedures were used to predict the bending strength and stiffness of each beam group based on the collected knot and MOE data. The results arc presented in table 8. The predicted bending design strength of the small beam group is 17.8 MPa (2,600 psi), compared to the predicted bending strength of 15.8 MPa (2,300 psi) for the large beam group. Predicted modulus of elasticity values were similar [12.0 MPa (1.74 × 10^6 psi) for the small beam vs. 12.2 MPa (1.77 × 10^6 psi) for the large beam].

Ultimate load data were used for the evaluation of the volume effect and bending strength of the beam groups. Evaluation of the small beam group involving the modulus

Table 4. Knot data results

Grade	Pieces (No.)	Average Knot Size*, $\bar{x}$	+ h†
Small beam group			
Tension lamination‡ (2.0E-1/6)	35	0.006	0.123
One-third Knot (2.0E and 1.8E)	19	0.053	0.388
No. 2	13	0.083	0.463
Large beam group			
Tension lamination‡ (2.0E-1/6)	33	0.022	0.225
One-third Knot (2.0E and 1.8E)	7	0.112	0.702
No. 2	12	0.104	0.458
"Pooled" data			
Tension lamination‡ (2.0E-1/6)	68	0.014§	0.219§
One-third Knot (2.0E and 1.8E)	26	0.068	0.568
No. 2	25	0.093	0.505
One-third Knot + No. 2	51	0.077§	0.558§

* Average of sum of all knot sizes within each 0.03 m (1 ft.) length, taken at 5-cm (2-in.) intervals (dimensionless fraction of cross-section).
† 99.5 percentile knot size.
‡ Includes tension lamination and one-sixth edge characteristic material.
§ Knot data used in "pooled data" ASTM D3737 analysis.

Table 5. Small beam group outer tension lamination properties*

Beam No.	MOE, GPa (10^6 psi)	Characteristic†	Relative Quality‡
RO4-1	11.9 (1.73) 17.8 (2.58) (dyn.)§	40% EK + GD clear	L
RO4-2	12.6 (1.83) 13.0 (1.89) (dyn.)	5% edge GD clear	H
RO4-3	14.4 (2.09) (dyn.)	15% EK + GD	M
RO4-4	10.5 (1.53) 18.4(2.67) (dyn.)	clear 30% EK + GD	L
RO4-5	12.5 (1.82) 9.9 (1.44)	<5% edge GD clear	L
RO4-6	18.9 (2.74) (dyn.)	clear	H
RO4-7	NA 12.2 (1.77)	clear clear	H
RO4-8	12.5 (1.82)	<5% edge GD	H
RO4-9	11.6 (1.68) 13.6 (1.98)	clear clear	M
RO4-10	14.8 (2.14) (dyn.) 16.9 (2.45) (dyn.)	clear 1:18 SOG	M
RO4-11	15.2 (2.20) 12.6 (1.83) 13.1 (1.90)	clear clear clear	H
RO4-12	15.2 (2.20) (dyn.) 13.5 (1.96) (dyn.)	clear 33% EK + GD	M
RO4-13	NA 13.7 (1.98) 15.4 (2.23) (dyn.)	clear <5% CK + GD	H
RO4-14	NA 16.6 (2.41) (dyn.)	clear clear	H
RO4-15	NA 15.9 (2.30) (dyn.)	>30% CK + GD < 5% EK + GD	L
RO4-16	13.4 (1.94) 12.5 (1.82)	clear <5% EK + GD	H
RO4-17	15.2 (2.20) (dyn.)	45% EK + GD	L
RO4-18	16.0 (2.32) (dyn.)	clear	H

* Average specific gravity of 70 pieces was 0.61 (S.D. = 0.04).
† CK – center knot, EK – edge knot, GD – grain deviation, SOG – slope of grain.
‡ L – low, M – medium, H – high.
§ MOE measured using transverse vibration E-computer method, all others measured by static bending.

Table 6. Large beam group outer tension lamination properties*

Beam No.	MOE, GPa (10^6 psi)	Characteristic†	Relative Quality‡
RO6-1	13.6 (1.98)§ 13.1 (1.90)	clear 15% EK + GD	M
RO6-2‖	11.4 (1.65) 17.9 (2.59)	40% CK + GD clear	L
RO6-3	15.8 (2.29) NA#	20% EK + GD 25% CK + GD	L
RO6-4	NA 15.6 (2.26)	20% EK + GD clear	M
RO6-5	15.6 (2.06) 14.6 (2.12)	30% EK + GD clear	L
RO6-6‖	15.2 (2.20) 13.9 (2.01)	40% CK + GD clear	L
RO6-7	15.0 (2.17) 13.9 (2.02)	clear clear	H
RO6-8	15.0 (2.17) 14.9 (2.16)	10% CK + GD 10% EK + GD	M
RO6-9	15.8 (2.29) 16.0 (2.32)	clear 10% GD	H
RO6-10	NA 14.7 (2.13)	30% EK + GD clear	L
RO6-11	15.0 (2.17) 20.1 (2.91)	clear clear	M
RO6-12	15.4 (2.24) 17.7 (2.56)	clear clear	M

* Average specific gravity of 70 pieces was 0.61 (S.D. = 0.04).
† CK – center knot, EK – edge knot, GD – grain deviation, SOG – slope of grain; characteristic determined by inspection of three sides of the lamination after beam manufacture.
‡ L – low, M – medium, H – high.
§ MOE measured using transverse vibration method.
‖ These beams did not meet the AITC 302-24 requirements (table 2) either because of planing of the beam width during manufacture or because knot size based on inspection of only three sides of lamination (see footnote *). All lumber was on-grade prior to beam manufacture.
\# Not available.

of rupture required an analysis using a sample size of 14 beams as well as a sample size of 18 beams. The difference in depth resulted in approximately a 0.02 m^3(87 in.^{2}ft) volume difference [0.11 m^3(567 in.^{2}ft) versus 0.13 m^3 (654 in.^{2}ft)]. The difference between the modulus of rupture using the 14 versus 18 beam sample size was only 0.1 MPa (11 psi) (table 9), (Shedlauskas, 1994). Consequently, the MOR results reported herein are based on the 18 beam sample for the small beam size group. ASTM D 3737 calculations for MOE are based on the number of laminations rather than the depth of the beam. The effect of lamination thickness difference on MOE were assumed small and a sample size of 18 beams was used for MOE calculations. A summary of the load data, including primary failure modes, is presented in table 9.

Based on test results, the mean modulus of rupture for the large beam group was significantly smaller than for the small beam group [46.0 MPa (6,670 psi) vs. 60.4 MPa (8,760 psi)]. The mean beam MOE values were not significantly different by size groups and ranged from 12.8 to 13.0 GPa (1.86 × 10^6 to 1.88 × 10^6 psi).

The first analysis approach was to use the actual (as collected) knot data for each beam size group. The effect of beam volume on the bending strength could not be evaluated directly with the load test results in table 9. The

Table 7. Mean modulus of elasticity and coefficient of variation by grade and beam group

Grade	MOE, GPa (10^6 psi)			*COV* (%)
	Target	Unadjusted	Adjusted*	
Small beam group				
Tension lamination	13.8 (2.00)	14.6 (2.12)	13.2 (1.92)	11.0
13.8 (2.0)-1/3	13.8 (2.00)	14.8 (2.15)	13.4 (1.94)	8.5
12.4 (1.8)-1/3	12.4 (1.80)	13.3 (1.93)	12.2 (1.77)	7.7
No. 2	10.3 (1.50)	11.4 (1.66)	10.8 (1.56)	12.6
Large beam group				
Tension lamination	13.8 (2.00)	14.7 (2.13)	13.8 (2.00)	8.0
13.8 (2.0)-1/3	13.8 (2.00)	14.3 (2.07)	13.4 (1.95)	8.2
12.4 (1.8)-1/3	12.4 (1.80)	12.4 (1.80)	12.0 (1.74)	6.8
No. 2	10.3 (1.50)	12.5 (1.82)	12.1 (1.76)	12.8

* Adjusted by regression.

Table 8. Predicted design values using ASTM D 3737 analysis and actual knot data

Beam Group	Predicted F_b, MPa (psi)	Predicted E, GPa (10^6 psi)
Small	17.8 (2579)	12.0 (1.74)
Large	15.8 (2298)	12.2 (1.77)

difference in modulus of rupture was a result of both the volume effect and the differences in lumber quality (Outer tension lamination quality—tables 5 and 6; knot data and MOE—tables 2 and 7) between the beam size groups (fig. 3). Therefore, a normlalization process was used to differentiate between lumber properties and volume effect.

To determine the effect of the variation of lumber properties, ASTM D 3737 was used to predict the bending design strength of both beam groups using the actual knot and MOE properties of lamination grades (tables 2 and 7). A theoretical bending design strength was found for the small beam group based on both the small and large beam group lumber data; similarly, a theoretical bending strength was found for the large beam group based on both the small and large beam group lumber data. The results are summarized in table 10.

The normalized values in table 10 were assumed to represent the bending strength for a sample with the same statistical distribution as the actual load test results (e.g., same COV, sample size, and probability level). A theoretical modulus of rupture (MOR) was then calculated based on the coefficients of variation and t-statistics of the actual load test data corresponding to the lumber data used for the ASTM D 3737 predictions (eqs. 2 and 3).

$$F_b = \frac{1}{2.1}\left[Adj.\ \overline{MOR_i} - K\left(\frac{COV_i}{100} Adj.\ \overline{MOR_i}\right)\right] \quad (2)$$

$$Adj.\ \overline{MOR_i} = \frac{2.1\ F_b}{\left[1 - K\left(\frac{COV_i}{100}\right)\right]} \quad (3)$$

where

F_b = beam bending strength [MPa (psi)]

$Adj.\ \overline{MOR_i}$ = adjusted mean modulus of rupture [MPa (psi)]

K = t-statistic based on α = 0.05 and sample size of load test data

COV_i = coefficient of variation of the load test data

Table 9. Bending test results

Group	n	K*	*MOR*, MPa (psi)	COV_{MOR} (%)	*MOE*, GPa (psi)	COV_E (%)
Small†	14	2.007	60.3 (8,750)	14.2	12.8 (1.86)	4.0
Small‡	18	1.951	60.4 (8,761)	14.7	13.0 (1.88)	4.4
Large§	12	2.048	46.0 (6,670)	10.0	12.8 (1.86)	3.3

* K value from ASTM D 2915 (n degrees of freedom; = 0.05; = 0.75) (ASTM, 1990).
† Includes only beams with depth of 305 mm (12.0 in.).
‡ Failure modes: Tension in clear wood (7); tension in end joint (8); tension in strength reducing characteristic (3).
§ Failure modes: Tension in clear wood (2); tension in end joint (5); tension in strength reducing characteristic (5).

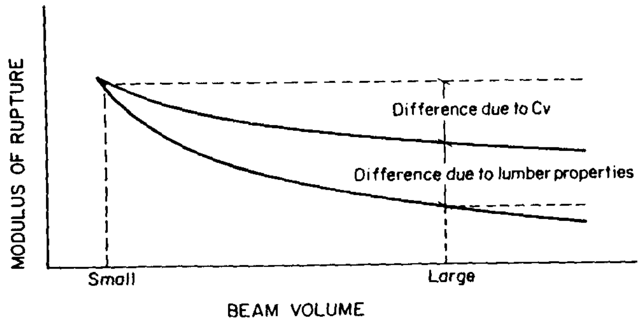

Figure 3–Schematic of *MOR* differences due to lumber properties and volume effect.

2.1 = modification factor for duration of load and safety, ASTM D 2915 (ASTM, 1990)

i = beam group (small or large)

The detailed normalization procedure was to:

1. Calculate the bending strength values for the standard size beam with the same lamination properties as the actual test beam using ASTM D 3737.
2. Calculate the bending strength values for the standard size beam using the lamination properties of the other beam size group.
3. Calculate the mean moduli of rupture for the bending design strength in steps one and two above, assuming the same sample statistics as test beam and using equation 3.
4. Calculate the difference between mean MORs calculated in step three (this represents the difference in mean MOR due to lamination knot data and MOE only).
5. Add or subtract the difference in mean MOR (step 4) to or from the actual mean MOR for the respective size group.

Sample calculations are presented by Shedlauskas (1994). Adjusted mean MOR's were calculated using a sample size of 18 for the small beam group and 12 for the large beam group. The differences between the adjusted and actual mean MORs for a beam size estimates the portion of the bending strength difference due to differences in lumber properties between the two beam groups. The remaining difference is indicative of the change in bending strength due to the volume effect (fig. 3).

The adjusted mean MOR of the large beam group was 52.2 MPa (7,570 psi) compared to the actual mean MOR of the small beam group of 60.4 MPa (8,760 psi). The resulting difference is 8.2 MPa (1,190 psi) for the 18 beam sample. Actual MOR for the large beam group was

Table 10. Predicted bending design strength of small and large beams using two lamination qualities

	ASTM D 3737 Bending Strength Based on Knot and MOE Data*	
Beam Group	Small Beams, MPa (psi)	Large Beams, MPa (psi)
Small	17.78 (2,580)†	15.89 (2,310)‡
Large	18.19 (2,640)‡	15.84 (2,300)†

* Knot and MOE data from tables 4 and 7.
† F_b values based on actual knot data for the respective beam size.
‡ Adjusted (normalized) F_b values.

Table 11. Mean MOR, beam volume, and volume effect exponent

	MOR, MPa (psi)		Mean volume, m³ (in.² × ft)		
Case*	Small Beam	Large Beam	Small Beam	Large Beam	x
B. ($\overline{MOR}_{4,18}$ vs. Adj. $\overline{MOR}_6$)	60.4 (8761)	52.2 (7570)†	0.12 (634)	1.06 (5391)	14.6
D. (Adj. $\overline{MOR}_{4,18}$ vs. $\overline{MOR}_6$)	54.8 (7950)†	46.0 (6670)	0.12 (634)	1.06 (5391)	12.2

* Cases defined in text.
† Adjusted MOR.

46.0 MPa (6,670 psi). The adjusted mean MOR for the small beam group was 54.8 MPa (7,950 psi). The difference was 8.9 MPa (1,280 psi). Results of these analyses are summarized in table 11 and figures 4 and 5. For all cases, the volume effect difference between mean and adjusted mean MOR's was significant.

The volume effect was assumed to be described by equation 1. The adjusted mean MORs for one size group, as calculated by equation 3 and summarized in table 11. were compared to the actual MORs for the other size group for four cases (A, B, C. D). Case A and C represent the analysis using a sample size of 14 for the small beam group. Only cases B and D are presented here. A complete analysis is detailed by Shedlauskas (1994). The exponent (x), which describes the difference, was then calculated using equation 4.

$$x = \left[\frac{\log_{10}\left(\frac{Adj.\ \overline{MOR}_i}{\overline{MOR}_j} \right)}{\log_{10}\left(\frac{\bar{V}_j}{\bar{V}_i} \right)} \right]^{-1} \quad (4)$$

where

x = volume effect exponent (eq. 1)
$Adj.\ \overline{MOR}_i$ = adjusted mean MOR of beam group i
$\overline{MOR}_j$ = actual mean MOR of beam group j
$\bar{V}_i, \bar{V}_j$ = mean volume of beams in groups i and j

Cases B and D are:

Case B: Actual mean MOR of small beam group [beams manufactured from 36 × 76 mm (2 × 4) laminations] using 18 beams ($\overline{MOR}_{4,18}$), compared to adjusted mean MOR of large [beams manufactured from 38 × 130 mm (2 × 6) laminations] beam group ($\overline{MOR}_6$).

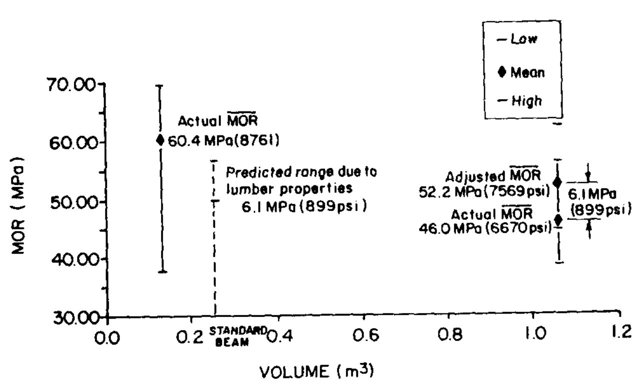

Figure 4–Comparison of the actual $\overline{MOR}$ of small beam group to the actual and adjusted $\overline{MOR}$ for large beam group.

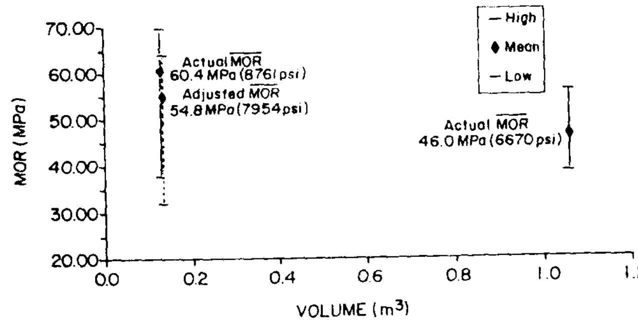

Figure 5-Comparison of the actual MOR of the large beam group to the actual and adjusted MOR of the small beam group.

Case D: Adjusted mean MOR of small beam group using 18 beams ($MOR_{4,18}$). compared to actual mean MOR of large beam group (MOR_6).

The exponent values derived from these test data were 14.6 and 12.2 for cases B and D, respectively, with a mean value of x = 13.4 (table 11). The exponent for the red oak beams is greater than the value used for size effect (x = 9) for solid sawn members (NFPA. 1991). However, the value is very close to the values reported for red maple (x = 14.1) and yellow poplar (x = 11.4) glued-laminated beams (Manbeck et al., 1993, 1994; Moody et al.. 1993). The exponent also compares favorably with AITC practice for hardwoods (x = 15) and NDS[R] recommendations (x = 10 to 20) for glued-lamintited beams.

The bending design stress was calculated for each beam group by calculating the mean modulus of rupture, corrected for the volume effect by normalizing the data to the standard size beam of 130 × 305 mm × 6.4 m (5.125 × 12.0 in. × 21 ft.), and applying equation 2. Mean MORs were normalized to the standard size beam by dividing the calculated bending design stress by the value given by equation 1, using an exponent of x = 13.4. lt was necessary to correct each beam individually for volume effect because beam dimensions within each group vary slightly due to machining processes. Final results arc summarized in table 12.

The actual calculated bending design stress for the small beam group was 19.5 MPa (2,820 psi) compared to a predicted value of 17.8 MPa (2,579 psi) giving an actual/predicted ratio of 1.09 (table 12). Similarly, the actual calculated bending strength for the large beam group was 19.4 MPa (2,810 psi) compared to the predicted value was 15.8 MPa (2,300 psi). The actual/predicted bending

(table 12). The actual bending design stress exceeded the ASTM D 3737 predicted values for all cases.

beam group using the slope of the load deflection curves. Analysis was performed in accordance with ASTM D 198 (ASTM, i984), and final results are listed in table 12.

Table 12. Comparison of actual vs. predicted results for standard size beam

	Actual*		Predicted†		Actual / Pred.	
Group	F_b, MPa (psi)	MOE, GPa (psi)	F_b, MPa (psi)	MOE, GPa (psi)	F_b	MOE
Small	19.5 (2823)	13.0 (1.88×10⁶)	17.8 (2579)	12.0 (1.74×10⁶)	1.09	1.08
Large	19.4 (2809)	12.8 (1.86×10⁶)	15.8 (2298)	12.2 (1.77×10⁶)	1.22	1.05

* Normalized to standard size beam using Cv exponent of x = 13.4.
† Using ASTM D 3737 procedures.

Ratios of actual MOE to predicted (1.08 and 1.05, respectively, for small and large beams) were slightly higher than published ratios for red maple (1.01) (Manbeck et al., 1993) and yellow poplar (1.02) (Moody et al., 1993).

The second analysis approach used combined (pooled) knot data for certain lamination grades. Knot data samples, by beam size and grade, were small (table 4) and may not accurately reflect the actual population knot characteristics. Thus, a comparison of beam strength and stiffness was performed using pooled knot data. This procedure may better reflect the characteristics of the laminating lumber. Similar lumber grades of the small and large beam groups in table 2 were combined to increase the knot data sample size. In addition, the knot data for the no. 2 and the one-third edge knot lumber were combined. The resulting knot data are summarized in table 4. Theoretical bending design strength and MOE were again calculated using ASTM D 3737 and the combined knot data. The results are presented in table 13.

Results from the pooled data indicate that both beam groups should be classified as 16.5 MPa (2,400 psi) beams. The bending design value for the small beam group [16.3 MPa (2,360 psi)] rounds to 16.5 MPa (2,400 psi). The calculated bending design value for the large beam group [17.6 MPa (2.550 psi)] cxceeds 16.5 MPa (2,400 psi); however, to achieve this design bending value, slope of grain in the tension lamination is limited to 1:20. Lumber was not initially sorted to meet this criteria (table 3). With a slope of grain limitation of 1:18, the predicted bending strength is 16.5 MPa (2,400 psi). The predicted MOE values did not change when pooled knot dots were used (table 12).

Based on the results using pooled knot data, the entire difference between the observed beam bending strength of the small and large beams (table 9) can be attributed to the volume effect. Using a regression analysis of the beam MOR data to calculate the volume effect, the best fit volume effect exponent (x) (eq. 4) is 8.18.

The volume effect exponent value (x = 8.18) using pooled knot data is close, but smaller than the value (x = 10) recommended for glued-laminated beams in the National Design Specification for Wood Construction (NFPA, 1991). The true value for x probably lies between the values obtained using the actual (13.4) and pooled (8.18) knot data in the analysis. Thus, the value recommended in the NDS (x = 10) appears appropriate for red oak glued-laminated beams.

Table 13. Design values using ASTM D 3737 and pooled knot data

Beam Group	Predicted F_b, MPa (psi)	Predicted E, GPa (10^6 psi)
Small	16.3 (2,361)	12.0 (1.74)
Large	17.6 (2,554)	12.2 (1.77)

Conclusions

The conclusions derived as a result of this research are:

- Red oak glued-laminated beams, using a high percentage of no. 2 grade material, with a bending design value of 16.5 MPa (2,400 psi) and MOE of 12.4 GPa (1.8 × 10^6) are technically feasible.
- ASTM D 3737 can be used to satisfactorily predict the bending design stress and stiffness of red oak glued-laminated beams. Bending strength values predicted by ASTM D 3737 were less than or equal to values calculated from load test data. Predicted modulus of elasticity values were within 8% of those calculated based on load test data.
- The volume effect model used for softwood, red maple, and yellow poplar glued laminated (eq. 1) satisfactorily estimates the volume effect on the bending strength of red oak glued-laminated beams.

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