United States
Department of
Agriculture

Forest Service

Forest
Products
Laboratory

Research
Paper
FPL–RP–541

Efficient Utilization of Red Maple Lumber in Glued-Laminated Timber Beams

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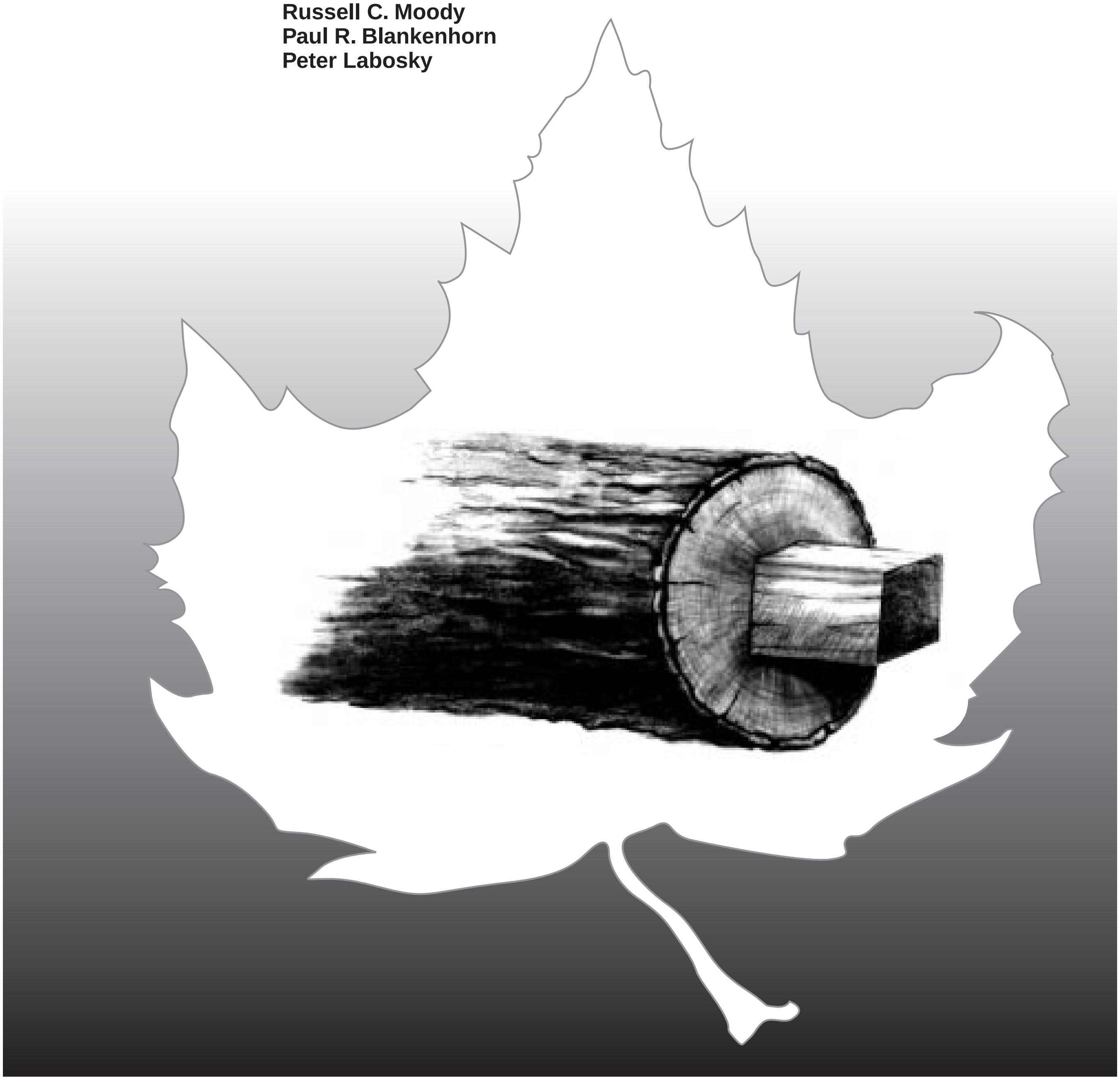

Abstract

The feasibility of utilizing cant-sawn hardwood lumber, which would not usually be desired for furniture manufacture, was studied for the manufacture of structural glued-laminated (glulam) timber. Two red maple beam combinations were evaluated: (1) a glulam combination designed with E-rated lumber in 25 percent of the outer laminations (top and bottom) and No. 3 grade lumber in 50 percent of the center laminations and (2) a wide-width glulam combination with laminations made from nominal 2- by 4- and 2- by 6-in. No. 2 grade lumber laid edge-to-edge having staggered end joints (termed 2 by 4/2 by 6 glulam combination). Test results of 42 red maple glulam beams showed that it was feasible to develop structural glulam timber from cant-sawn lumber. The glulam combinations made from E-rated lumber exceeded the target design bending stress of 2,400 lb/in^2 and met the target modulus of elasticity (MOE) of 1.8×106 lb/in^2. In addition, the 2 by 4/2 by 6 glulam combination exceeded published design stresses for vertically laminated bending strength, MOE in both the horizontally and vertically laminated orientations, and horizontal shear stress in the vertically laminated orientation. Based on the results of the 2 by 4/2 by 6 glulam combination, it was determined that edge gluing the laminations to form wide-width lumber is not required to achieve targeted strength and stiffness levels.

Data analysis showed that ASTM D3737 procedures developed for softwood species accurately predict beam stiffness and provide conservative bending and horizontal shear strength estimates for red maple glulam beams. Also, it was shown that results from ASTM D143 shear-block tests could be used to accurately predict horizontal shear strength of 2 by 4 and 2 by 6 red maple glulam beams.

Keywords: Red maple, hardwood, glulam, E-rated lumber, log cants

September 1995

Janowiak, John J.; Manbeck, Harvey B.; Hernandez, Roland; Moody, Russell C.; Blankenhorn, Paul R.; Labosky, Peter. 1995. Efficient utilization of red maple lumber in glued-laminated timber beams. Res. Pap. FPL–RP–541. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 23 p.

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The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

Acknowledgment

We express sincere gratitude to Bradford Forest Products, Inc. in Bradford, Pennsylvania, for preparing essential cant-sawn lumber supplies and Unadilla Laminated Products in Unadilla, New York, for fabrication of the test beams. In addition, special thanks to the Engineering Mechanics Laboratory technicians of the USDA Forest Service, Forest Products Laboratory, in Madison, Wisconsin, for their valuable assistance in the beam testing.

The research reported herein was sponsored and funded by the Pennsylvania Department of Transportation, Office of Special Studies (Project No. SS–043), and the Pennsylvania Agriculture Experiment Station. The project was conducted jointly between the Pennsylvania State University, and the USDA Forest Service, Forest Products Laboratory.

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Introduction

Several recent publications have presented experimental results on the mechanical performance of hardwood glued-laminated (glulam) timbers (Manbeck and others 1993; Moody and others 1993; Shedlauskas and others 1994). These glulam studies are related to broader research efforts in the development of timber bridge systems. Glulam is a vital element for many proposed timber bridge designs. One key issue in bridge research is the use of local, underutilized forest resources. Published performance results of red maple, yellow poplar, and red oak support the feasibility that hardwood glulam timbers are well-suited for bridge applications. These hardwood species are abundant, with significant saw-timber volume in Pennsylvania and numerous other states where annual growth accumulations exceed harvest.

The project reported here was initiated to examine the use of low-grade, small-dimension red maple obtained from cant-sawn lumber for glulam timber manufacture. Cant refers to the remaining log heart or inner-log portion after grade sawing removes the higher quality, outer-zone material for appearance-type lumber.

Background

Design values of 2,400 lb/in^2 bending stress and 1.8×10^6 lb/in^2 stiffness (modulus of elasticity (MOE)) were found to be feasible for red maple, yellow poplar, and red oak glulam (Manbeck and others 1993; Moody and others 1993; Shedlauskas and others 1994). (See Table 1 for SI conversion factors.) These cited studies intended to improve upon hardwood glulam performance with efficient beam combinations using E-rated outer and No. 2 visually-graded lumber inner laminations. These studies served to verify the applicability of ASTM D3737 (ASTM 1993) analytical procedures to predict hardwood glulam design performance on the basis of lumber properties. Also, the studies defined appropriate volume effect coefficients for flexural strength adjustment for red maple, yellow poplar, and red oak glulam timber products. Results from these studies have been accepted by the American Institute for Timber Construction (AITC), and hardwood glulam combinations using E-rated lumber are being incorporated in the AITC 119 (AITC 1985) standard.

Table 1—SI conversion factors

English unit	Conversion factor	SI unit
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
pound (lb)	0.4535	kilogram (kg)
pound per square inch (lb/in^2)	6.894	pascal (Pa)

Other studies are also emerging to explore the yield recovery and lumber properties of structural-graded hardwoods. Green and McDonald (1993) investigated the mechanical properties of red oak nominal 2- by 4-in. (2 by 4) lumber. Janowiak and others (1992) reported on flexural properties and computed design values for Select Structural and No. 2 red maple 2 by 4's. Janowiak and others (1994) also reported on the compressive strength properties of red maple and northern red oak glulam. McDonald and others (1993) conducted a study on the conversion of red maple factory-grade logs for production of structural 2 by 4's. Study results indicated that hardwood design property values may only be conservatively estimated on the basis of clear wood computational procedures. Another study is investigating joist and plank lumber grade yield from railroad switch ties for five hardwood species (McDonald and others [in press]), in an attempt to develop a structural lumber product that does not compete with hardwood sources used by the furniture industry. Preliminary results with red oak, hickory, yellow poplar, and red maple switch ties indicate yields of nominal 2- by 7-in. lumber to exceed 90 percent No. 3 & better lumber.

Railroad switch ties and log cants have significant potential as a source for structural lumber. Hardwood sawmills frequently avoid processing inner-log portions because of inadequate appearance grade recovery. Hardwood cants sawn into structural lumber would provide sawmills with an enhanced opportunity for value-added production. The recovery concept first obtains appearance-type lumber from high quality outer-log portions, then stress-graded dimension lumber from the heart cant. Small 2- by 4- or 2- by 6-in. (2 by 6) nominal cant-sawn lumber could be used for manufacture of hardwood glulam timbers. Wide-width glulam timber products could be fabricated by manufacturing laminations with two narrow-width lumber specimens laid edge-to-edge. Using laminations made from lumber placed edge-to-edge is an accepted practice for glulam beam fabrication (ANSI 1992). More commonly, this practice is reserved where glulam beam width exceeds largest available dimension lumber. These two-member laminations can include lumber pieces of either a glued or unglued edge joint.

Several articles have reported on the mechanical properties of edge-glued dimension lumber. Edge-glued Southern Pine lumber was studied to develop a solution to projected shortages of wide-dimension construction lumber (McAlister 1973). Another study was conducted with Douglas-fir clear wood that was edge-glued in various combinations with structural No. 3 and L1, L2, and L3 lamination grades of lumber (Johnson 1978). Both studies suggest that edge-to-edge combinations can provide enhanced lumber products or beams with increased mechanical performance. This is due to the reduced influence of width effect in the laminating stock, as a result of using two narrow-width pieces of lumber.

Objectives and Scope

No research has been reported that thoroughly evaluates the mechanical performance of glulam products composed of unglued two-member laminations. Design stresses for these structural glulam timbers are established according to ASTM D3737. This standard specifies for laminations that lumber edge joints must be glued unless calculations or experimental data provide verification of structural performance. In addition, no research has been reported on glulam timber made from two-member laminations when tested in the vertically laminated orientation (loads applied parallel to the wide face of the laminations).

In our study reported here, two objectives were addressed to examine several aspects of red maple glulam product performance using low grade and small nominal-sized lumber processed from resawn cants. The first objective was to develop a glulam beam configuration using No. 3 grade lumber for 50 percent of the inner laminations that would achieve a design bending stress of 2,400 lb/in^2 and a design bending MOE of 1.8×10^6 lb/in^2 (24F–1.8E). Fifteen 24F–1.8E red maple glulam beams were manufactured for evaluation of bending strength and stiffness. The second objective focused on determining bending strength, shear strength, and bending stiffness properties of glulam beams made with No. 2 grade laminations having unglued nominal 2 by 4's and 2 by 6's laid edge-to-edge. These beams were evaluated with loads applied parallel to the wide face of the laminations (y–y beam axis). In addition, fifteen 2 by 4 and 2 by 6 glulam beams made with No. 2 visually-graded red maple lumber were manufactured for evaluation of flexural properties with load applied perpendicular to the wide face of the laminations (x–x beam axis). An additional set of twelve 2 by 4 and 2 by 6 glulam beams were fabricated for evaluation of beam shear strength in the y–y beam axis.

Experimental Design

Prior to procuring materials and manufacturing the glulam beam combinations for our study, it was necessary to determine the feasibility of achieving the targeted design stresses. Research by Manbeck and others (1993), Moody and others (1993), and Shedlauskas and others (1994) showed that glulam combinations made from red maple, yellow poplar, and red oak lumber, respectively, could achieve design stresses of 2,400 lb/in^2 in bending strength and 1.8×10^6 lb/in^2 in bending stiffness. Based on these research studies, E-rated hardwood lumber properties were established for ASTM D3737 analytical procedures. Results of these previous studies provided estimates of the lumber properties (Table 2).

Table 2—Estimated property values of red maple lumber for use in ASTM D 3737 procedures

Lamination grade	MOE ($\times 10^6$ lb/in^2)	$\bar{x}$[a] (%)	$\bar{x}$ + h[b] (%)	SR_{min}[c]	Bending stress index (lb/in^2)
2.0-1/6	2.0	3.0	27.0	0.70	3,250
2.0-1/3	2.0	5.0	35.0	0.60	3,250
1.8-1/3	1.8	5.0	35.0	0.60	2,750
No. 2	1.5	8.0	42.0	0.54	2,470
No. 3	1.4	10.0	50.0	0.39	2,470

[a] $\bar{x}$ = average of sum of all knot sizes within each 1-ft length, taken at 2-in. intervals.
[b] $\bar{x}$ + h = 99.5 percentile knot size (ASTM 1993).
[c] SR_{min} = minimum bending strength ratio.

Glulam With No. 3 Core Laminations

Efficient, red-maple glulam combinations studied by Manbeck and others (1993) were recently proposed for inclusion in the industry standard for hardwood glulam, AITC 119. The major differences between the Manbeck and others study and our study presented here are that all lumber for our study was obtained from sawn cants and No. 3 grade lumber was targeted for the core laminating stock. Past research has also shown that ASTM D3737 procedures adequately predict the performance of hardwood glulam. The analysis conducted for this study was carried out to determine if targeted glulam design stresses (24F–1.8E) were technically feasible while utilizing the low grade core material.

Based on ASTM D3737 analytical procedures and the lumber property information in Table 2, the experimental 24F–1.8E beam configuration with No. 3 beam core laminations was developed (Fig. 1). The glulam beams were composed of outer zones of E-rated lumber and a core zone of No. 3 visually-graded lumber. Allowable edge-knot size of the E-rated lumber for the outermost 10 percent of the tension laminations was limited to one-sixth (1/6) the area of the cross section. Edge-knot size in the outer 10 percent of the compression laminations was restricted to one-third (1/3) the area of the cross section. Bending stiffness for these two outermost tension and compression zones required E-rated lumber meeting an average MOE of 2.0×10^6 lb/in^2. Edge-knot size in the next inner 15 percent of the tension and compression laminations was restricted to one-third (1/3) the area of the cross section. Bending stiffness for the two next inner zones required average lumber MOE values of 1.8×10^6 lb/in^2. In addition, ASTM D3737 procedures require that 5 percent of the outermost tension laminations be replaced with a special tension grade lumber meeting the criteria summarized in Table 3.

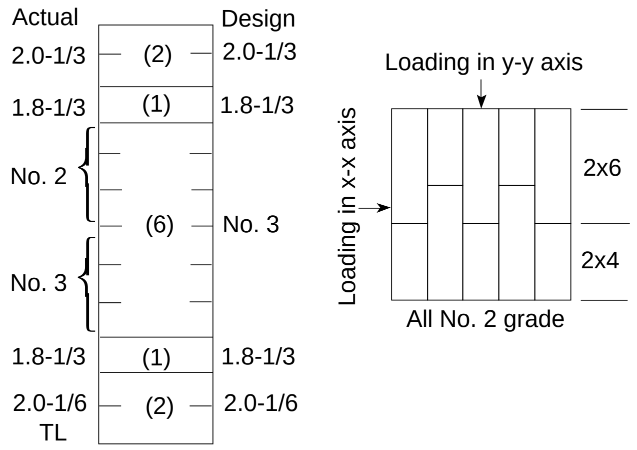


Figure 1—Illustration of red maple glulam: (left) 24F–1.8E combination and (right) 2 by 4/2 by 6 combination.

Table 3—Maximum allowable tension lamination criteria for 24F–1.8E glulam beam combination

Characteristic	Maximum allowable[a]
Edge knot + grain deviation	30 percent
Center knot + grain deviation	40 percent
Slope of grain	1:16

[a] Knots plus grain deviations are given in percentages of cross section per ASTM D3737 (1993).

2 by 4 and 2 by 6 Wide-Width Glulam Beams

This research targeted the evaluation of the beams for bending strength in the y–y beam axis and horizontal shear strength in the same y–y beam axis. Glulam timber beams with laminations made with nominal 2 by 4’s and 2 by 6’s placed edge-to-edge are referred to as 2 by 4/2 by 6 beams throughout the remainder of this report.

The dimensions of the 2 by 4/2 by 6 beams in our study were designed with a staggered arrangement of nominal 2 by 4’s and 2 by 6’s (Fig. 1), having a total of five laminations. Visually-graded No. 2 red maple lumber was used throughout the layup, and the edge interface between the 2 by 4 and 2 by 6 plies was not glued. In the proposed AITC 119 standard, vertically laminated red maple glulam beams with four or more laminations of No. 2 grade lumber have assigned design bending stresses in the y–y beam axis (F_{by}) of 1,450 lb/in^2 and design horizontal shear in the y–y beam axis (F_{vy}) of 160 lb/in^2. When laminations are made using edge-to-edge lumber, F_{vy} values are reduced to 65 lb/in^2.

Material and Methods

Lumber Manufacture and Grade Yield

Lumber for manufacture of the 24F–1.8E and 2 by 4/2 by 6 glulam combinations was processed from residual red maple log cants. Red maple (*Acer rubrum*) logs were harvested from several northcentral Pennsylvania sites. Logs were first processed with primary breakdown to recover appearance grade hardwood lumber. Primary breakdown included sawing of appearance-type lumber to recovery down to a No. 3A Common NHLA (National Hardwood Lumber Association) grade face (NHLA 1992). After appearance material was removed, the log hearts (approximate 6-in. to a minimum 4-1/2 in. dimension cants) were processed through a secondary bandmill resaw operation. Cants were sawn to a heavy 6/4 **(**final dressed thickness will equal 1.5 in.**)** hardwood lumber thickness tolerance. Immediately after sawing, the rough lumber was tallied to monitor the amount of 2 by 4 and 2 by 6 material available for experimental beam fabrication and graded green according to NELMA (Northeastern Lumber Manufacturers Association) grading rules to estimate structural grade yield.

Initial green lumber tally indicated a structural grade recovery as follows: 5.8 percent Select Structural (SS), 24.8 percent No. 1, 40.9 percent No. 2, 19.8 percent No. 3, and 8.7 percent below grade material. Collectively, No. 3 & better lumber equaled a 91.3 percent recovery for the resawn cants. Recovery coincided closely to the grade yield results for structural lumber processed from sawn railroad switch ties. A yield of 30.6 percent for SS and No. 1 lumber was greater than anticipated. The No. 1 & better recovery and relatively low percentage of below grade lumber (cull) were undoubtedly influenced by cant selection.

Grading, Sorting, and Stiffness Evaluation

The lumber was kiln dried to approximately 12-percent moisture content. After drying, the red maple lumber was processed through a surface planer. Planer operation was set-up for a 1.49-in. thickness for dressing of lumber surfaces. Lumber shrinkage dictated this dressed dimension to minimize planer skip. Dressed lumber was then transported to the cooperating glulam manufacturing facility. Lumber was sorted again at the laminating plant to account for lumber degradation after the kiln-drying process. Significant amounts of No. 3 green grade were removed from the initial lumber population as a result of drying-related defects of bow, twist, and excessive end splits, which fell outside of the No. 3 grade limitations. Less severe end-split defects of all lumber were removed. The four lumber grades were visually sorted into grades meeting tension lamination criteria, one-sixth (1/6) and one-third (1/3) edge-knot size restrictions, as well as No. 3 lumber. The fractions, 1/6 and 1/3, refer to the amount of cross-sectional area of the lumber that is occupied by a knot. The remaining lumber not meeting the stated edge-knot requirements was assigned to the No. 3 visual grade. Additional sorting was conducted to separate supplies of nominal 2 by 4 and 2 by 6 No. 2 lumber for fabrication of the 2 by 4/2 by 6 glulam beams.

When the lumber grades were visually sorted, stiffness properties were determined with commercial transverse vibration equipment (Metriguard 1993). Each piece of lumber was marked with an identification number, and the corresponding stiffness was recorded. A small sample of lumber was tested for flatwise MOE as specified in AITC T116 (AITC 1992) to establish a regression relationship between dynamic and static lumber MOE (Fig. 2). The difference between dynamic MOE and static MOE was found to be greater than 5 percent; this was due to inconsistent calibration of the test equipment. Thus, for subsequent analyses with the ASTM D3737 procedures, dynamic MOE values were adjusted using the regression relationship. Sorting of the lumber to achieve the targeted MOE levels (Table 2) followed specifications published in AITC 117–Manufacturing for E-rated laminating lumber (AITC 1993) (Table 4). Special tension lamination material meeting the criteria in Table 3 was selected from the available E-rated 2.0–1/6 lumber.

Knot Properties

After the required amounts of lumber were sorted, knot property data were measured for most of the grades. Knot data were collected for all specimens of special tension lamination material, all 2.0–1/6 pieces, and randomly selected samples of the No. 2 and No. 3 lumber. Additional knot data were collected for the No. 2 grade 2 by 4 lumber intended for the

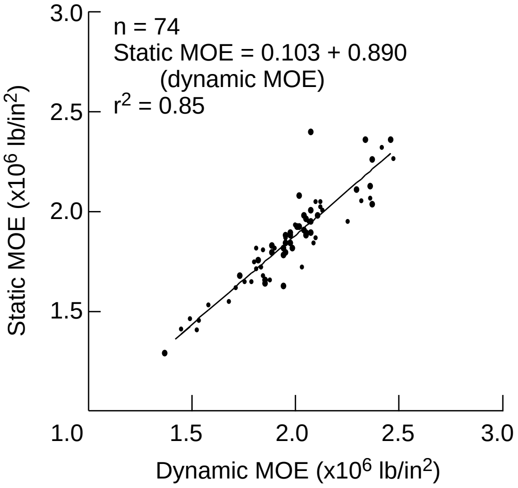


Figure 2—Relationship between static and dynamic MOE.

Table 4—Target MOE values and sorting scheme

Lamination grade	Sorting and grading criteria
2.0–1/6	MOE average between 2.0 to 2.1×10^6 lb/in^2 No piece < 1.60×10^6 lb/in^2 5th percentile of at least 1.67×10^6 lb/in^2 No piece > 2.4×10^6 lb/in^2 Edge knot limited to 1/6 cross section
2.0–1/3	MOE restrictions same as for 2.0–1/6 grade Edge knot limited to 1/3 cross section
1.8–1/3	MOE average between 1.8 to 1.9×10^6 lb/in^2 No piece < 1.40×10^6 lb/in^2 5th percentile of at least 1.45×10^6 lb/in^2 No piece > 2.2×10^6 lb/in^2 Edge knot limited to 1/3 cross section

2 by 4/2 by 6 beam fabrication. As a result of the time constraints, knot data for the 1/3 edge-knot grades were not gathered (2.0–1/3 and 1.8–1/3). Knot data were later analyzed according to procedures in USDA Technical Bulletin 1069 (Freas and Selbo 1954). Later analyses requiring knot data information for the 1/3 edge-knot grades would use that reported by Manbeck and others (1993).

Glulam Beam Manufacture

24F–1.8E Glulam Beams

The 12-lamination 24F–1.8E red maple glulam beams of 30-ft length were manufactured from nominal 2 by 6's. As a result of greater than anticipated drying losses of No. 3 grade lumber, approximately half the core laminations had to be replaced with No. 2 grade lumber. The No. 3 grade laminations were placed on the tension side of the core, and No. 2 grade laminations were placed in the compression side of the core (Fig. 1). Thus, ultimate glulam beam failures occurring in the core laminations would likely be caused by the strength of the No. 3 grade lumber. Based on a simple transformed section analysis, it was determined that the three No. 2 grade core laminations would account for approximately 6.2 percent of the glulam beam stiffness. Two additional No. 3 core laminations were substituted into glulam beams RM6-12, RM6-13, and RM6-14. For later analysis, all E-rated laminations and the outer-core laminations were identified during dry layup to develop beam maps of lumber stiffness properties. A total of 15 glulam beams were manufactured based on the available supplies of lumber having proper grade characteristics.

Because the performance of the tension lamination finger joints are a critical part of glulam beam performance, finger-joint specimens were gathered during beam manufacture to determine their ultimate tensile strength. Finger joints used in this study were vertically oriented (fingers visible on the wide face of the lumber). Because of the low-quality cant-sawn lumber resource, adequate sample sizes of lumber specimens meeting the special tension lamination grade requirements for both glulam beam and finger-joint specimen manufacture were difficult to obtain. Thus, beam manufacture was given greater priority for allocation of available tension lamination material compared with finger-joint sampling. After an initial selection of tension lamination quality material from the sorted 2.0–1/6 lumber, it was apparent that adequate quantities of tension lamination material would not be available for finger-joint sampling. Thus, a second selection process was carried out to gather those pieces of lumber that had grade characteristics at or near the allowable tension lamination grade requirements. Thus, those lumber specimens gathered for beam manufacture had a range of qualities meeting the tension lamination grade requirements, and the grade characteristics of the finger-joint specimens were heavily weighted toward the maximum characteristics allowed in the grade.

2 by 4/2 by 6 Glulam Beams

The 2 by 4/2 by 6 glulam beams were manufactured with five laminations that resulted in approximately a 6.5-in. depth, 8-in. width, and 13.3-ft length. Procedural steps followed for manufacture of 2 by 4/2 by 6 glulam beams were almost identical to conventional lumber lamination procedures. One major difference was that lumber widths were staggered in adjacent beam lamination layers (Fig. 1) during final layup. No attempt was made to bond the lumber on the longitudinal edge-to-edge joint. Some edge-to-edge joints became partially bonded as adhesive flowed into a joint as a result of the application of clamp pressure during beam assembly. Edge-joint quality varied from having tight-edge surface contact to open gaps observed along the lamination edge length. Figure 3 shows a cross section of a 2 by 4/2 by 6 glulam beam to illustrate the variable nature of edge-joint gaps. The location of lumber identification numbers of each 2 by 4 and 2 by 6 specimen was mapped so that MOE properties of the glulam beam could be later estimated based on the MOE properties of the constituent lumber. Fifteen 13.3-ft-long 2 by 4/2 by 6 beams were fabricated for evaluation of bending strength and twelve 7.5-ft-long 2 by 4/2 by 6 beams were fabricated for evaluation of horizontal shear strength.

Modifications to Manufacturing Procedures

In previous work (Manbeck and others 1993), portions of tested red maple glulam beams exhibited shallow wood failure at the gluelines that were caused by an inadequate gluing surface. The rough surfaces of the red maple lumber were caused by processing of the high-density lumber through surface planers operating at speeds that were adequate for

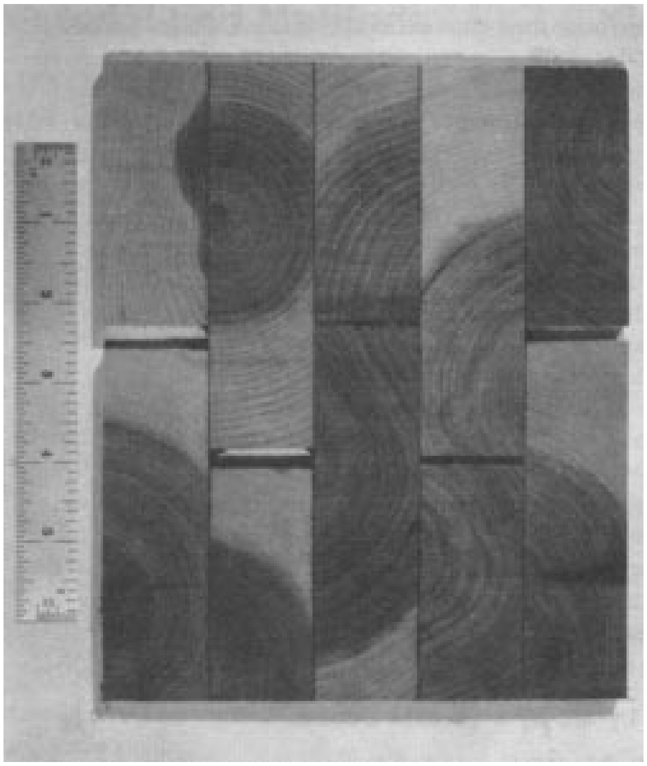


Figure 3—Cross section of 2 by 4/2 by 6 glulam combination, showing variation in gaps between edge joints.

softwoods. To produce adequate bonding surfaces, lumber feed rates into the surface planer were reduced and clamping pressures applied during glulam beam curing were increased. The AITC T103 (1992) procedures were followed to develop a relationship between torque and tension bolt force.

Preparation for Testing

After manufacture, the 24F–1.8E glulam beams were transported to the testing facilities. Beams were visually inspected to ensure conformance to ANSI A190.1 (1992) for glulam products. The inspection was also conducted to determine relative visual qualities of the tension lamination in the midlength region that would be subjected to greater than 85 percent of maximum bending moment during test. The midlength region was rated with a system developed on the basis of maximum allowable strength-reducing characteristics (Table 3). The relative rating system to assign lamination quality is detailed in Table 5.

Evaluation Procedures

Testing equipment and procedures for evaluating the glulam beams and the end-jointed lumber specimens followed criteria in ASTM D198 (1993a).

24F–1.8E Glulam Beams

The glulam beams were destructively evaluated using ASTM D198 procedures. Loading configuration included a 28-ft reaction support span with a 6-ft load span as shown in Figure 4. Long-span deflection was measured at the neutral axis over the unsupported beam length. Shear-free deflection was also measured over a 5-ft span between the loading points. Physical properties of weight, moisture content, and dimensions were measured on individual beam specimens. Measurements were recorded for the failure load and time-to-failure tests. Efforts were also made to take notes on failure type with sketches of beam failure pattern. Moisture content was determined after failure using a resistance-type moisture meter with measurements on each lamination near mid-span location. Beam weights were measured prior to testing on a mobile scale to an approximate 10-lb accuracy. Dimensions of width and depth were taken at beam load positions. During loading, full-span deflection readings were recorded at specified incremental loads to compute beam stiffness from a regressed fit of load-deflection data up to design load.

Finger-Jointed Lumber

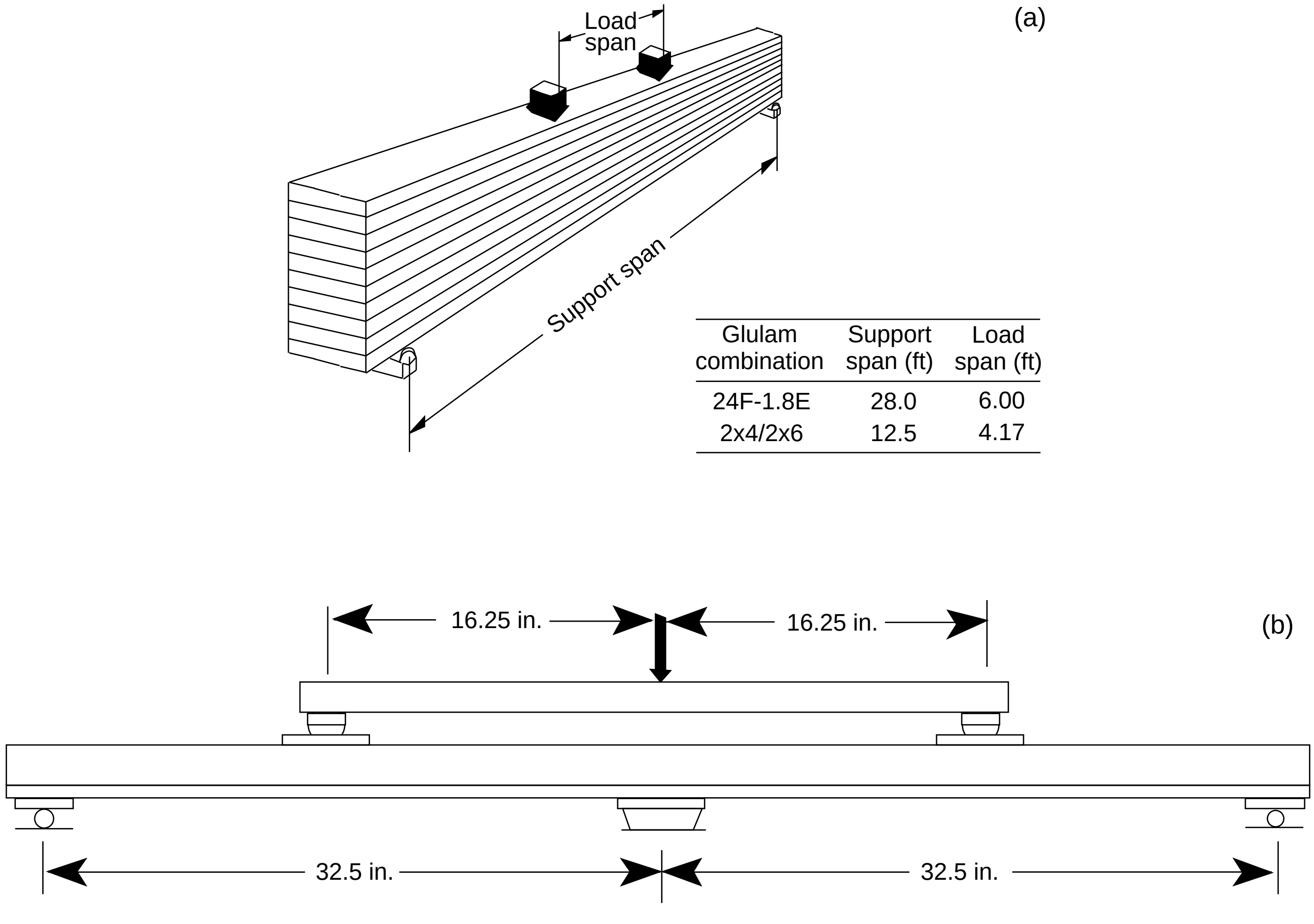
The finger-jointed specimens were evaluated to determine their ultimate joint tensile strength. Only 15 test specimens had been prepared for tensile strength evaluation because of the limited supplies of special tension lamination grade material. Test specimens were face- and surface-planed prior to testing to similar dimensions as the laminations used for beam manufacture. Prior to test, each specimen was evaluated with an E-computer to obtain a dynamic MOE measurement. Specimens were approximately 8-ft long with the finger joint located near midlength. Tests included a 30-in. gage length centered between machine grips, with increasing tensile load applied until failure. Loading rate was calibrated to achieve an approximate 5- to 10-min time to failure. This loading is longer than the 3 to 5 min recommended by AITC T119 for daily quality control testing. The 5 to 10 min used in our study coincided with the failure times targeted for the full-size glulam beam tests, which followed ASTM D198 procedures.

Upon test completion, observed fracture was mapped for each finger-joint specimen. For specimen mapping, the location of the finger joint between the tension machine grips was defined as zero (0), and the propagation of failure was mapped from a positive (+) to negative (−) distance with respect to the finger joint. If the 0 location was absent from a mapped failure description, then failure did not occur at a finger joint and the test result was not considered in the finger-joint analysis. After tension testing, small wooden sections from either side of the finger joint were removed for specific gravity determination.

Table 5—Relative rating system for tension lamination quality of 24F–1.8E glulam beams

Characteristic	ASTM D3737 allowable value	Lamination quality		
		Low	Medium	High
Edge Knot + Grain Deviation	30 percent	>20 percent	10–20 percent	10 percent
Center Knot + Grain Deviation	40 percent	>20 percent	15–30 percent	<15 percent
Slope of Grain	1:16	<1:18	1:18–:20	>1:20
MOE (x10^6 lb/in^2)	2.0E (avg.)	<1.75 w/char[a]	<1.75 and clear	—

[a] w/char designates lumber with characteristics. For example, if a board has an MOE of <1.7E and a edge-knot, center-knot, or slope-of-grain characteristic, it is classified as low quality.



Glulam combination	Support span (ft)	Load span (ft)
24F-1.8E	28.0	6.00
2x4/2x6	12.5	4.17

Figure 4—Loading configurations for (a) bending and (b) shear tests of red maple glulam beams.

2 by 4/2 by 6 Glulam Beams

Flexural tests followed ASTM D198 procedures for all 2 by 4/2 by 6 glulam beam specimens. A computerized data acquisition system was used to monitor load-deflection response. Loading rate for maximum load was adjusted for a 5- to 10-min time-to-failure test duration. Deflection measurements were taken using a linear variable differential transformer (LVDT) on a yoke affixed to the neutral axis of the specimen. The MOE values were computed from a linear regression analysis of load-deflection data up to design load.

The 2 by 4/2 by 6 specimens of 80-in. (7.5-ft) length were also processed from the 2 by 4/2 by 6 glulam materials to characterize beam shear strength (τ). Beam shear strength evaluation was conducted utilizing a five-point loading scheme recommended by Soltis and Rammer (1994). The test apparatus consists of three reaction supports, located at either beam end and midspan, and two loading points, each located equidistant from midspan (Fig. 4). Specimen length was 10 times the member depth, with span between the reaction supports equal to 5 times the depth. Concentrated loads were applied through bearing plates to minimize compressive failure. Test speed was selected so that shear failures would occur between 5 and 10 min after load application. After failure, beam shear failure zones were sketched and moisture content determined with a resistance-type meter.

The ASTM D143 (1993b) shear-block specimens were fabricated using wood samples obtained from locations adjacent to the shear failure zones of the 2 by 4/2 by 6 glulam beams. An evaluation could include one or more observations of shear strength relative to the multiple lumber piece construction. Individual observations were averaged as a measurement of ASTM D143 shear strength for each failed 2 by 4/2 by 6 lamination. Two data sets were developed with one set tested at ambient or unconditioned moisture content and the other after conditioning to constant weight at 12 percent equilibrium moisture content. A numerical code system was developed to describe location of each solid-wood shear specimen relative to its position within a particular 2 by 4/2 by 6 glulam beam. For example, a sample observation removed from the third lamination (3) of the red maple 2 by 4/2 by 6 beam having the identification number RMC6-1 (6-1) would have a shear-block identification number of 6–1–3.

Evaluation Results

Glulam Manufacture

To determine if the targeted laminating lumber MOE criteria in Table 2 were achieved, the glulam beam maps compiled during beam manufacture were analyzed to determine the final arrangement of the sorted lumber. Table 6 gives a statistical summary of MOE measurements of those lumber specimens used in the fabricated beams for both the 24F–1.8E and 2 by 4/2 by 6 glulam combinations. Note that the special tension lamination and all the E-rated grades (2.0–1/6, 2.0–1/3, 1.8–1/3) met or slightly exceeded the targeted average MOE values. Both visual grades (No. 2 and No. 3) greatly exceeded the assumed property values in Table 2.

Table 6—MOE values of sorted laminating lumber in glulam beams

Lumber width (in.)	Lumber grade	Number of pieces	Average MOE ($\times 10^6$ lb/in^2)	COV (%)
2 by 6	TL[a]	55	2.15	7.8
	2.0–1/6	56	2.05	9.7
	2.0–1/3	113	2.02	9.4
	1.8–1/3	114	1.79	9.1
	No. 2	160	1.84	10.9
	No. 3	25	1.68	11.4
2 by 4	No. 2	161	1.82	15.3

[a] TL = tension lamination.

Table 7—Knot sizes of sorted laminating lumber

Nominal lumber size	Lumber grade	Lineal footage (ft)	$\bar{x}$[a] (%)	$\bar{x}+h$[b] (%)
2 by 6	TL[c]	212	0.5	15.0
	2.0–1/6	282	1.5	34.8
	TL and 2.0–1/6 combined	494	0.9	29.3
	No. 2	221	2.3	27.4
	No. 3	221	5.2	51.5
2 by 4	No. 2	200	3.0	47.5
2 by 4/ 2 by 6 combined	No. 2	421	2.7	36.4

[a] $\bar{x}$ = average of sum of all knot sizes within each 1-ft length, taken at 2-in. intervals.

[b] $\bar{x}$ + h = 99.5 percentile knot size (ASTM 1993).

[c] TL = tension lamination.

The measured knot properties on the sorted lumber grades were also analyzed to determine knot size statistics. Table 7 includes a statistical summary of the knot sizes observed in each grade for lumber used in both the 24F–1.8E and 2 by 4/2 by 6 glulam beam combinations. A comparison of the results in Table 7 to knot properties observed by Manbeck and others (1993) for similar grades and widths of red maple lumber was conducted. We observed that lumber grades sorted in our study resulted in significantly larger knots when compared with those of Manbeck and others (1993). This could

Table 8—Relative quality of tension laminations in midlength region of 24F–1.8E glulam beams

Level of quality	Percentage of beams (number)
Low	47 (7)
Medium	13 (2)
High	40 (6)

be a result of the difference in lumber resource, where the lumber from our study was sawn from center log cants.

Relative qualities of the tension laminations for the 24F–1.8E glulam beams were also determined based on the criteria in Table 5. The tension lamination properties observed for each beam are summarized in Appendix A, Table A1. Results of this inspection are given in Table 8. Note the nearly equal number of low and high quality glulam beams, based on the visual characteristics of their respective tension laminations.

24F–1.8E Glulam Beams

During testing, beams emitted fiber fracture sounds before reaching ultimate failure load. Some beams were observed with localized compressive wrinkling between the load points prior to ultimate failure on the tension side. Most failures were attributed to finger joints, and other beams failed because of a combination of finger joint and other intrinsic strength-controlling characteristics. Failure occurred throughout three E-rated laminations and into the No. 3 interlaminations (Fig. 5). A tally of the estimated causes of failure is provided in Table 9. In comparison to the Manbeck and others red maple glulam study, improved glueline bonding was indicated in our study by greater percentages of wood failure and deeper adhesive penetration. Glueline-type failures were not observed and tension-side beam rupture was commonly a failure mechanism with fracture propagation through several consecutive laminations. Destructive test evaluation results on 24F–1.8E beam strength and stiffness are summarized in Table 10. Results of individual beam tests are provided in Appendix B, Table B1, and illustrations of individual glulam beam failures are provided in Appendix C. All calculations of glulam beam MOR include the dead weight of the beams.

Finger-Jointed Lumber

Results on tensile strength, moisture content, and specific gravity for the finger-jointed special tension lamination specimens are given in Table 11. Individual results for the end-joint tests and other collected data are presented in Appendix B, Table B2.

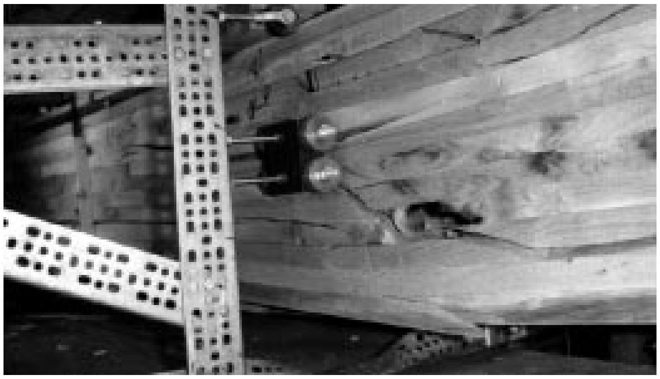


Figure 5—Rupture of a beam at ultimate load through the three E-rated laminations on the tension side and into the No. 3 grade inner laminations.

2 by 4/2 by 6 Combination Glulam Beams

For bending tests of the 2 by 4/2 by 6 glulam beams, the majority of failures involved a strength-reducing characteristic, such as knots, slope of grain, or grain deviation. The use of the edge-to-edge laminations did not appear to affect the bending strength results. Summary results from the flexural testing are presented in Table 10. Individual test observations for the 2 by 4/2 by 6 glulam beam flexural tests are included in Appendix B, Table B3.

For the horizontal shear tests of the 2 by 4/2 by 6 glulam beams, the first audible sound of failure was emitted at ultimate load; then the load-carrying capacity was observed to decrease. Because no catastrophic failure was observed during this loading sequence, cross sections of each of the 12 beams were cut at the location of failure, and the propagation of horizontal shear failure was observed. The descriptions of each failure were mapped and are illustrated in Appendix C. Summary test results for beam horizontal shear are presented in Table 12. Individual test observations for the combination beam shear tests are given in Appendix B, Table B4. The results of the ASTM D143 shear-blocks that correspond to the glulam beams are given in Table 13. Individual test observations from the ASTM D143 shear-block tests are collectively presented in Appendix B, Table B5.

Analysis of Results

The analysis conducted in this section assumes the lognormal distribution for strength property characterization, recommended by ASTM D3737. Analysis of glulam MOE, moisture content, and specific gravity were conducted assuming the normal distribution.

Table 9—Estimated causes of failure in 24F–1.8E glulam beam combination

Failure type[a]	Number of beams[b]
Compression wrinkling followed by rupture on tension side	3
Tension-side rupture in strength-reducing characteristic (other than finger joint)	2
Tension-side in clear lumber	0
Tension-side in finger joint (three had compression wrinkling)	13

[a] Tension-side refers to the outer tension laminations of a glulam beam in bending.
[b] Sum of all failures is greater than the total number of beams tested (15) as a result of beam failures with compression wrinkling.

Table 10—Summary of bending test results on 24F–1.8E and 2 by 4/2 by 6 red maple glulam beams (15 specimens)

	24F–1.8E		2 by 4/2 by 6	
	Normal	Lognormal	Normal	Lognormal
Moisture content (percent)	12.6	12.6	8.9	8.9
Modulus of rupture[a]				
Average (lb/in^2)	7,970	7,980	6,620	6,630
Coefficient of variation (percent)	12.4	12.1	10.2	10.8
5th percentile at 75 percent tolerance (lb/in^2)	6,010	6,230	5,280	5,320
Adjusted to design[b] (lb/in^2)	3,060	3,180	2,340	2,360
Modulus of elasticity				
Horizontally laminated				
Average (x10^6 lb/in^2)	1.77		1.86	
Coefficient of variation (percent)	3.0		8.3	
Vertically laminated				
Average (x10^6 lb/in^2)			1.87	
Coefficient of variation (percent)			7.1	

[a] For 24F–1.8E glulam beams, load was applied perpendicular to wide face of laminations; for 2 by 4/2 by 6 glulam beams, load was applied parallel to wide face of laminations.
[b] Adjusted MOR equals 5th percentile divided by $C_v = (5.125/W)^{0.1} (21/L)^{0.1} (12/d)^{0.1}$ and by 2.1.

Table 11—Results of 15 tension tests on finger-jointed red maple tension lamination material (specimens with failure involving end joint)[a]

Property	Value
Sample size	15
Average moisture content (percent)	13.1
Average specific gravity[b]	0.55
Average tensile strength (lb/in^2)	6,490
COV tensile strength (percent)	27.0

[a] Moisture content is based on oven-drying methods. Strength calculations assume a lognormal distribution.
[b] Based on volume at time of test and ovendry weight

Table 12—Results of beam shear strength (τ) for 2 by 4/2 by 6 glulam beam combination (sample size: 12 beams, 8.9-percent moisture content)

Distribution	Average τ (lb/in^2)	COV of τ (%)	$\tau_{0.05}$ at 75% tolerance
Normal	1,730	7.1	1,490
Lognormal	1,730	7.4	1,490

Table 13—Results of ASTM D143 solid wood shear (τ) strength from failed laminations of 2 by 4/2 by 6 glulam beams (sample size: 25 each)[a]

Distribution	Average τ (lb/in^2)	COV of τ (%)	Average MC (%)	$\tau_{0.05}$ at 75% tolerance	(τadjusted)[b]
Normal					
Unconditioned	1,940	11.7	8.7	1,490	362
Conditioned to 12 percent EMC	1,820	8.3	12.7	1,520	371
Lognormal					
Unconditioned	1,940	11.8	—	1,490	364
Conditioned to 12 percent EMC	1,830	8.5	—	1540	384

[a] EMC is equilibrium moisture content; COV is coefficient of variation; MC is moisture content based on oven-drying method.

[b] (τadjusted) equals $\tau_{0.05}$ divided by 4.1.

Design Strength and Stiffness Comparison

24F–1.8E Glulam Beams

The design bending strength of the 24F–1.8E glulam beams is reported in Table 10. The design bending strength level of 3,180 lb/in^2 far exceeds the targeted 2,400 lb/in^2. The results in our study are similar to the 24F–1.8E glulam beam results observed by Manbeck and others (1993), where the design bending strength for 42 beams from 3 different sizes was 3,150 lb/in^2.

For structural finger joints, the ANSI A190.1 standard requires that the 5th percentiles of finger-joint tensile strength (at 75 percent tolerance) meets a strength level that is 1.67 times the targeted design bending strength of the glulam beams. For the 2,400 lb/in^2 glulam in our study, the end joints were required to meet a 5th percentile tensile strength of approximately 4,010 lb/in^2. From the results shown in Table 11, a 5th percentile of end-joint tensile strength of 3,480 lb/in^2 was calculated, which translates to a design level of 2,080 lb/in^2. The previous discussion on material sorting explained that sampling of tension lamination grade lumber for finger-joint specimen fabrication was heavily weighted towards maximum allowable characteristics of the grade. A comparison of finger-joint tensile strength in Table 11, with the red maple finger-joint results from Manbeck and others (1993), gives some insight on the probable quality of the finger joints sampled in our study. Only average values were compared because of the relatively small sample sizes. For nominal 2 by 6 tension lamination quality finger joints, Manbeck and others observed an average tensile strength of 8,720 lb/in^2 for the 26 finger joints sampled, which is much greater than the 6,530 lb/in^2 value we observed. However, the average tensile strength for 16 specimens of 2.0-1/6 finger joints in the Manbeck and others study had an average of 7,160 lb/in^2, which is closer to the average observed in our study. Thus, it appears that the group of finger joints sampled for our study had tension lamination grade characteristics that were heavily weighted toward the maximum allowable characteristics. Because 13 of the 15 beams exhibiting failures at end joints (Table 9) and glulam beam results greatly exceeded targeted strength levels (Table 10), all evidence indicates that the end joints used for beam manufacture were adequate for the 2,400 lb/in^2 design bending strength.

For glulam beam bending stiffness, the average MOE reported in Table 10 was 1.77×10^6 lb/in^2. Results show that the use of E-rated lumber in the beam configuration (Fig. 1) will achieve the targeted 1.8×10^6 lb/in^2 beam stiffness. In addition, as is typical with the use of E-rated lumber in glulam manufacture, the variability of beam MOE was quite low (3 percent coefficient of variation).

2 by 4/2 by 6 Glulam Beams

The results in Table 10 show that the calculated design bending strength for the 2 by 4/2 by 6 glulam beam combination was 2,360 lb/in^2, which greatly exceeds the published design bending stress for No. 2 red maple of 1,450 lb/in^2 (AITC 1985). From Table 12, the calculated 5th percentile (at 75 percent tolerance) of horizontal shear strength for the 2 by 4/2 by 6 glulam beams was 1,490 lb/in^2. Methods for determining horizontal shear design values from glulam beam test results are not established. For small, clear test specimens, design values for horizontal shear strength are determined by dividing the calculated 5th percentile horizontal shear strength of ASTM D143 shear-block specimens by a factor of 4.1, which accounts for a combined effect of duration of load, stress concentration, and safety. Given that published design horizontal shear strength for No. 2 red maple glulam with multiple-piece laminations and having 4 or more laminations is 65 lb/in^2, the results observed in Table 12 would greatly exceed published values, even with a factor of 4.1.

For bending stiffness, the proposed AITC 119 standard publishes the same value for orientations loaded with respect to the y–y and x–x beam axes (see Fig. 1 for orientations). For No. 2 red maple glulam, the published MOE is 1.3×10^6 lb/in^2, which is very conservative compared with the 1.87×10^6 lb/in^2 experimental value observed in the y–y orientation and the 1.86×10^6 lb/in^2 value observed in the x–x orientation (Table 10).

Predicted Strength and Stiffness Comparison

In this section, analysis procedures were used to predict the performance of the glulam test results using the available lumber properties information.

Bending Strength of 24F–1.8E

Actual MOE data from Table 6 and actual knot property data from Table 7 were used to predict the performance of the 24F–1.8E glulam combination using ASTM D3737 procedures. Knot property information from Manbeck and others (1993) was used for the 2.0–1/3 and 1.8–1/3 grades, because data were not obtained for these grades in our study. Minimum strength ratios were used as originally planned (Table 2). For bending stress indices, a value of 3,250 lb/in^2 for E-rated lumber having an average MOE of 2.0×10^6 lb/in^2 (2.0E) was planned (Table 2). This value is currently in the ASTM D3737 standard, which is based on a linear interpolation between a bending stress index value of 3,000 lb/in^2 for 1.9E lumber to a bending stress index of 4,000 lb/in^2 for 2.1E lumber. In Manbeck and others (1993), an analysis was made to determine appropriate bending stress index levels for 2.0E red maple lumber. Based on the analysis of 42 red maple glulam beams, a bending stress index of 3,500 lb/in^2 was found to be applicable for 2.0E red maple lumber. Thus, we concluded that the bending stress indices specified in the D3737 standard for E-rated grades of lumber, which are based on softwood data from past research, are conservative when applied to red maple. Based on the findings of Manbeck and others, a bending stress index of 3,500 lb/in^2 was used in our study for 2.0E red maple lumber, and a bending stress index of 3,000 lb/in^2 was used for 1.8E red maple lumber.

Analysis of the 12-lamination 24F–1.8E glulam combination resulted in a maximum design glulam bending strength of approximately 2,800 lb/in^2. The analysis indicates that the calculated strength is controlled by the strength of the region occupied by the 2.0–1/6 grade. A comparison between the 2.0–1/6 knot properties from our study ($x = 1.5$ percent and $x + h = 34.8$ percent) and those from Manbeck and others ($x = 0.1$ percent and $x + h = 13.6$ percent) shows a significant difference, especially with the $x + h$ values. The knot properties reported by Manbeck and others for the 2.0-1/6 grade resemble the properties reported in this study for the tension lamination grade ($x = 0.5$ percent and $x + h = 15.0$ percent). When the same combination was analyzed using the tension lamination knot properties instead of the 2.0–1/6 knot properties from this study, the maximum calculated design bending strength was 3,080 lb/in^2.

Although the large knot sizes observed in our study could be attributed to the small sample size, note that another explanation could be the resource of cant-sawn lumber. The gathered 2.0–1/6 material from cant-sawn lumber would likely have different knot characteristics (e.g., pith-associated wood, spike knots) than lumber sawn from full-sized logs, such as used in the Manbeck and others study. Analysis of knot sizes on two types of timber resources may have resulted in vastly different knot properties for the two studies. Consequently, this would affect the predicted design bending strength values using standard ASTM D3737 procedures. Similarities between our study and that of Manbeck and others showed that D3737 predictions of design bending strength values for 24F–1.8E glulam beams made with E-rated red maple lumber were very conservative.

24F–1.8E Bending Stiffness

For glulam stiffness, actual lumber MOE values from individual beam maps were used in a transformed section analysis to predict each individual glulam beam MOE (portions of the beam map are shown in Appendix C). The calculated glulam MOE values were then reduced by a factor of 0.95 to account for shear deformation effects. The transformed section method of analysis and the 0.95 factor are specified in the ASTM D3737 standard for calculating horizontally laminated glulam beam MOE. The individual analyses resulted in a predicted average glulam beam MOE of 1.85×10^6 lb/in^2, having a coefficient of variation of 2.0 percent. This compares well with the actual average glulam beam MOE of 1.77×10^6 lb/in^2, having an actual coefficient of variation of 3.0 percent (less than 5 percent difference in the average). These differences can be attributed to the variations in the regression relationship shown in Figure 2, which indicates a coefficient of determination (r^2) value of less than 0.9.

2 by 4/2 by 6 Bending Strength

The 2 by 4/2 by 6 glulam beams in our study were evaluated for loads applied parallel to the wide face of the laminations (y–y beam axis). The ASTM D3737 standard specifies procedures for determining the design bending strength of vertically laminated glulam beams (F_{by}). The procedures are based on the characteristics of the single-ply laminations using the allowable edge- and center-knot sizes and allowable slope-of-grain for the particular grade of lumber. For No. 2 red maple (NELMA 1991), the allowable edge-knot size is 35 percent of the cross section, allowable center-knot size is 50 percent of the cross section, and allowable slope-of-grain is 1:8 (1 in. of grain deviation per 8 in. of length). Because the finished depth of the beams (width of the vertically oriented laminations) was approximately 7.88 in., an allowable 50 percent center knot would have a diameter of 3.94 in. and an allowable 35 percent edge knot of 2.76 in. However, because the laminations in our study were made from a combination of nominal 2 by 4's and 2 by 6's, the largest allowable center and edge-knot characteristics would be the allowable sizes for the 2 by 6's. After planing of the glulam beams, the final width of the 2 by 6's was approximately 4.25- to 4.88-in. wide (based on estimates in Fig. 3). Using a width of 4.88-in., the allowable center and edge-knot sizes would be 2.44 and 1.71 in., respectively.

For No. 2 red maple vertically laminated glulam, D3737 analyses predicted a design bending strength of 1,310 lb/in^2. This prediction was based on the controlling strength ratio for slope-of-grain. If the analysis was based solely on the calculated strength ratios for the allowable knot sizes (overriding the slope-of-grain strength ratio), the predicted design bending strength would be 1,550 lb/in^2. Details of the ASTM D3737 calculations are provided in Appendix D. Note that the inherent nature of analyzing 2 by 4/2 by 6 glulam combinations using D3737 procedures would result in greater predicted design bending strength values than those predicted for single-member laminations.

In the AITC 119 standard (AITC 1985), the use of two-member laminations is not considered for establishing design bending stresses for vertically laminated members. Published design bending stress for vertically laminated glulam beams (F_{by}) made from No. 2 red maple lumber is 1,450 lb/in^2. All predicted and published F_{by} values are very conservative when compared with the calculated design bending strength of 2,360 lb/in^2 given in Table 10.

2 by 4/2 by 6 Bending Stiffness

For stiffness of the 2 by 4/2 by 6 glulam beam combination, ASTM D3737 procedures were used to determine the glulam MOE of the members tested in both the horizontally (MOE_x) and vertically laminated (MOE_y) orientations. The analysis resulted in a predicted average glulam beam MOE_x of 1.74×10^6 lb/in^2, which is approximately 7 percent less than the observed value of 1.86×10^6 lb/in^2. Predicted glulam MOE_y was 1.75×10^6 lb/in^2, which was also approximately 7 percent less than the observed value of 1.87×10^6 lb/in^2. As was the case with the 24F–1.8E glulam beams, differences between actual and predicted glulam MOE were attributed to the variation in the regression relationship of the lumber properties illustrated in Figure 2.

2 by 4/2 by 6 Horizontal Shear Strength

Procedures are also given in ASTM D3737 for determining design horizontal shear stresses for vertically laminated glulam timber. Similar procedures to those shown in Appendix D for determining 5th percentile of clear wood MOR were used to determine 5th percentiles of clear wood shear strength. An 886 lb/in^2 clear wood shear strength for red maple (ASTM 1993c) was multiplied by a 0.222 horizontal shear adjustment factor for hardwoods and a 1.13 seasoning factor, as specified in ASTM D3737. The resulting horizontal shear stress index of 222 lb/in^2 was further reduced by a horizontal shear stress modification factor of 0.5, as a result of the unglued edge joints present in each of the 2 by 4/2 by 6 laminations. Thus, based on ASTM D3737 procedures, vertically laminated glulam timber manufactured with 2 by 4/2 by 6 laminations of No. 2 red maple lumber have a calculated design horizontal shear stress of 111 lb/in^2.

This value is similar to the design horizontal shear stress of 65 lb/in^2 published in the proposed AITC 119 standard. However, both the predicted and published values are very conservative when compared with the actual values given in Table 12.

In addition to establishing design horizontal shear values for the full-sized glulam beams with ASTM D3737 procedures, a different approach to determining horizontal shear strength of glulam timber was studied. Rammer and Soltis (1994) established a method of predicting the horizontal shear strength of full-size glulam timber based on the tests of ASTM D143 shear-block specimens. Results from the ASTM shear-block tests are shown in Table 13. For shear-block specimens conditioned to 12-percent equilibrium moisture content, the average shear strength of 1,830 lb/in^2 is almost identical to the average shear strength of 1,850 lb/in^2 published in the *Wood Handbook* (Forest Products Laboratory 1987) for red maple.

Rammer and Soltis (1994) developed a relationship between average results of ASTM shear-block tests and full-size horizontal shear tests of glulam timber, represented by the following formula:

$$\tau = \frac{1.3C_f \tau_{ASTM}}{A^{1/5}} \qquad (1)$$

where

τ = average glulam horizontal shear strength (lb/in^2),
C_f = 2, a stress concentration factor for an ASTM shear-block notch,
τ_{ASTM} = average shear strength from ASTM D143 test (lb/in^2), and
A = shear area of glulam beam (in^2).

Substituting the average ASTM shear-block values (unconditioned specimens) in Table 13 and the shear area of the combination glulam beams into Equation (1) resulted in an estimated average glulam horizontal shear strength of 1,660 lb/in^2. This predicted result is within 4 percent of the actual average horizontal shear strength of 1,730 lb/in^2 reported in Table 12. Thus, it appears that the ASTM D143 shear-block approach developed by Rammer and Soltis (1994) provides more accurate predictions of glulam horizontal shear stresses than current the ASTM D3737 procedures.

Conclusions

Based on the full-size evaluation of 42 red maple beams, it was found technically feasible to manufacture structural glulam timber from a cant-sawn hardwood lumber resource. Specific points observed in this study include the following:

- Structural glued-laminated (glulam) timber beams manufactured with E-rated red maple lumber in the outer zones and No. 3 lumber in the core met or exceeded the target design bending stress of 2,400 lb/in^2 and modulus of elasticity (MOE) of 1.8×10^6 lb/in^2.

- Structural glulam timber beams manufactured with laminations made from No. 2 red maple 2 by 4's and 2 by 6's are technically feasible. Test results indicate that target design stresses were exceeded for vertically laminated bending strength (F_{by}), MOE in both the horizontally and vertically laminated orientations (MOE_x and MOE_y), and horizontal shear strength in the vertically laminated orientation (F_{vy}).

- The ASTM D3737 procedures developed for softwood species accurately predict beam stiffness and provide conservative bending and horizontal shear strength estimates for glulam beams made with red maple lumber.

- Using results from ASTM D143, shear-block tests accurately predicted the horizontal shear strength of red maple glulam timber made from 2 by 4/2 by 6 laminations.

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Appendix A—Relative Quality Estimates of Red Maple Lumber

Relative quality estimates of red maple lumber used for the midlength region of tension lamination of 24F–1.8E glulam beams corresponding to the relative rating system given in Table 5 are listed for each individual tension lamination in Table A1. Dynamic MOE values are listed for each piece of lumber in the critical region. Strength-reducing characteristics are described for tension laminations of the 24F–1.8E glulam beams. The MOE values and lamination characteristics correspond to those illustrated in Appendix C.

Table A1—Properties of 2 by 6's used in tension lamination

Beam	Dynamic MOE ($\times 10^6$ lb/in^2)	Characteristic	Relative quality of midlength region[b]
RM6-1	2.09	20 percent CK + GD	L
	2.30	1:10 S.O.G.	
RM6-2	1.97	Clear	L
	1.93	1:10 S.O.G.	
RM6-3	2.19	Clear	H
	2.19	Clear	
RM6-4	2.19	Clear	H
	1.75	Clear	
RM6-5	1.94	Clear	L
	2.38	50 percent grain deviation	
RM6-6	2.06	Clear	L
	2.68	25 percent EK + GD (spike knot cluster)	
RM6-7	1.94	1:18 S.O.G.	L
	2.24	Clear	
RM6-8	2.15	<10 percent CK and GD	H
	1.93	Clear	
RM6-9	1.93	20 percent GD	M
	2.05	Clear	
RM6-10	1.78	Clear	H
	2.14	Clear	
RM6-11	1.98	Clear	H
	2.19	1:18 S.O.G.	
RM6-12	2.04	1:8 Edge S.O.G.	L
	2.20	30 percent CK + GD	
RM6-13	2.36	20 percent CK and GD	M
	1.90	<5 percent CK + GD	
RM6-14	1.97	<5 percent CK + GD	H
	2.22	Clear	
RM6-15	1.88	1:10 S.O.G. and 20% t CK	L
	2.40	and GD1:20 S.O.G.	

[a] CK is center knot; GD is grain deviation; S.O.G. is slope of grain.
[b] L is low; M is medium; H is high.

Appendix B—Destructive Tests

Tables B1 to B5 give the results of the following individual destructive test evaluations:

- Bending tests of horizontally laminated (x) 24F–1.8E red maple glulam beams
- Tension tests on red maple finger-jointed tension lamination grade lumber
- Bending tests of 2 by 4/2 by 6 red maple glulam beams
- Shear strength tests of 2 by 4/2 by 6 red maple glulam beams
- ASTM D143 test evaluation of wood shear strength of failed beam laminations

Table B1—Results of bending tests of horizontally laminated 24F–1.8E red maple glulam beams[a]

		Dimension						
Beam	Beam weight (lb)	Width (in.)	Depth (in.)	MC (%)	Load at failure (lb)	Beam MOR_x (lb/in^2)	Beam MOE_x ($x10^6$ lb/in^2)	Failure type (CW,EJ,Lam)
RM6-1	746	5.00	18.03	13.8	28,360	7,161	1.85	EJ
RM6-2	743	5.00	18.03	13.1	33,750	8,503	1.78	EJ
RM6-3	743	5.00	18.09	13.0	40,990	10,240	1.73	EJ
RM6-4	740	5.00	18.11	12.7	27,890	6,982	1.76	EJ
RM6-5	743	5.00	18.10	11.6	31,200	7,808	1.73	EJ
RM6-6	743	5.00	18.05	12.6	35,600	8,945	1.78	EJ
RM6-7	743	5.00	18.05	12.6	36,510	9,172	1.78	EJ
RM6-8	743	5.00	18.05	11.9	32,000	8,050	1.78	CW,EJ
RM6-9	743	5.00	18.06	13.5	27650	6,961	1.83	EJ
RM6-10	743	4.95	18.06	12.0	28,590	7,267	1.78	EJ
RM6-11	743	5.00	18.10	12.3	26,640	6,681	1.82	CW,EJ
RM6-12	743	5.00	18.10	12.4	34,900	8,723	1.67	Lam
RM6-13	743	4.95	18.05	12.7	30,900	7,855	1.79	CW,EJ
RM6-14	743	5.00	18.05	12.0	29,000	7,304	1.76	EJ
RM6-15	743	5.00	18.08	13.0	31,710	7,952	1.67	Lam

[a] MC is moisture content based on a resistance-type meter reading; MOR is modulus of rupture; MOE is modulus of elasticity; CW is compression wrinkling; EJ is end joint; Lam is lamination. Subscript x refers to beams loaded perpendicular to the wide face of the laminations.

Table B2—Results of tension tests on red maple finger-jointed tension lamination grade

Specimen	Height (in.)	Width (in.)	SG(1)[a]	SG(2)[a]	Maximum load (lb)	Maximum stress (lb/in^2)	Failure zone
RMFJ-1	1.30	4.84	0.51	0.54	39,800	6,317	0,0
RMFJ-2	1.30	4.82	0.53	0.54	25,420	4,047	0,+18
RMFJ-3	1.30	4.83	0.57	0.54	36,960	5,873	−16,0
RMFJ-4	1.30	4.76	0.54	0.51	36,760	5,919	0,0
RMFJ-5	1.30	4.83	0.54	0.57	21,100	3,358	0,0
RMFJ-6	1.31	4.83	0.57	0.54	41,060	6,513	0,+6
RMFJ-7	1.31	4.87	0.54	0.57	68,080	10,666	0,0
RMFJ-8	1.30	4.83	0.62	0.59	45,100	7,179	0,0
RMFJ-9	1.30	4.83	0.52	0.51	40,840	6,497	−24,0
RMFJ-10	1.30	4.84	0.60	0.53	42,260	6,707	0,0
RMFJ-11	1.30	4.84	0.59	0.53	26,520	4,213	0,0
RMFJ-12	1.30	4.83	0.53	0.55	49,280	7,840	0,+8
RMFJ-13	1.31	4.85	0.55	0.59	40,640	6,419	−9,0
RMFJ-14	1.31	4.84	0.52	0.54	49,320	7,802	−4,0
RMFJ-15	1.31	4.83	0.60	0.53	50,710	8,044	−12,0

[a] SG is specific gravity based on volume at time of test and ovendry weight; SG(1) and SG(2) refer to the specific gravity of lumber on each side of the finger joint.

Table B3—Results of bending tests of vertically laminated 2 by 4/2 by 6 red maple glulam beams[a]

Beam	Depth (in.)	Width (in.)	MC (%)	Maximum load (lb)	MOR$_y$ (lb/in^2)	MOE$_y$ ($\times 10^6$ lb/in^2)	MOE$_x$ ($\times 10^6$ lb/in^2)
RMC1-1	7.94	6.49	8.5	19,354	7,099	1.92	1.75
RMC1-2	7.95	6.48	8.3	20,419	7,474	1.92	1.82
RMC1-3	7.95	6.48	8.6	15,751	5,766	1.89	1.78
RMC2-1	7.92	6.39	9.1	20,173	7,545	1.88	1.97
RMC2-2	7.91	6.39	9.3	18,759	7,038	1.73	1.56
RMC2-3	7.93	6.42	10.0	17,578	6,529	1.80	1.73
RMC3-1	7.95	6.45	9.3	16,470	6,059	1.87	2.04
RMC3-2	7.94	6.45	9.2	17,592	6,484	1.90	1.82
RMC3-3	7.94	6.46	8.1	16,440	6,064	1.65	1.76
RMC4-1	7.95	6.46	8.7	19,607	7,205	1.84	1.92
RMC4-2	7.97	6.45	8.6	20,274	7,411	1.97	1.91
RMC4-3	7.96	6.46	9.0	17,498	6,418	1.86	1.71
RMC5-1	7.92	6.47	9.3	15,715	5,812	1.88	1.84
RMC5-2	7.96	6.48	8.9	14,664	5,359	1.90	2.02
RMC5-3	7.97	6.20	8.9	18,614	7,087	2.01	2.21

[a] MC is moisture content based on a resistance-type meter reading; MOR is modulus of rupture; MOE is modulus of elasticity; subscript y refers to beams loaded parallel to the wide face of the laminations; subscript x refers to beams loaded perpendicular to the wide face of the laminations.

Table B4—Results of shear strength tests of vertically laminated 2 by 4/2 by 6 red maple glulam beams

Beam	Weight (lb)	Width (in.)	Depth (in.)	MC[a] (%)	Maximum load (lb)	Shear stress (lb/in^2)[b]
RMC6-1	108.0	6.48	7.88	8.8	164,800	1,669
RMC6-2	105.8	6.48	7.88	8.6	176,400	1,772
RMC6-3	109.5	6.48	7.88	9.1	196,000	1,985
RMC6-4	103.5	6.50	8.00	8.6	171,200	1,704
RMC6-5	110.0	6.50	7.94	10.8	182,800	1,827
RMC7-1	106.0	6.50	7.88	7.5	170,300	1,715
RMC7-2	110.5	6.48	7.88	8.6	172,600	1,748
RMC7-3	109.0	6.50	7.94	8.5	185,200	1,851
RMC7-4	106.0	6.50	7.88	8.0	176,400	1,772
RMC7-5	110.5	6.48	7.88	9.5	167,000	1,687
RMC10-1	107.0	6.50	8.00	9.0	151,200	1,499
RMC10-2	109.5	6.50	7.94	9.5	157,200	1,565

[a] MC is moisture content based on a resistance-type meter reading.
[b] Load applied parallel to wide face of the lamination.

Table B5—Results of ASTM D143 shear block tests for failed beam laminations

Block sample	Shear stress unconditioned (lb/in^2)	Shear stress at 12% EMC[a] (lb/in^2)
6-1-3	1,648	2,156
6-1-5	2,052	1,845
6-2-2	1,769	1,800
6-2-8	1,926	1,929
6-3-1	2,443	1,698
6-3-3	2,092	1,932
6-4-2	1,697	1,720
6-5-9	2,026	1,802
7-1-3	2,419	1,729
7-1-7	1,901	1,620
7-2-7	2,149	2,028
7-2-9	1,901	1,620
7-3-2	1,913	1,917
7-3-4	1,737	1,719
7-3-8	2,066	1,897
7-4-7	1,789	1,590
7-4-9	1,632	1,856
7-5-4	1,811	1,969
7-5-6	1,823	1,615
7-5-8	1,675	1,569
10-1-2	2,049	2,111
10-1-4	1,930	1,877
10-1-6	2,091	1,721
10-2-7	1,581	1,882
10-2-9	1,979	1,730

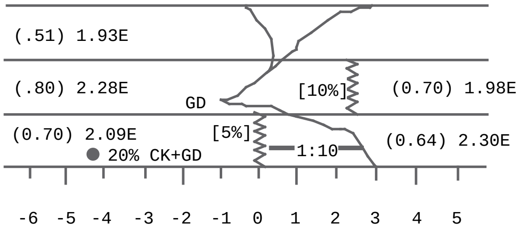
[a] EMC is equilibrium moisture content.

Appendix C—Glulam Beam Failure Maps and Lumber Properties

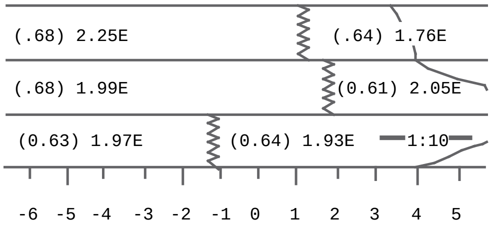
24F–1.8E Glulam Beams

Location of failure propagation in the tension zone of the beams is given in the following glulam beam failure maps. Failure through finger joints is reported by an indication of the percentage of the failure that occurred across the finger-joint cross section (value in brackets). Modulus of elasticity values are given for each piece of lumber in the critical tension zone. Values in parentheses are specific gravity of the lumber based on weight, moisture content, and dimensions taken at time of beam manufacture. All failure descriptions are given with reference to the centerline of the beam (dimensions are in ft).

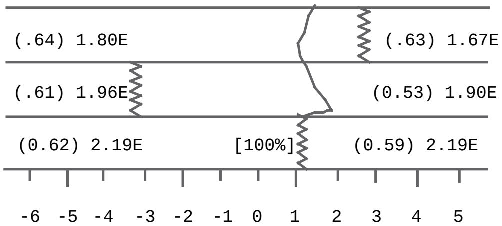
Beam No. RM6-1



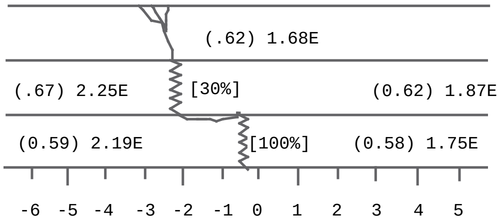
Beam No. RM6-2



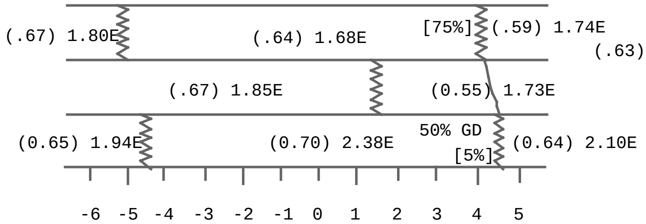
Beam No. RM6-3



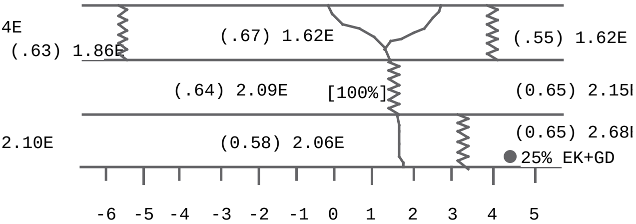
Beam No. RM6-4



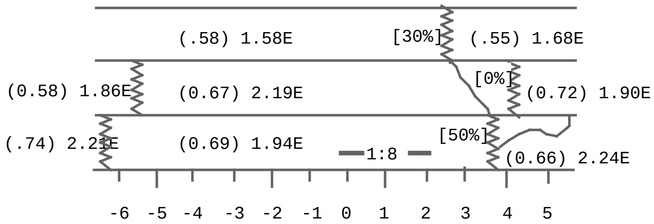
Beam No. RM6-5



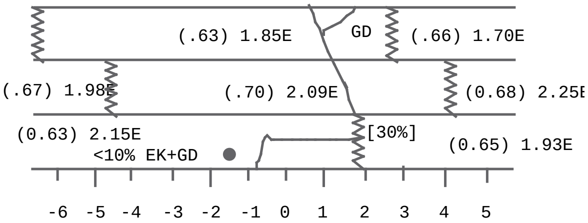
Beam No. RM6-6



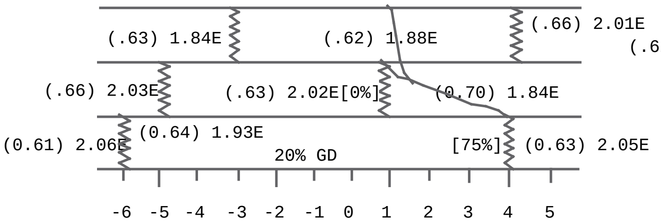
Beam No. RM6-7



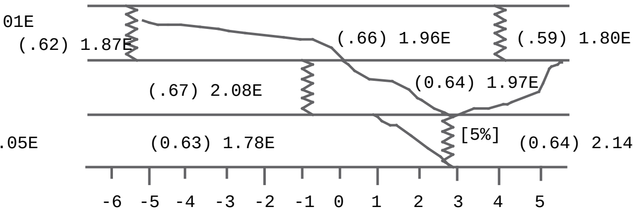
Beam No. RM6-8



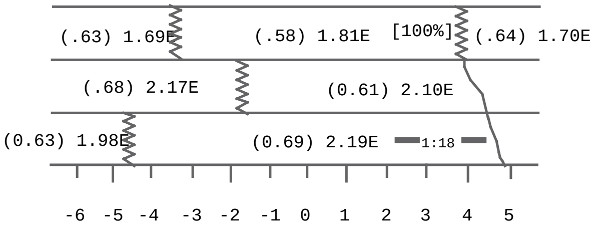
Beam No. RM6-9



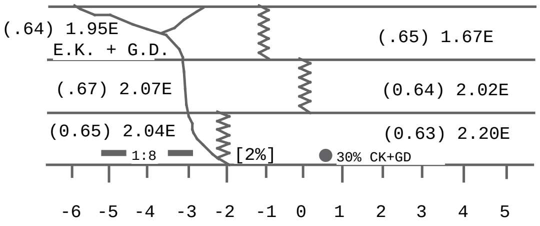
Beam No. RM6-10



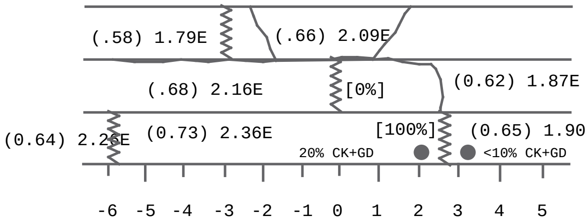
Beam No. RM6-11



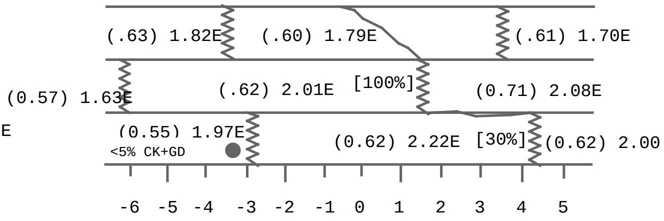
Beam No. RM6-12



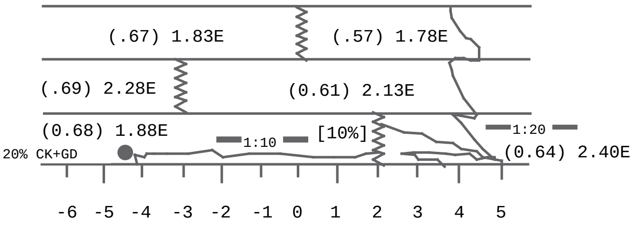
Beam No. RM6-13



Beam No. RM6-14



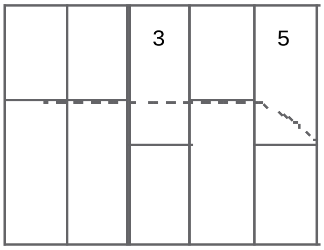
Beam No. RM6-15



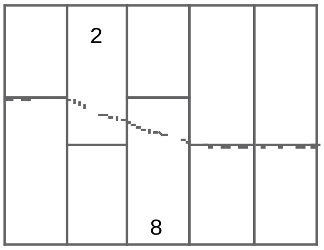
2 by 4/2 by 6 Combination Beams

Horizontal shear failure through the cross sections of the 2 by 4/2 by 6 combination glulam beams are illustrated in the following:

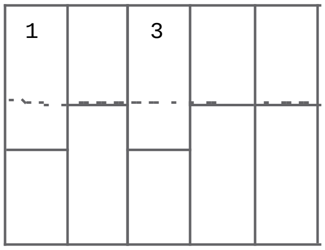
RMC6-1



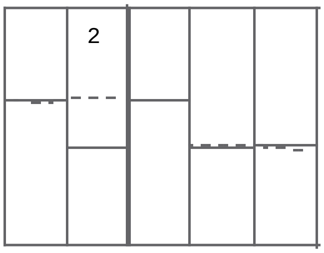
RMC6-2



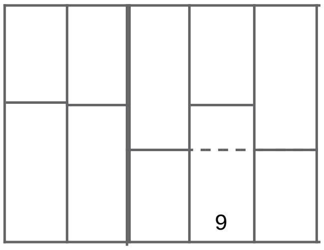
RMC6-3



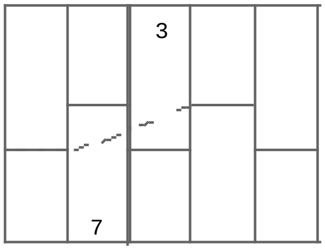
RMC6-4



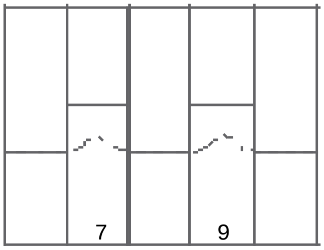
RMC6-5



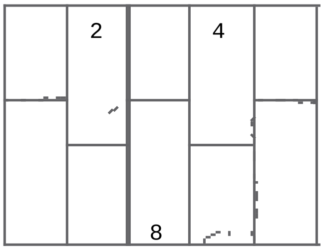
RMC7-1



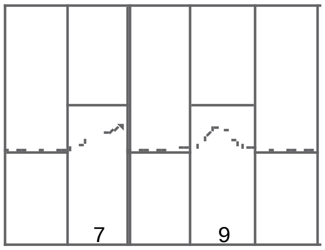
RMC7-2



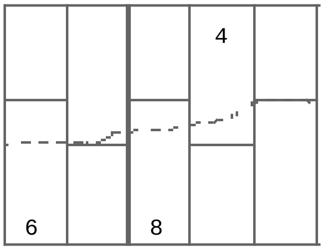
RMC7-3



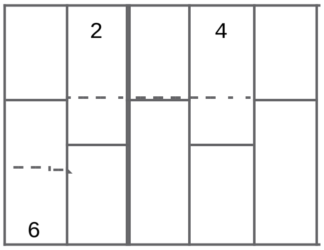
RMC7-4



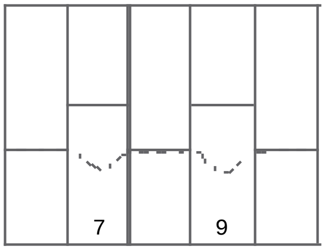
RMC7-5



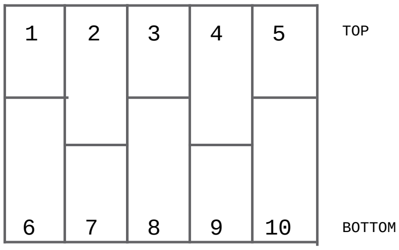
RMC10-1



RMC10-2



Key



Numbers in key correspond to shear-block specimen locations and their identification numbers

Appendix D—ASTM Procedures

The following calculations document ASTM D3737 procedures for determining design bending strength for the 2 by 4/2 by 6 glulam combination with loads applied parallel to the wide face (vertically laminated). The procedures involve four steps that determine the following:

1. Bending stress index for red maple using ASTM D2555 procedures
2. Critical strength ratios for the No. 2 red maple lumber using ASTM D245 procedures
3. Critical stress modification factors based on ASTM D3737 criteria
4. Design bending strength from calculated information

Bending Stress Index

5th percentile of clear wood modulus of rupture from ASTM D2555, Table 2.

$$CWS_{5th} = 7{,}690 \text{ lb/in}^2 - 1.645\ (1{,}230 \text{ lb/in}^2) = 5{,}667 \text{ lb/in}^2$$

Bending adjustment factor for hardwoods from ASTM D3737, Table 1.

BAF = 0.435

Seasoning factor from ASTM D3737, Table 1.

SEAS = 1.35

Size factor to adjust to a 12-in. deep, uniformly loaded simple beam with a 21:1 span-to-depth ratio.

SIZE = 0.743

Multiply all factors to get bending stress index (BSI).

BSI = 2,473 lb/in^2

Critical Strength Ratio

Wide face dimension of laminating lumber	h = 4.875-in.
Narrow face dimension of laminating lumber	b = 1.3-in.
Size of center knot based on width of resurfaced 2 by 6	k1 = 2.44-in.
Size of edge knot based on width of resurfaced 2 by 6	k2 = 1.71-in.

Strength ratio for center knots on wide face of lumber using ASTM D245 procedures

$$SR1 = 100\left[1 - \left(\frac{k1 - 1/24}{h + 3/8}\right)\right] \qquad SR1 = 54.4\%$$

Strength ratio for edge knots on wide face of lumber using ASTM D245 procedures.

$$SR2 = 100\left[1 - \left(\frac{k2 - 1/24}{h}\right)\right]^2 \qquad SR2 = 43.4\%$$

Critical strength ratio is governed by edge knots (SR2 controls).

SR = 0.434

Critical Stress Modification Factor

Stress modification factor for knots from ASTM D3737.

$$SMF_1 = C_1(SR)^{\gamma} N^{\alpha}\left(1 - 1.645\frac{\Omega_1}{N^{0.5}}\right)$$

where

$C_1 = 1.256$	(ASTM D3737, Table 5)
$\gamma = 0.81$	(ASTM D3737, Section 7.2.2.1)
$\alpha = 0.329\ (1 - 1.049\ SR)$	(ASTM D3737, Section 7.2.2.1)
$\Omega_1 = 0.36$	(ASTM D3737, Section 7.2.2.1)
$N = 5$	(for 5-lamination glulam beam)

Substitute all factors to get stress modification factor for knots.

$SMF_1 = 0.626$

Stress modification factor for slope of grain.

$SMF_2 = 0.53$ from ASTM D3737, Table 4.

Critical stress modification factor is governed by slope of grain (SMF_2 controls).

SMF = 0.53

Design Bending Strength

Multiply clear wood bending stress index by critical stress modification factor to get glulam design bending stress.

$F_b = 1{,}311$ lb/in^2

If calculations were based only on the size of knots (ignore critical stress modification factor for slope of grain), the calculated glulam design bending stress would be

$F_b = 1{,}549$ lb/in^2