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# Improved Performance of Southern Pine Structural Glued-Laminated Timber

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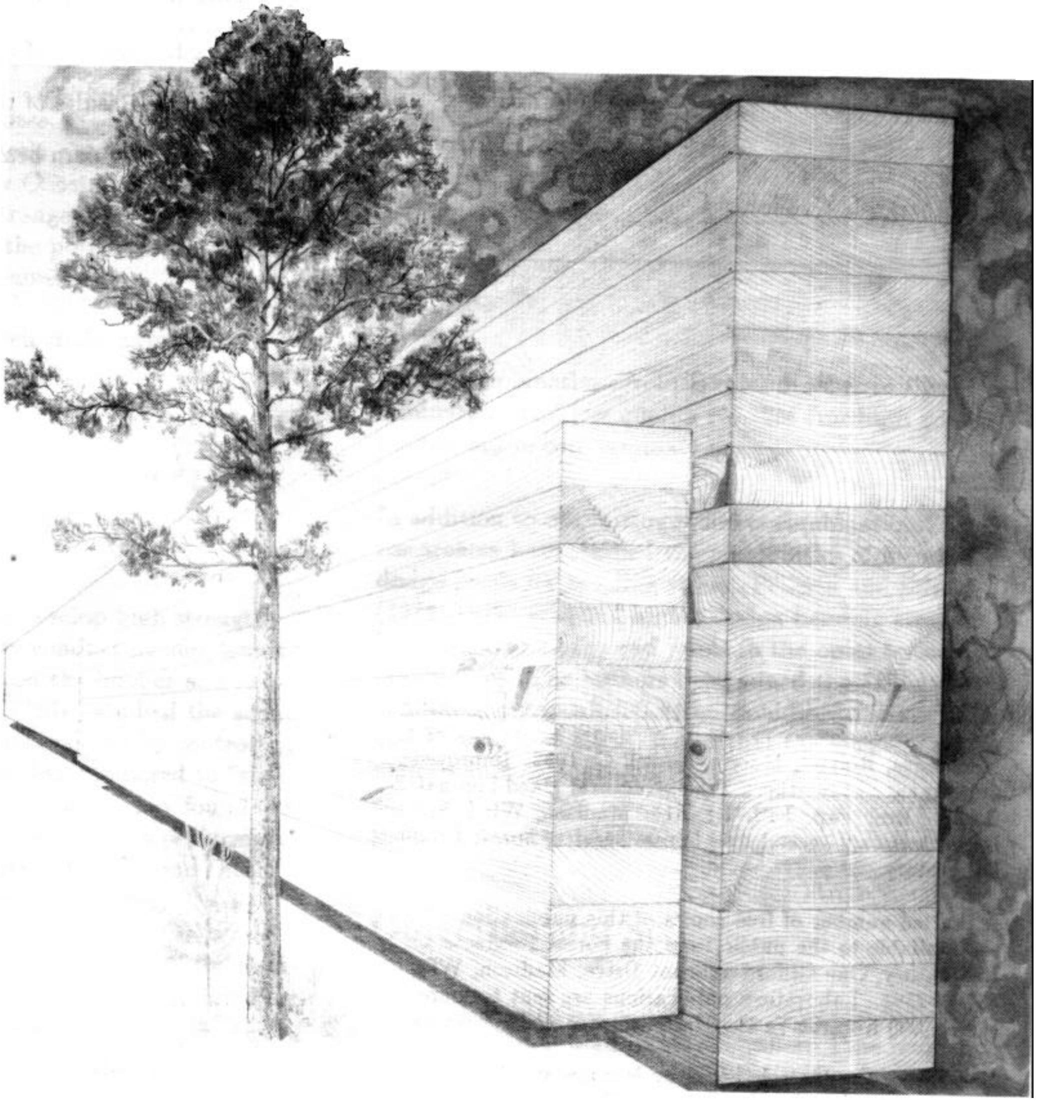

# Abstract

A high strength/stiffness glued-laminated (glulam) beam combination was developed to achieve a design bending stress of 3,000 lb/in$^2$ and modulus of elasticity of 2.0 x 10$^6$ lb/in$^2$; 40 beams were evaluated. The properties of the lumber grades used in the layup, as well as the placement of the lumber within the beams, were closely monitored during beam manufacture. In addition, an extra 199 specimens of end-jointed lumber were gathered during manufacture to relate the individual tensile strength performance of the end joints to their performance in the beams. The evaluations of the end-jointed specimens and the full-sized beams indicate that a glulam beam combination with a design stress of 3,000 lb/in$^2$ in bending and modulus of elasticity of 2.0 x 10$^6$ lb/in$^2$ is possible if certain manufacturing criteria are followed.

Keywords: Strength, stiffness, glulam, end joints, beams

# Contents

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# Improved Performance of Southern Pine Structural Glued-Laminated Timber[1]

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## Introduction

The Southern Pine lumber commonly used to manufacture structural glued-laminated (glulam) timber significantly exceeds the required performance for tensile strength (Marx and Evans 1986, 1988). However, because end-joint performance generally controls beam performance, there has been little need to examine a more efficient use of the resource. Recent unpublished results of beam and lumber tests conducted by the American Institute of Timber Construction (AITC) indicated that significantly stronger end-joints can be made. These results suggest the potential for improving the performance of glulam beams.

This report describes a research study aimed at developing a Southern Pine glulam beam combination with a design bending stress of 3,000 lb/in$^2$ and modulus of elasticity (MOE) of 2.0 x $10^6$ lb/in$^2$. (See Table 1 for SI conversion factors.)

**Table 1—SI conversion factors**

| English unit | Conversion factor | SI unit |
|---|---|---|
| foot (ft) | 0.3048 | meter (m) |
| inch (in.) | 25.4 | millimeter (mm) |
| pound per square inch (1b/in$^2$) (stress) | 6.895 | kilopascal (kPa) |
| pound-force (lbf) | 4.448 | newton (N) |
| degree Fahrenheit (°F) | $t_{°C} = \frac{t_{°F} - 32}{1.8}$ | Celsius (C) |

## Background

Previous studies attempted to develop high strength-stiffness beam combinations by conducting supplemental quality control procedures on the lumber and end joints. Moody and Bohannan (1970) studied the advantages of fabricating glulam combinations by controlling the MOE of the laminating lumber compared to fabricating beams with visual criteria only. They found that the beams fabricated with stiffness criteria performed at levels approximately 12 percent higher than that of beams fabricated with visual criteria only. Johnson (1971) achieved Southern Pine beam MOE levels of 2.0 x $10^6$ lb/in$^2$ by controlling the MOE of the laminating lumber. Moody (1977) developed Southern Pine glulam combinations from E-rated lumber in the outer laminations and low quality No. 2M (medium grain) lumber in the core laminations.

In addition to optimizing stiffness combinations, researchers have studied the possibilities of increasing design levels for bending stress. Pellerin and Strickler (1971, 1972) achieved higher design bending stresses by proof loading the end joints in the outer tension laminations. The authors determined that design bending stresses >2,800 lb/in$^2$ could be achieved. Marx and Evans (1986, 1988) found that the tensile strength performance of Southern Pine lumber consistently exceeded the levels permitted by the Southern Pine Inspection Bureau (SPIB) grading rules (SPIB 1970).

## Objective and Scope

The overall objective of our research was to improve the utilization of high quality Southern Pine lumber in glulam timber construction. The specific aims were as follows:

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[1] Conducted in cooperation with the American Institute of Timber Construction.

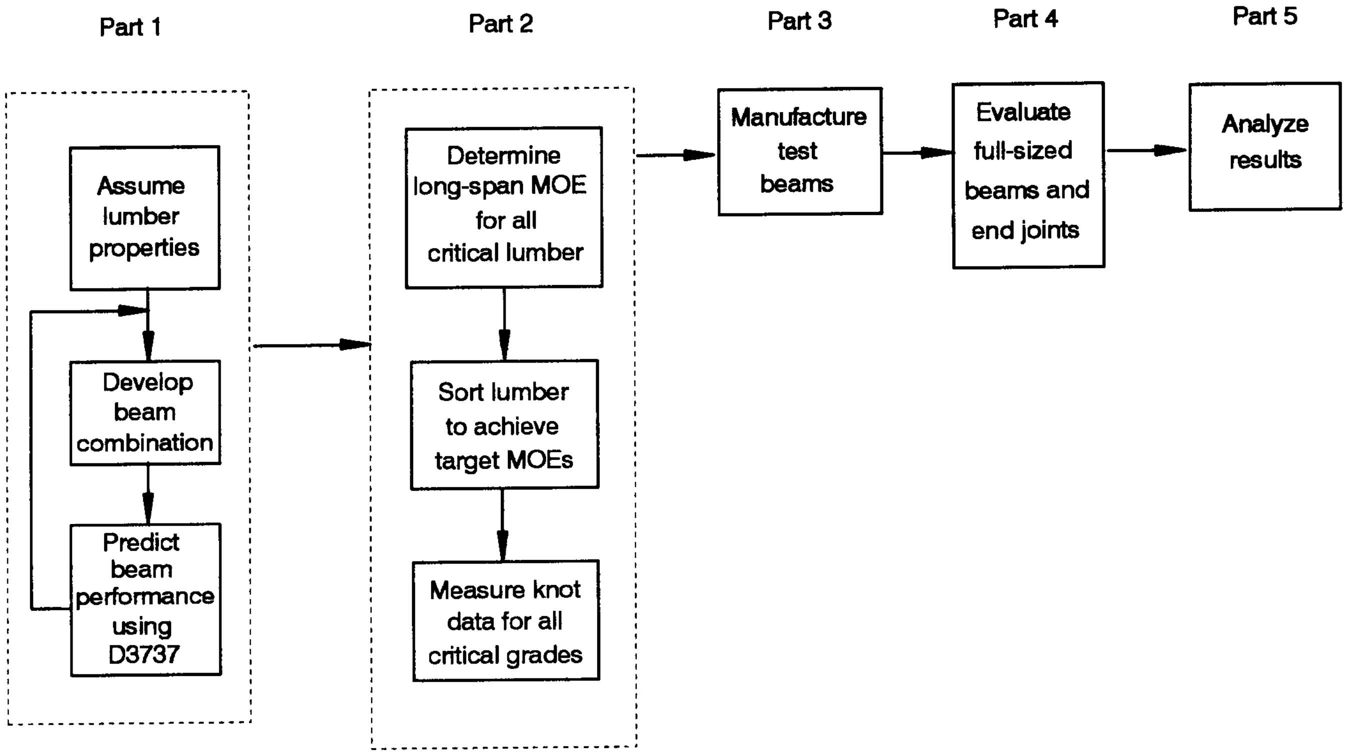


*Figure 1—Research procedure for high performance Southern Pine glulam beams.*

1. to determine if the ASTM D3737 (ASTM 1990c) procedures are applicable for predicting the bending strength and stiffness properties of Southern Pine glulam beams with a proposed design bending stress of 3,000 lb/in$^2$ and MOE of 2.0 x $10^6$ lb/in$^2$ through full-sized beam tests, and

2. to develop the basis for a specification for Southern Pine glulam beams with a target design stress in bending of 3,000 lb/in$^2$ and a target MOE of 2.0 x $10^6$ lb/in$^2$.

The study included field surveys of existing lumber, theoretical analyses, and lumber evaluations, followed by the manufacture and evaluation of 40 full-sized beams. Twenty beams were manufactured using nominal 2 by 4 lumber with the following dimensions: 3 in. wide, 13.75 in. deep, and 24 ft long. The remaining 20 beams were manufactured using nominal 2 by 6 lumber with the following dimensions: 5 in. wide, 23.375 in. deep, and 40 ft long. The research was conducted in five parts: (1) development of beam combinations, (2) determination of lumber properties and grades, (3) beam manufacture, (4) beam and end-jointed lumber evaluations, and (5) analysis of results (Fig. 1).

Additional research is underway on modeling the strength and stiffness of the beams evaluated. Once additional information on the tensile strength of the lumber collected during this study is available, results of that research will be published in a separate report.

## Development of Beam Combinations

A beam combination was targeted to achieve a design bending stress of 3,000 lb/in$^2$ and a MOE of 2.0 x $10^6$ lb/in$^2$. Although the goal of this research was to take advantage of high quality Southern Pine lumber, we needed to assure that adequate amounts of high grade material were available for both the present and the future. Thus, we conducted a field study on lumber MOE with the cooperation of several Southern Pine glulam manufacturers. Results of this field study, along with procedures used by AITC, were used to develop the proposed beam combination.

### Procedures

Three Southern Pine laminators cooperated with us to determine the relative quality of the lumber being used in production. Only 302-24 tension lamination (AITC 117, AITC 1988) and No. 1D (Dense) material (SPIB 1970) were surveyed in three structural sizes: nomininal

2 by 4 in. = standard 38 by 89 mm; 2 by 6 in. = 38 by 140 mm; 2 by 8 in. = 38 by 184 mm. This lumber will be referred to by the common nomenclature (2 by 4, etc.) in the text.) The methods used to measure the lumber MOE (such as two-point static bending and transverse vibration) were closely correlated to the center-point, 100:1 span-to-depth ratio configuration recommended in ASTM D3737 (ASTM 1990c). Results of this survey, along with data used by AITC to develop the combinations in AITC 117, were used with the ASTM D3737 procedures to develop the beam combinations.

## Results

The results of the field survey showed that the long-span MOE significantly exceeded the nominal value of 2.0 x $10^6$ lb/in$^2$ used by AITC in all three sizes and both grades (Table 2). This indicated that the high quality Southern Pine lumber was available with high yields for the required MOE. Results equaled or exceeded values found by Marx and Evans (1986, 1988).

Preliminary analyses were conducted using the ASTM D3737 procedures with the lumber grades shown in Table 3. The table also shows the assumed lumber properties (AITC 117, AITC 1979) required by the D3737 procedures.

The two beam combinations (Fig. 2) were developed to represent a critical beam size at approximately 12 in. deep (13.75 in., 10 laminations) and another size at a greater depth (23.375 in., 17 laminations). The glulam beams were balanced combinations with approximately 10 percent 2.3E material in the outer zones, 15 percent No. 1D material in the adjacent zones, and No. 2M material in the core laminations. The quality of tension lamination required to achieve the 3,000-lb/in$^2$ design bending stresses is shown in Table 4. The actual quality selected by an AITC Task Committee for the two beam sizes tested included slightly steeper slope-of-grain and slightly smaller knots plus grain deviations than that indicated by the ASTM D3737 procedures. Note that the D3737 procedures were not evaluated in past research at the high strength ratios (0.80) encountered in our research.

## Lumber Properties and Grades

Care was taken in evaluating and controlling beam lumber properties so that the final results would be meaningful for establishing the basis for a specification.

**Table 2—Results of field study on lumber MOE**

| | | | Long-span MOE (x$10^6$ lb/in$^2$) | |
|---|---|---|---|---|
| Nominal size | Grade | n | Measured[a] | Marx and Evans[b] |
| 2 by 4 | 302-24 | 149 | 2.60 | |
| | No. 1D | 150 | 2.46 | — |
| 2 by 6 | 302-24 | 201 | 2.39 | 2.38 |
| | No. 1D | 147 | 2.31 | 2.15 |
| 2 by 8 | 302-24 | 78 | 2.75 | — |
| | No. 1D | 36 | 2.55 | — |

[a] Measured using AITC Test T116.
[b] Marx and Evans (1986, 1988).

**Table 3—Assumed properties of lumber grades for D3737 analysis**

| | | Parameter[a] | | Bending |
|---|---|---|---|---|
| Grade | MOE (x$10^6$ lb/in$^2$) | $\bar{x}$ (%) | $\bar{x} + h$ (%) | stress index (lb/in$^2$) |
| No. 1D-2.3E | 2.3 | 3.3 | 35.6 | 4,000 |
| No. 1D | 2.0 | 3.3 | 35.6 | 3,500 |
| No. 2M | 1.5 | 7.9 | 51.5 | 3,000 |

[a] Parameters from ASTM D3737. $\bar{x}$ is average of sum of all knot sizes within 1-ft segments, taken at 2-in. intervals. $\bar{x} + h$ is 99.5-percentile knot size.

**Table 4—Tension lamination criteria**

| Beam combination and tension criterion | D3737 required value | Selected value |
|---|---|---|
| lo-lamination | | |
| Edge knot and grain deviation | 0.40 | 0.33 |
| Center knot and grain deviation | 0.45 | 0.33 |
| Slope of grain | 1:14 | 1:12 |
| 17-lamination | | |
| Edge knot and grain deviation | 0.25 | 0.20 |
| Center knot and grain deviation | 0.30 | 0.25 |
| Slope of grain | 1:18 | 1:16 |

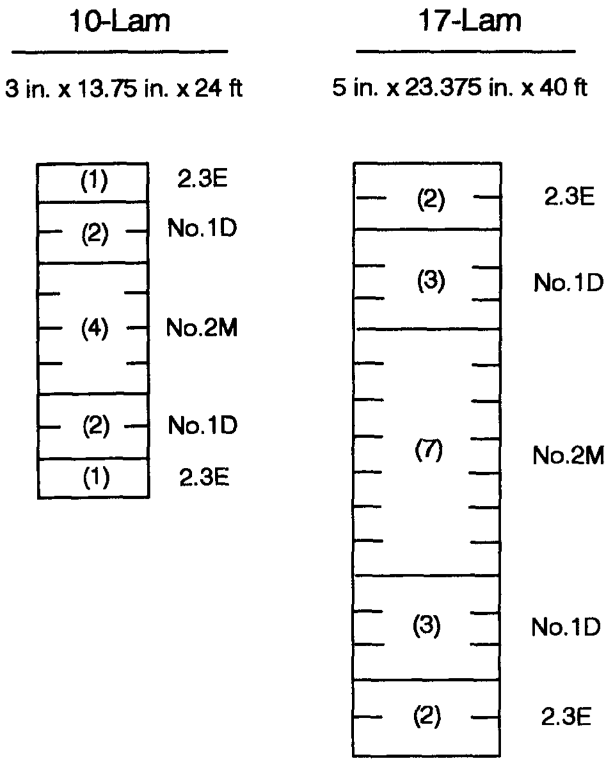


*Figure 2—Southern Pine glulam beam combinations; 10 and 17 laminations (Lam). 1 in. = 25.4 mm; 1 ft = 0.3048 m.*

## Procedures

Once a sufficient amount of lumber for manufacturing the beams was available, steps were taken to

1. grade the No. 1D lumber,
2. separate by grade the tension lamination material from the No. 1D lumber,
3. remove all dense material from the No. 2M lumber,
4. conduct lumber tests (MOE measurements, moisture content, dimensions, etc.),
5. sort the tension lamination material to assure an average MOE of 2.3 x $10^6$ lb/in$^2$,
6. sort the No. 1D lumber to obtain the 2.3E and 2.0E grades, and
7. measure knot properties of the sorted grades.

### MOE Measurement and Lumber Sorting

The physical and mechanical properties were evaluated after all the lumber was visually graded (steps 1 to 3). Moisture contents were measured using a resistance-type moisture meter. Identification numbers were stamped on the narrow edge of each piece of lumber so that the specimens could easily be located following the beam fabrication. The MOE values for all the tension lamination, all the No. 1D lumber, and representative samples of No. 2M lumber were measured using a transverse vibration technique (Ross and others 1991). Lumber weights were determined during the MOE measurements. Table 5 shows the sorting scheme used to arrive at the target MOE levels for each grade.

The objective for sorting the No. 1D lumber was to divide the entire population into two groups. One group (approximately 33 percent of the population) was sorted to obtain an average MOE of 2.3 x $10^6$ lb/in$^2$. The remaining group (67 percent of the population) was sorted to obtain an average MOE of 2.0 x $10^6$ lb/in$^2$. The difference between the two sorting schemes was that the 2.3E material was grouped according to the E-rating criteria set forth in AITC-117—Manufacturing (AITC 1988); this would result in a coefficient of variation (COV) of approximately 9 percent. The 2.0E material, on the other hand, was targeted to have a COV of approximately 17 percent, which was more representative of a visual grade of lumber. It was imperative to initially separate the 33-percent and 67-percent groups so that the sorting scheme of one set of lumber would not alter the MOE distribution of the other. The No. 2M lumber was not sorted.

The lumber was sorted at the plant using a laptop computer to continuously monitor the distribution of lumber MOE. Whenever lumber was tested for stiffness and physically removed (or added) to a particular grade, the corresponding MOE values were removed from (or added to) a spreadsheet. After every sort, the newly acquired distribution of MOE was displayed on-screen to observe if the target levels had been reached and to detect if the sorting process was skewing the MOE distributions.

### Knot Characterization

To accurately analyze the beams for bending strength using the ASTM D3737 procedures, knot sizes were measured for each grade of lumber after the lumber was sorted by MOE. Initially, knots were measured using the AITC method, in which knots are categorized into one of nine knot types. However, because of time constraints, a majority of the remaining lumber was measured for knots using an approximate method, in which a “straight-through” knot having the same cross-sectional area as an AITC knot-type was estimated. The knot properties were mapped for all the tension lamination material and for representative samples of the remaining grades of lumber. The knot measurements were collected manually at the plant on prepared data sheets, and the information was later transferred to spreadsheet form in preparation for final analysis. The knot data were analyzed using procedures outlined in Freas and Selbo (1954).

**Table 5—Target MOE values and details of sorting scheme**

| Lamination grade | Sorting or grading criterion[a] |
|---|---|
| Tension lamination | All material meeting the TL criteria removed from available No. 1D lumber. TL lumber then sorted for MOE to obtain the following:<br>average MOE of 2.3 to 2.4 x $10^6$ lb/in$^2$<br>5th percentile at 1.96 x $10^6$ lb/in$^2$<br>no MOE value $<$ 1.9 x $10^6$ lb/in$^2$<br>no MOE value $>$ 2.7 x $10^6$ lb/in$^2$<br>COV of approximately 9 percent |
| No. 1D lumber | Remaining No. 1D lumber randomly divided into two groups representing identical populations:<br>Group A, to be sorted for 2.3E<br>Group B, to be sorted for 2.0E |
| Group A (E-rated No. 1D) | Group of lumber representing a No. 1D population sorted for MOE of 2.3 x $10^6$ lb/in.$^2$ Same MOE sorting scheme as that for TL material. |
| Group B (visually rated No. 1D) | Lumber sorted to possess allowable average MOE established by AITC for No. 1D lumber. COV controlled to simulate a visually rated grade:<br>average MOE of 2.0 to 2.1 x $10^6$ lb/in$^2$<br>5th percentile at 1.60 x $10^6$ lb/in$^2$<br>no MOE value 1.55 x $10^6$ lb/in$^2$<br>no MOE value 2.45 x $10^6$ lb/in$^2$<br>COV of approximately 17 percent |
| No. 2M | No MOE restrictions |

[a] COV is coefficient of variation, TL tension lamination.

### Results

Table 6 summarizes the MOE values for each grade of lumber. Only those lumber MOE values that physically appeared in the beam layups were used in determining the statistics. The results showed that the lumber clearly matched the target MOE levels for each grade.

The $\bar{x}$ and $h$ values calculated from the knot measurements are listed in Table 7. Knot sizes were considerably smaller than those assumed in Table 3.

## Beam Manufacture

Two beam sizes were manufactured (Fig. 2) along with extra end-jointed specimens from each grade for separate testing. In addition to controlling the properties of the lumber used to fabricate the beams, we aimed to produce test beams that covered a range of qualities. This was accomplished by controlling the placement of certain tension laminations in the outer ply. Also, to predict beam stiffness, the lumber MOE properties were mapped as they occurred in the beam combinations.

### Procedures

For each beam size, lumber was graded and sorted to produce 20 beams and approximately 30 end-jointed specimens from each grade. The procedures used in manufacturing these beams and end joints followed the specifications in ANSI A190.1 (ANSI 1983).

Prior to beam fabrication, the tension lamination lumber for the first five beams of each group was organized in a sequence that would assure the placement of certain strength-reducing characteristics (knot and slope-of-grain characteristics near the maximum size permitted in Table 4) in the central region of the beams. This was done to assure that the test beams would represent a wide range of beam qualities.

Additional lumber was end-jointed immediately after the beam lumber was processed. The excess laminations were cut into 8-ft specimens with the end joint located at the center. These extra end-joint specimens represented the joints that were placed in the beams and were used in tests relating individual end-joint performance to performance in the beams.

**Table 6—MOE properties of laminating lumber**

| Nominal size and grade[a] | Sample size | Average MOE ($10^6$ lb/in$^2$) | COV (%) |
|---|---|---|---|
| 2 by 4 | | | |
| 302 TL | 78 | 2.33 | 10.3 |
| No. 1D–2.3E | 33 | 2.33 | 8.4 |
| No. 1D | 191 | 2.08 | 12.7 |
| No. 2M | 76 | 1.68 | 16.1 |
| 2 by 6 | | | |
| 302 TL | 98 | 2.36 | 9.4 |
| No. 1D–2.3E | 194 | 2.32 | 8.4 |
| No. 1D | 317 | 2.07 | 11.4 |
| No. 2M | 131 | 1.75 | 15.4 |

[a] TL is tension lamination.

**Table 7—Knot properties of laminating lumber[a]**

| Nominal size and grade | Sample size | $\bar{x}$ (%) | $\bar{x} + h$ (%) |
|---|---|---|---|
| 2 by 4 | | | |
| 302 TL | 64 | 0.29 | 3.17 |
| No. 1D–2.3E | 40 | 0.34 | 10.60 |
| No. 1D | 75 | 1.28 | 12.82 |
| No. 2M | 20 | 3.88 | 17.87 |
| 2 by 6 | | | |
| 302 TL | 71 | 0.20 | 6.19 |
| No. 1D–2.3E | 28 | 0.35 | 5.23 |
| No. 1D | 29 | 0.72 | 8.92 |
| No. 2M | 25 | 5.90 | 27.76 |

[a] See footnote to Table 3 for definitions of $\bar{x}$ and $\bar{x} + h$.

The beam manufacturer used a melamine-urea adhesive for end-joint and face-lamination bonding. The end joint was a finger-type joint with the fingers cut horizontally across the lumber width. The laminations were cured in a radio-frequency tunnel at 200°F. The end-jointed laminations were then face-planed to a uniform thickness of 1.375 in. and cut to the desired beam length. After the beam combinations were assembled, the face laminations were bonded in a separate radio-frequency press. The beams were manufactured with a slight camber (1 in. of camber for every 1,200 in. of beam length).

After beams are assembled, glued, and cured, the usual procedure is to immediately edge-plane the full-sized beams through a large planer. However, for this research study, it was important to locate the identification numbers on the sides of each beam so that the MOE profile could be mapped. Therefore, after the beams left the radio-frequency press and before they entered the planer, the identification numbers of all No. 1D and better laminations were recorded onto prepared beam maps. The beams were numbered 4-1 through 4-20 (for beams made from 2 by 4 lumber) and 6-1 through 6-20 (for beams made from 2 by 6 lumber).

Following manufacture, the relative qualities of the tension laminations were rated by the allowable percentage of lumber cross-sectional areas that could be occupied by knots, the slope-of-grain limitations, and the MOE restrictions (Table 8). The rating considered those portions of the tension laminations subjected to about 85 percent of the maximum moment during testing.

## Results

During the recording process, two beams were found to be mismanufactured. Beam 4-11 had a No. 2M lamination in the third tension lamination (laminations 3 and 4 were inadvertently switched). Beam 6-2 had a defective end-joint (1/2 in. gap) in the outer tension lamination 5 ft from the end. These two beams were removed from the test population at this stage. Therefore, a total of 38 beams (19 small, 19 large) were used for the test program. In addition, a total of 199 end-jointed lumber specimens, representing each size and grade of material, were gathered during manufacture.

The beams were categorized by quality of tension lamination as follows (percentage of total):

| Beam combination | Low | Medium | High |
|---|---|---|---|
| 10-lamination | 16 | 37 | 47 |
| 17-lamination | 32 | 42 | 26 |

Note that the large beams had a higher percentage of low quality tension laminations than did the small beams. This is not unusual in that a greater amount of the length of large beams is in the critical moment region. Additional details on the qualities of the tension laminations are provided in Appendix A.

**Table 8—Relative rating system for tension laminations**

| | Strength-reducing characateristic | | | |
|---|---|---|---|---|
| Beam combination and rating | Edge knot and grain deviation (%) | Center knot and grain deviation (%) | Slope of grain | Grade[a] |
| 10-lamination | | | | |
| Low | 25-33 | 25-33 | 1:12 | <2.0E + SR char |
| Medium | 10-25 | 10-25 | 1:14-1:16 | <2.0E and clear |
| High | <10 | <10 | ≥1:18[b] | |
| Maximum | 33 | 33 | 1:12 | 1.9E minimum |
| 17-lamination | | | | |
| Low | 15-20 | 20-25 | 1:16 | <2.0E + SR char |
| Medium | 5-15 | 5-20 | 1:18 | <2.0E and clear |
| High | <5 | <5 | ≥1:20 | — |
| Maximum | 20 | 25 | 1:16 | 1.9E minimum |

[a] SR char is strength-reducing characteristic, such as edge knots, center knots, and slope of grain.
[b] Slope of 1:18 and straighter (1:20, 1:22, etc.).

# Beam and End-Jointed Lumber Evaluations

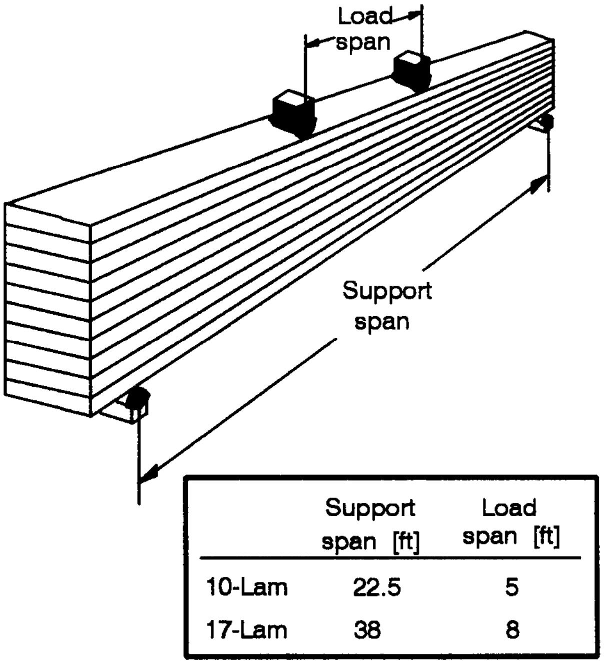
All the full-sized beam tests followed the procedures established in the ASTM D198 standard (ASTM 1990a). The end-jointed lumber tests followed the tension test procedures established in AITC Test T119 (AITC 200, 1991a), except that the target time-to-failure was 5 to 10 min (rather than 2 min) to correspond to the time-to-failure of the beams.

## Procedures

### Beam Evaluations

The loading configuration used to test the full-sized beams is illustrated in Figure 3. The test took into account

1. physical properties (moisture content, weight, and dimensions),
2. stiffness properties (full-span deflections),
3. failure load, and
4. failure types.



| | Support span [ft] | Load span [ft] |
|---|---|---|
| 10-Lam | 22.5 | 5 |
| 17-Lam | 38 | 8 |

*Figure 3—Loading configuration for full-sized glulam beam tests.*

Moisture contents of laminations were measured with a resistance-type moisture meter at the midlength of the beams. For the smaller beams, the beam weights were measured on a mobile scale. For the larger beams, the beam weights were measured using the scale on the test machine; the beam weight was recorded as the difference between the weight of the test machine before and after the beam was loaded. Beam dimensions were measured at each load point

During the application of load, beam deflections were measured using a precision ruler (0.02 in. markings) attached to the beam. Deflections were recorded with respect to a stringline at mid-depth that was attached over each support. The readings were taken at specified load increments with a surveyor's scope; this allowed the recorder to take readings to the nearest 0.01 in. The elapsed time of each load-deflection reading was also recorded to indicate when initial cracking occurred (noise) and when compression wrinkling was first detected. The elapsed time could then be traced back to applied load. The testing was videotaped with a high-speed camera for selected beams.

After the beams failed, detailed descriptions of the failure propagations were recorded, along with an assessment of the cause of failure (end joint, knot, or slope-of-grain). Each beam failure was photographed for future reference. Modulus of rupture (MOR) and MOE were calculated with the measured readings using standard flexural formulas. Dead load stress was included in the MOR calculations.

### End-Jointed Lumber Evaluations

End-jointed lumber specimens from each grade and size were tested (1) to determine if the end joints in the beams, which were being represented by the test sample, met the ANSI A190.1 (ANSI 1983) manufacturing requirements and (2) to obtain information for developing input properties for advanced glulam models.

The test specimens were 8 ft long with the end joint located at the center. Prior to testing, these specimens were face- and edge-planed to the exact dimensions of the laminating lumber used in the glulam beams and conditioned to 12 percent moisture content.

To develop input properties for advanced glulam models (Hernandez and others, in press), short-span stiffness properties were obtained on the 2-ft lumber segments on each side of the joint and on the 2-ft segment across the joint. The bending tests were conducted on a screw-driven bending machine. Applied forces were measured with a load cell, and corresponding shear-free deflection between the load points was measured using a linear variable differential transformer. The loading configuration for the bending test was 5 ft between the supports and 2 ft between the applied load points. Load-deflection readings were taken in 5-lb increments. The 2 by 4 specimens were loaded to a maximum load of 300 lb, and the 2 by 6 specimens were loaded to a maximum load of 400 lb. The MOE values were calculated using the slope of the load-deflection readings.

After the nondestructive static bending tests, the specimens were tested to failure in tension. The tension testing machine was adjusted such that the grips were 30 in. apart. The specimens were placed in the machine with end joints located near the center of the 30-in. span. This span was used because of the minimum span limitations of the tension machine. Thus, the 24-in. segment tested in bending was centered within the 30-in. span.

## Results

### Beam Failures

Most beams failed through the end joints in one or both of the outer two tension laminations. Several 3-in. beams and one 5-in. beam exhibited compression wrinkling in the top lamination prior to ultimate failure (Fig. 4). Only a few limiting characteristics in the tension laminations were involved in the failures, indicating that the quality of the tension lamination was adequate for the designed strength. The end joints appeared to control beam strength. The types of failures observed in the beams are described in Table 9.

Two large beams failed at strength levels considerably lower than that of the other 17 beams. Further inspection of the two low-strength beams suggested that some low-density material may have unintentionally been used in beam 6-19 in the second lamination. An area in beam 6-8 in the second lamination was also further examined for unusual density characteristics.

To address these areas of concern, small specimens were cut from the failed section of beam 6-19 at certain locations along the beam length to further study the ring count, percentage of latewood, stiffness, and specific gravity of the material. For beam 6-8, standard procedures were conducted to determine if compression wood existed in the second lamination (wood sliver/light box test).

Results of the additional examination of beam 6-19 are shown in Figure 5. As shown, the piece of lumber in the second lamination fell within the visual criteria allowed for the No. 1D material. For beam 6-8, the wood sliver/light box test results indicated that compression wood did not exist in the second lamination above the end joint in the tension lamination (at approximately 15 ft from the left end of the beam).

### Beam and End-Jointed Lumber Evaluations

The cumulative distribution functions of MOR and tensile strength for the 3-in. and 5-in.-wide beams and end-jointed lumber are shown in Figures 6 and 7, respectively. Detailed descriptions of each beam failure are provided in Appendixes B and D. Results of tension tests on the other grades of end joints are shown in Appendix C.

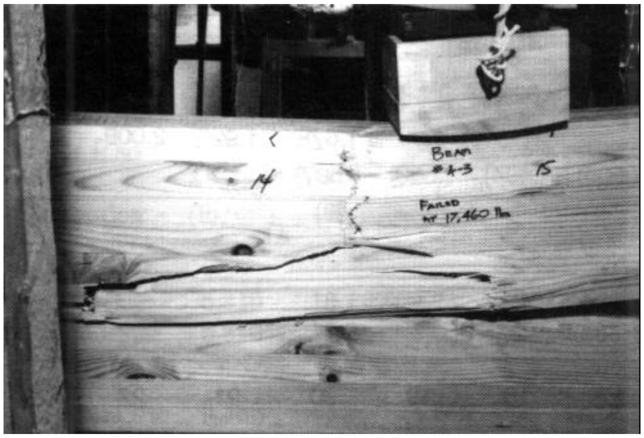


*Figure 4—Compression-type failure in 10-lamination beam. (M91-0166-3)*

**Table 9—Test beam failures**

| Failure type | Failed beams (no.) 10-lamination | Failed beams (no.) 17-lamination |
|---|---|---|
| Selected characteristic in outer tension lamination | 0 | 0 |
| End joint in one tension lamination | 11 | 17 |
| Tension-no specific characteristic | 3 | 1 |
| Compression zone | 5 | 1 |
| Total | 19 | 19 |

The results of bending tests of full-sized beams are summarized in Table 10. The results of tension tests of the representative sample of tension lamination end-joints are summarized in Table 11.

The results in Tables 10 and 11 were calculated assuming both the normal and lognormal distributions. However, to conduct an analysis of the data, the ASTM D3737 standard (ASTM 1990c) recommends that a lognormal distribution be used. Therefore, the analysis conducted in the following section assumes a lognormal distribution.

## Data Analysis

To determine if the ASTM D3737 standard could predict the strength and stiffness of glulam timber designed with strength ratios outside the standard range, actual lumber MOE and knot properties were used as input for the D3737 procedures, and predicted values were related to target design levels. Next, to develop a basis for a specification for a beam combination with design bending stresses of 3,000 lb/in$^2$ for strength and 2.0 x 10$^6$ lb/in$^2$ for stiffness, we studied manufacturing criteria such as end-joint quality.

### Adequacy of Prediction Method

Initially, the proposed glulam beam combinations were developed using the assumed lumber properties listed in Table 3 and ASTM D3737 procedures. Once the data on the actual properties of the lumber used for manufacturing beams were gathered and processed, the beam combinations were analyzed again using actual laminating lumber MOE and knot values. The actual MOE and knot properties of the laminating lumber are listed in Tables 6 and 7. The assumed bending stress indexes and minimum strength ratios (Table 3) were also used in this analysis. To study beam stiffness more accurately, beam maps were used to calculate MOE values for each individual beam.

#### Beam Strength

The design bending stresses predicted with the ASTM D3737 procedures using actual lumber properties and the design bending stresses estimated from the actual beam tests are listed in Table 12. The following equation was used to calculate the design bending stress from the actual beam test results:

$$F_b = \frac{MOR_{0.05}}{2.1C_v}$$

where

$F_b$ is design stress in bending (target = 3,000 lb/in$^2$),

MOR$_{0.05}$ is 5 percent lower exclusion limit at 75 percent tolerance for sample size of 19 (D2915, ASTM 1990b),

2.1 is the factor that includes adjustments for safety and load duration, and

$C_v$ is the volume effect factor from Moody and others (1988) (1/10 exponent) and AITC (1991b) (1/20 exponent).

An analysis of the results adjusted to standard conditions indicated that the performance of the two beam sizes was not significantly different at the 5-percent level using the 1/10 exponent. Thus, an argument can be presented for combining the results shown in Table 12. However, the adjusted beam results using the 1/20 exponent were determined to be significantly different at the same 5-percent level, and it is questionable if these values could be combined.

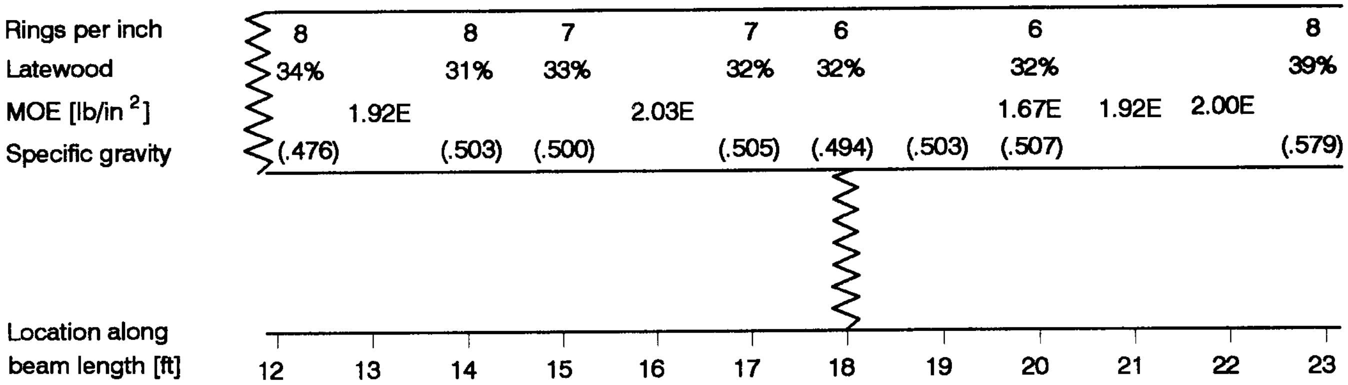


*Figure 5—Results of additional stiffness and density studies on beam 6-19.1 lb/in² = 6.895 kPa.*

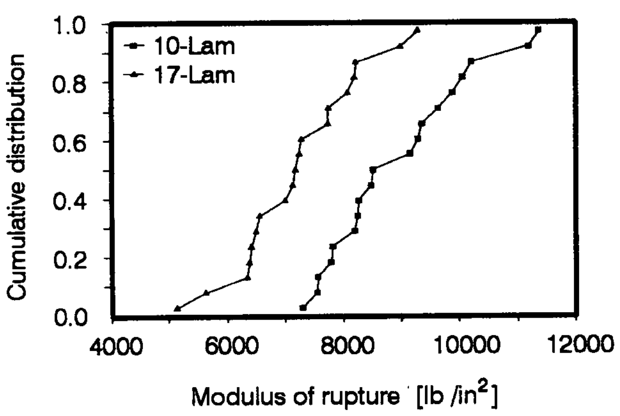


*Figure 6—Cumulative distributions of modulus of rupture for 10- and 17-lamination beams.*

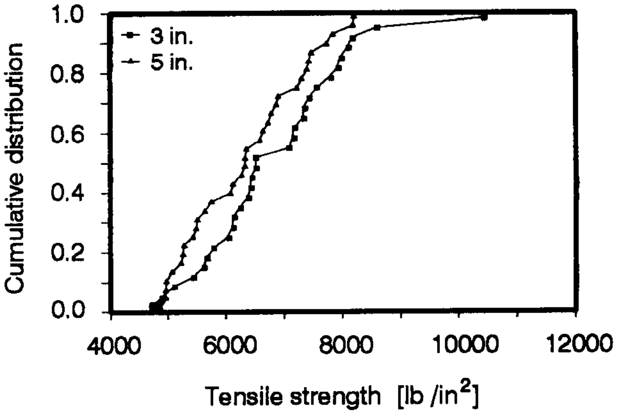


*Figure 7—Cumulative distributions of end-joint tensile strength for 3- and 5-in.-wide specimens.*

**Table 10—Bending strength of full-sized glulam beams**

| | Modulus of rupture | | | | Modulus of elasticity | |
|---|---|---|---|---|---|---|
| Beam combination and distribution[a] | Average (lb/in²) | COV (%) | 5% point estimate | 5% estimate at 75% tolerance | Average (×10⁶ lb/in²) | COV (%) |
| 10-lamination | | | | | | |
| Normal | 8,950 | 13.6 | 6,950 | 6,590 | 2.04 | 4.5 |
| Lognormal | 8,950 | 13.4 | 7,130 | 6,850 | — | — |
| 17-lamination | | | | | | |
| Normal | 7,230 | 14.8 | 5,470 | 5,150 | 1.96 | 3.7 |
| Lognormal | 7,240 | 15.2 | 5,580 | 5,340 | — | — |

[a] Sample size of 19 beams.

**Table 11—Tensile strength of end-jointed tension lamination lumber**

| Nominal size and distribution | Tensile strength | | | |
|---|---|---|---|---|
| | Average (lb/in$^2$) | COV (%) | 5% point estimate | 5% estimate at 75% tolerance |
| 2 by 4[a] | | | | |
| Normal | 6,810 | 18.1 | 4,780 | 4,500 |
| Lognormal | 6,810 | 18.0 | 5,000 | 4,800 |
| 2 by 6[b] | | | | |
| Normal | 6,350 | 16.0 | 4,680 | 4,470 |
| Lognormal | 6,350 | 16.1 | 4,820 | 4,660 |

[a] Sample size of 30 specimens.
[b] Sample size of 34 specimens.

**Table 12—Analysis of glulam beam strength using lognormal distribution**

| Variable | 10-Lam | 17-Lam | Combined |
|---|---|---|---|
| Sample size | 19 | 19 | 38 |
| Average MOR (1b/in$^2$) | 8,950 | 7,240 | 8,090 |
| MOR COV (%) | 13.4 | 15.2 | 17.9 |
| Average adjusted by $C_v$ | | | |
| 1/10 exponent | 8,660 | 8,190 | 8,420 |
| 1/20 exponent | 8,800 | 7,700 | (*a*) |
| 5th percentile adjusted by $C_v^b$ | | | |
| $MOR_{0.05}/2.1$, 1/10, point estimate | 3,280 | 3,010 | 3,140 |
| $MOR_{0.05}/2.1$, 1/20, point estimate | 3,340 | 2,830 | 3,000 |
| $MOR_{0.05}/2.1$, 1/10, at 75% tolerance | 3,160 | 2,880 | 3,050 |
| $MOR_{0.05}/2.1$, 1/20, at 75% tolerance | 3,210 | 2,710 | 2,910 |
| $F_b$ predicted with D3737[c] | 3,300 | 3,200 | — |

[a] Analyses conclude that the two data sets cannot be combined when using the 1/20 exponent.
[b] Modulus of rupture at 5% level of significance calculated with 2.1 factor and 1/10 or 1/20 exponent; 5% point estimate and 5% estimate at 75% tolerance.
[c] $F_b$ (design bending stress) prediction based on actual lumber properties.

Two design bending stresses were determined for each actual beam size: one with a volume effect exponent of 1/10 and the other with a volume effect exponent of 1/20. The results in Table 12 show that the 10-lamination beams performed at an estimated design bending stress level that was slightly higher than the target 3,000-lb/in$^2$ level (3,160 lb/in$^2$ for the 1/10 exponent and 3,210 lb/in$^2$ for the 1/20 exponent). For the 17-lamination beams, estimated design bending stresses were slightly lower than 3,000 lb/in$^2$ (2,880 lb/in$^2$ for the 1/10 exponent and 2,710 lb/in$^2$ for the 1/20 exponent). When the results of the two sizes were combined using the 1/10 exponent, a design stress of 3,000 lb/in$^2$ was shown to be adequate. For the 1/20 exponent, the values were slightly lower.

For the ASTM D3737 procedure, on the other hand, predicted design bending stresses greatly exceeded the target 3,000-lb/in$^2$ level; lo-lamination beams were predicted to perform at approximately 3,300 lb/in$^2$, and 17-lamination beams at approximately 3,200 lb/in$^2$. These predictions were based on a tension lamination with the limiting knot characteristics listed in Table 4 and were based on the assumption that end-joint quality was adequate for the specified beam design. Therefore, since the actual performance of the beams was lower than the predicted levels and the majority of the failures were attributed to end joints (shown in Table 9), we can assume that the end joints not only controlled beam strength but were inadequate for the predicted stress levels of 3,300 and 3,200 lb/in$^2$.

### Beam Stiffness

Results in Table 10 indicate that the average MOE of the small beams slightly exceeded 2.0 x 10$^6$ lb/in$^2$, and the average MOE of the large beams fell slightly below this figure. Using the ASTM D3737 round-off procedures, both groups of beams would be assigned a design MOE of 2.0 x 10$^6$ lb/in$^2$. Using the actual lumber MOE values in Table 6, MOE of 2.07 x 10$^6$ lb/in$^2$ was predicted for each beam size using the D3737 procedures. Thus, the target beam MOE level of 2.0 x 10$^6$ lb/in$^2$ was achieved for both beam sizes. However, the actual beam MOE values were slightly lower than the predicted values.

In addition, beam MOE values were calculated with the ASTM D3737 procedures for each individual beam using the lumber MOE values recorded on the beam maps. Figure 8 shows the predicted beam MOE values plotted against the actual beam MOE values. A 1:1 line is also shown on the graph. The cluster of data below the 1:1 line illustrate how the actual beam MOE values were slightly lower than the predicted values.

An investigation of the 17-lamination beam with the lowest MOE value (1.76 x 10$^6$ lb/in$^2$) (beam 6-14) produced some interesting results. Investigation of the corresponding beam map (illustrated in Appendix D), revealed that two pieces of lumber with low MOE values were randomly placed in the bottom and adjacent laminations (MOE of 1.96 and

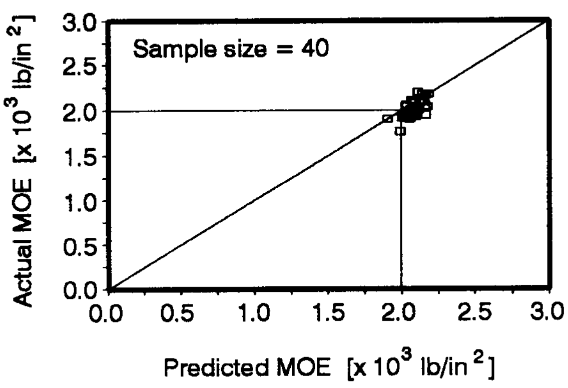


*Figure 8—Actual and predicted modulus of elasticity for all beams.*

1.94 x 10$^6$ lb/in$^2$, respectively). These two pieces still met the sorting criteria in Table 5, which shows a minimum allowable MOE value for the 2.3E grade of 1.90 x 10$^6$ lb/in$^2$. Using the D3737 procedures and the minimum and maximum allowable MOE values for each grade from Table 5, beam MOE values ranging from 1.65 to 2.40 x 10$^6$ lb/in$^2$ are possible for the beam combinations used in this research project (Fig. 2).

## Development of Specification

Our second objective was to determine the feasibility of manufacturing beams with the high strength and stiffness levels targeted in this research. From the previous analysis, we determined that the results of the actual beam tests met the target stiffness level but the strength level was slightly lower than that targeted for the large beams. To study the possibility of producing high strength and stiffness beams on a consistent basis, we examined why the large beams failed to meet the target strength level.

Past research results of hundreds of beam tests have shown that beam strength is often controlled by the strength of the end joints, as was the case in our study. For this reason, quality control procedures are applied to the manufacture of end joints intended for glulam beam construction. The industry standard for the manufacture of end joints (ANSI A190.1) specifies that end joints should qualify at 1.67 times the design bending stress of the beams. For example, for a beam with a design bending stress of 2,400 lb/in$^2$, the tensile strength distribution of the end joints used in the tension lamination should have a 5-percent lower exclusion limit (at 75 percent tolerance) of at least 1.67 x 2,400 lb/in$^2$, which is equal to approximately 4,000 lb/in$^2$. For our test program, the required qualification level would be 1.67 x 3,000 lb/in$^2$ = 5,010 lb/in$^2$.

**Table 13—Analysis of end-jointed lumber evaluations using lognormal distribution**

| Variable | 2 by 4 | 2 by 6 | Combined |
|---|---|---|---|
| Sample size | 30 | 34 | 64 |
| Average tensile strength (lb/in$^2$) | 6,810 | 6,350 | 6,560 |
| Tensile strength COV (%) | 18.0 | 16.1 | 17.2 |
| 5% point estimate | 5,000 | 4,820 | 4,880 |
| 5% estimate at 75% tolerance | 4,800 | 4,660 | 4,770 |
| End-joint/beam MOR ratio[a] | | | |
| Average EJ TS/average MOR | | | |
| 1/10 exponent | 1.65 | 1.63 | 1.64 |
| 1/20 exponent | 1.62 | 1.73 | (*b*) |
| EJ/MOR 5% point estimate | (1.67)[c] | (1.61)[c] | — |
| 1/10 exponent | 1.52 | 1.60 | 1.56 |
| 1/20 exponent) | 1.50 | 1.70 | (*b*) |
| EJ/MOR 5% point estimate at 75% tolerance | (1.60)[c] | (1.55)[c] | — |
| 1/10 exponent | 1.52 | 1.62 | 1.56 |
| 1/20 exponent | 1.50 | 1.72 | (*b*) |

[a] Adjusted to 12 in. beam. EJ is end joint; TS tensile strength. Ratios calculated with 2.1 factor.

[b] Analysis indicated that the two data sets cannot be combined when using the 1/20 exponent.

[c] Values in parentheses are 5% EJ ÷ 3,000 lb/in$^2$.

The analysis in Table 13 shows the ratios between beam bending strength and end-joint tensile strength. Of particular importance are the values shown in parentheses, which show the ratio between the 5-percent lower exclusion limit (at 75 percent tolerance) of the end-joint tensile strength and the target design stress of 3,000 lb/in$^2$ for the beams. The end-joint qualification factor was slightly less than the target of 1.67 for the small beams and significantly less for the large beams. Based on this analysis, we believe that the 3,000-lb/in$^2$ design stress in bending for glulam beams is possible if the end joints are qualified at 5,010 lb/in$^2$ in tension. Thus, end joints with higher strength values than the end joints tested in this study would be required for regular production of these beams.

The testing of the full-sized beams and the end joints was conducted at approximately the same load rates for this research project, following ASTM D198 (ASTM 1990a), which specifies a time-to-failure of 5 to 10 min. The AITC 200 (AITC 1991a) standard test for end-joint qualification (Test T119) permits a faster load rate (2 min), and the relationship between the various rates needs to be addressed.

## Conclusions

Based on the evaluation and analysis of 38 Southern Pine glulam beams, a design bending stress of 3,000 $lb/in^2$ and design MOE of 2.0 x $10^6$ $lb/in^2$ are obtainable if the following criteria are met:

1. the outer 10 percent of the laminations (top and bottom) are E-rated to have an MOE of 2.3 x $10^6$ $lb/in^2$,
2. the adjacent 15 percent of the laminations are No. 1D lumber with an average MOE of 2.0 x $10^6$ $lb/in^2$,
3. the end-joint qualifications follow procedures recommended in ANSI A190.1, and
4. tension lamination grading criteria are used.

## References

**AITC.** 1979. Determination of design values for structural glued laminated timber. AITC 117-79. American Institute of Timber Construction, Vancouver, WA.

**AITC.** 1988. Standard specifications for structural glued-laminated timber of softwood species. AITC 117–88—Manufacturing. American Institute of Timber Construction, Vancouver, WA.

**AITC.** 1991a. Inspection manual. AITC 200-91. American Institute of Timber Construction, Vancouver, WA.

**AITC.** 1991b. Use of a volume effect factor in the design of glued laminated timber beams. Tech. Note No. 21. American Institute of Timber Construction, Vancouver, WA. October.

**ANSI.** 1983. Structural glued laminated timber. ANSI A190.1. American Institute of Timber Construction, Englewood, CO.

**ASTM.** 1990a. Standard methods of static tests of timbers in structural sizes. ASTM D198-84. American Society for Testing and Materials, Philadelphia, PA.

**ASTM.** 1990b. Standard practice for evaluating allowable properties for grades of structural lumber. ASTM D2915-90. American Society for Testing and Materials, Philadelphia, Pa.

**ASTM.** 1990c. Standard method for establishing stresses for structural glued-laminated timber (glulam). ASTM D3737-89a. American Society for Testing and Materials, Philadelphia, PA.

**Freas, A.D.; Selbo, M.L.** 1954. Fabrication and design of glued laminated wood structural members. Tech. Bull. No. 1069. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

**Hernandez, R.; Bender, D.A.; Richburg, B.A.; Kline, K.S.** 1992. Probabilistic modeling of glued-laminated timber beams. Wood and Fiber Science. 24(3): 294-306.

**Johnson, J.W.** 1971. Design and test of large glued-laminated beams made of nondestructively tested lumber. Report T-27. Corvallis, OR: Oregon State University.

**Marx, C.M.; Evans, J.W.** 1986. Tensile strength of AITC 302-24 grade tension laminations. Forest Products Journal. 36(1): 13-19.

**Marx, C.M.; Evans, J.W.** 1988. Tensile strength of laminating grades of lumber. Forest Products Journal. 38(7/8): 6-14.

**Moody, R.C.** 1977. Improved utilization of lumber in glued laminated beams. Res. Pap. FPL-292. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

**Moody, R.C.; Bohannan, B.** 1970. Flexural properties of glued-laminated southern pine beams with laminations positioned by visual-stiffness criteria. Res. Pap. FPL-127. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

**Moody, R.C.; Dedolph, C., Jr.; Plantinga, P.L.** 1988. Analysis of size effect for glulam beams. In: Proceedings of the 1988 international conference on timber engineering; 1988 September; Seattle, WA. Madison, WI: Forest Products Research Society. 1: 892-898.

**Pellerin, R.F.; Strickler, M.D.** 1971. Tension proof loading of lam stock for laminated beams. Forest Products Journal. 21(5): 50-55.

**Pellerin, R.F.; Strickler, M.D.** 1972. Proof loading of tension laminations for large glued-laminated beams. Forest Products Journal. 22(10): 24-30.

**Ross, R.J.; Geske, E.A.; Larson, G.H.; Murphy, J.F.** 1991. Transverse vibration nondestructive testing using a personal computer. Res. Pap. FPL-RP-502. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

**SPIB.** 1970. Grading rules for Southern Pine lumber. Pensacola, FL: Southern Pine Inspection Bureau, 1970 Standard.

# Appendix A—Properties of Tension Laminations

**Table A-1-Properties of 2 by 4 outer tension laminations**

| Beam no. | SG | Moisture content (%) | MOE (× $10^6$ lb/in$^2$) | Characteristic[a] | Quality[b] |
|---|---|---|---|---|---|
| 4-1 | 0.61 | 12 | 2.91 | Clear | H |
| | 0.61 | 14 | 2.26 | 5% CK, GD | |
| 4-2 | 0.57 | 15 | 2.34 | 5% CK, GD | M |
| | 0.55 | 15 | 2.44 | 1:16 SOG | |
| 4-3 | 0.55 | 15 | 2.41 | Clear | H |
| 4-4 | 0.60 | 15 | 2.77 | Clear | H |
| | 0.52 | 13 | 1.98 | Clear | |
| 4-5 | 0.57 | 15 | 2.21 | 15% CK, GD | M |
| | 0.58 | 14 | 2.27 | Clear | |
| 4-6 | 0.57 | 14 | 2.22 | 15% CK, GD | M |
| 4-7 | 0.61 | 14 | 2.19 | Clear | H |
| 4-8 | 0.66 | 12 | 2.52 | 1:12 SOG | L |
| | 0.51 | 16 | 2.15 | Clear | |
| 4-9 | 0.59 | 13 | 2.61 | 1:12 SOG | L |
| | 0.48 | 16 | 1.92 | Clear | |
| 4-10 | 0.59 | 13 | 2.25 | Clear | H |
| | 0.57 | 13 | 2.22 | Clear | |
| 4-11 | 0.58 | 13 | 2.73 | Clear | H |
| 4-12 | 0.58 | 14 | 2.35 | Clear | H |
| 4-13 | 0.51 | 14 | 2.36 | Clear | M |
| 4-14 | 0.57 | 16 | 2.38 | Clear | H |
| | 0.55 | 15 | 2.22 | Clear | |
| 4-15 | 0.57 | 15 | 2.40 | 20% CK, GD | M |
| | 0.51 | 15 | 2.04 | Clear | |
| 4-16 | 0.51 | 16 | 1.99 | Clear | H |
| 4-17 | 0.59 | 12 | 2.60 | Clear | H |
| | 0.57 | 12 | 2.13 | Clear | |
| 4-18 | 0.57 | 15 | 2.67 | 1:16 SOG | M |
| 4-19 | 0.59 | 12 | 2.26 | 1:12 SOG | L |
| | 0.53 | 13 | 2.28 | Clear | |
| 4-20 | 0.62 | 12 | 2.61 | Clear | H |
| | 0.58 | 14 | 2.56 | Clear | |

[a] CK is center knot, GD grain deviation, and SOG slope of grain.

[b] Relative quality of midlength region of beam subjected to >85 percent maximum moment using rating system in Table 8. L is low, M medium, and H high.

**Table A-2—Properties of 2 by 6 outer tension laminations**

| Beam no. | SG | Moisture content (%) | MOE (× $10^6$ lb/in$^2$) | Characteristic[a] | Quality[b] |
|---|---|---|---|---|---|
| 6-1 | 0.55 | 12 | 1.90 | Clear (low E) | M |
| | 0.58 | 9 | 2.50 | Clear | |
| 6-2 | 0.56 | 13 | 2.22 | 10% CK, GD | M |
| | 0.58 | 10 | 2.11 | Clear | |
| 6-3 | 0.57 | 11 | 2.14 | 10% CK, GD | M |
| | 0.53 | 13 | 2.48 | Clear | |
| 6-4 | 0.61 | 15 | 2.54 | Clear | M |
| | 0.57 | 10 | 2.40 | 10% CK, GD | |
| 6-5 | 0.51 | 10 | 2.23 | Clear | H |
| | 0.60 | 10 | 2.49 | Clear | |
| | 0.52 | 15 | 2.10 | Clear | |
| 6-6 | 0.62 | 11 | 2.71 | Clear | H |
| | 0.54 | 12 | 2.10 | Clear | |
| 6-7 | 0.60 | 12 | 2.56 | Clear | H |
| | 0.62 | 14 | 2.45 | Clear | |
| | 0.55 | 12 | 2.15 | Clear | |
| 6-8 | 0.56 | 13 | 2.52 | Clear | H |
| | 0.55 | 15 | 2.40 | Clear | |
| 6-9 | 0.54 | 12 | 2.50 | 10% CK, GD | M |
| | 0.55 | 12 | 2.03 | Clear | |
| | 0.53 | 12 | 2.44 | Clear | |
| 6-10 | 0.60 | 10 | 2.56 | 5% GD | M |
| | 0.65 | 12 | 2.27 | 10% GD | |
| 6-11 | 0.59 | 14 | 2.44 | Clear | L |
| | 0.58 | 12 | 1.97 | 15% CK, GD | |
| | 0.55 | 14 | 2.50 | Clear | |
| 6-12 | 0.56 | 11 | 2.61 | 15% EK, GD | L |
| | 0.60 | 13 | 2.20 | Clear | |
| 6-13 | 0.60 | 13 | 2.33 | Clear | L |
| | 0.51 | 14 | 1.98 | 15% CK, GD | |
| | 0.57 | 12 | 2.03 | Clear | |
| 6-14 | 0.62 | 10 | 2.34 | Clear | M |
| | 0.54 | 10 | 1.96 | Clear (low E) | |
| 6-15 | 0.61 | 15 | 2.64 | Clear | L |
| | 0.51 | 13 | 2.15 | 20% CK, GD | |
| 6-16 | 0.49 | 12 | 2.18 | Clear | L |
| | 0.53 | 15 | 2.35 | 1:16 SOG | |
| 6-17 | 0.58 | 12 | 2.63 | Clear | M |
| | 0.57 | 11 | 2.35 | 15% CK, GD | |
| 6-18 | 0.63 | 12 | 2.56 | 10% CK, GD | L |
| | 0.59 | 14 | 1.92 | Clear (low E) | |
| 6-19 | 0.58 | 11 | 2.68 | 10% EK, GD | M |
| | 0.55 | 13 | 2.69 | Clear | |
| 6-20 | 0.55 | 14 | 2.10 | Clear | H |
| | 0.62 | 12 | 2.57 | Clear | |

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

[b] Relative quality of midlength region of beam subjected to >85 percent maximum moment using rating system in Table 8. L is low, M medium, and H high.

# Appendix B—Results of Bending Tests

**Table B–1—Results of bending tests on 24-ft (22.5-ft span) beams**

| Beam no. | Width (in.) | Depth (in.) | MC (%) | Wt (lb) | Time and load at failure (min:s) | Time and load at failure (lb) | MOR[a] (lb/in$^2$) | MOE (lb/in$^2$) | EJ in TL[b] | EJ failure | Comment[c] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4-1 | 3.01 | 13.70 | 10 | 255 | 4:58 | 13,400 | 7,559 | 2.11 | Y | Y | Failed in TL at EJ at 10.7 ft (100%), propagated to GD in 2d lam at 6 ft. |
| 4-2 | 3.00 | 13.76 | 12 | 256 | 5:40 | 13,920 | 7,794 | 1.91 | Y | N | Noise at 11,000 lb; failed in TL (lumber) at 7 ft, thru 3d lam, with low MOE at 8.5 ft thru GD in 4th lam at 11 ft. |
| 4-3 | 3.00 | 13.45 | 10 | 249 | 8:20 | 17,460 | 10,218 | 2.20 | N | Y | Noise at 9,200 lb; COMP failure at 15,200 lb at 9.8 ft in top lam; COMP wrinkles thru top 4 lams at 14.4 ft at 17,000 lb; failure in TL EJ at 19.2 ft (100%). |
| 4-4 | 3.00 | 13.62 | 11 | 248 | 6:09 | 14,920 | 8,525 | 1.94 | Y | Y | Noise at 14,600 lb; failed in TL EJ at 13 ft (10%). |
| 4-5 | 3.01 | 13.77 | 12 | 255 | 6:27 | 16,480 | 9,170 | 2.08 | Y | Y | Noise at 8,800 lb; cracked in TL (lumber) at 14,300 lb at 14.5 ft, failed in TL EJ at 13 ft (100%) thru 2d lam EJ at 8 ft (100%), to 4th lam EJ at 12 ft (100%). |
| 4-6 | 3.02 | 13.77 | 12 | 257 | 5:04 | 13,120 | 7,304 | 1.93 | N | Y | Noise at 11,800 lb; failed in TL (lumber) at 14.7 ft in low MOE area, thru EJ in 3d lam at 7.1 ft (15%). |
| 4-7 | 3.00 | 13.73 | 11 | 257 | 9:17 | 19,970 | 11,206 | 1.95 | N | Y | Noise at 11,000 lb; COMP wrinkling in top lam at 14.6 ft at 11,000 lb; failed in TL EJ at 18.6 ft (100%) thru 2d lam EJ at 9.1 ft (40%). |
| 4-8 | 3.00 | 13.68 | 11 | 264 | 4:46 | 13,806 | 7,821 | 2.18 | Y | Y | Noise at 12,700 lb; failed in TL EJ at 13.5 ft (100%) thru 2d and 3d lams. |
| 4-9 | 2.98 | 13.76 | 11 | 258 | 5:40 | 14,660 | 8,260 | 2.05 | Y | Y | Noise at 14,000 lb; failed in TL EJ at 12.2 ft (100%) thru EJ in 3d lam at 11.8 ft (100%). |
| 4-10 | 3.00 | 13.71 | 13 | 261 | 5:14 | 14,540 | 8,205 | 2.04 | Y | Y | No noise until failure; failed in TL (lumber) at 15.8 ft; failed in EJ in 3d lam at 11.7 ft (50%). |
| 4-11[d] | 3.00 | 13.63 | 11 | 258 | 8:33 | 17,520 | 9,902 | 2.17 | N | N | Noise at 14,000 lb; sliver popped in TL at 16,000 lb from 11 ft to 19 ft; COMP wrinkles thru top 4 lams at 14.2 ft. |
| 4-12 | 2.98 | 13.65 | 10 | 256 | 6:15 | 16,370 | 9,363 | 2.04 | N | N | Noise at 9,700 lb; failure in TL at 5.0 ft thru 12.3 ft.; propagated thru 2d lam at 9.5 ft. |
| 4-13 | 2.99 | 13.74 | 10 | 259 | 8:09 | 20,260 | 11,382 | 2.17 | N | Y | Noise at 15,000 lb; COMP wrinkling at load head at 20,000 lb; failure at EJ in 2d lam at 12.4 ft (100%) and EJ in 3d lam at 15.2 ft (100%). |
| 4-14 | 3.00 | 13.70 | 11 | 263 | 5:25 | 14,650 | 8,273 | 2.08 | Y | Y | No noise until failure; failed in TL EJ at 14.3 ft (100%). |
| 4-15 | 3.01 | 13.63 | 11 | 298 | 5:14 | 13,280 | 7,569 | 1.99 | Y | Y | Noise at 7,000 lb; failed in TL EJ at 11.8 ft (95%). |
| 4-16 | 3.00 | 13.65 | 12 | 254 | 7:51 | 16,360 | 9,301 | 1.98 | N | N | Noise at 11,000 lb; COMP wrinkles at 14.3 ft in top 5 lams; failed in TL (lumber) at 14.2 ft. |
| 4-17 | 3.00 | 13.78 | 10 | 252 | 7:28 | 17,300 | 9,646 | 2.04 | Y | Y | No noise until failure; failed in TL EJ at 16.8 ft (90%). |
| 4-18 | 3.00 | 13.75 | 11 | 255 | 9:52 | 18,000 | 10,071 | 2.10 | N | Y | Noise at 13,600 lb; COMP wrinkles in top 2 lams at 14,000 lb; failure at EJ in 2d lam at 15.4 ft (100%). |
| 4-19 | 3.00 | 13.75 | 12 | 257 | 7:54 | 17,680 | 9,887 | 1.90 | Y | Y | Noise at 6,000 lb; failed in TL EJ at 13.4 ft (100%), in 2d lam EJ at 12.0 ft (100%), to 3d lam EJ at 10.8 ft (100%). |
| 4-20 | 3.00 | 13.72 | 11 | 256 | 5:39 | 15,060 | 8,482 | 2.10 | Y | Y | Noise at 11,800 lb; failed in TL EJ at 8.3 ft (100%), thru 2d lam lumber, to 3d lam EJ at 11.2 ft (100%). |

[a] MOR calculations include dead load stress.

[b] End joint (EJ) in tension lamination (TL) within >85% maximum moment region. Y is yes, N no.

[c] COMP is compression, GD is grain deviation, and lam is lamination.

[d] Beam 4-11 excluded from analysis as a result of inadvertent switching of 3d and 4th laminations.

## Table B-2—Results of bending tests on 40-ft (3%ft span) beams[a]

| Beam no. | Width (in.) | Depth (in.) | MC (%) | Wt (lb) | Time and load at failure (min:s) | Time and load at failure (lb) | MOR (lb/in$^2$) | MOE (lb/in$^2$) | EJ in TL | failure | Comment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6-1 | 5.00 | 23.48 | 11 | 1,200 | 7:36 | 40,500 | 8,090 | 1.97 | Y | Y | Noise at 38,000 lb; failed in TL EJ at 30.6 ft (100%), thru EJ in 2d lam at 24.8 ft (100%). |
| 6-2[b] | 5.00 | 23.38 | 11 | 1,200 | 8:35 | 43,300 | 8,694 | 1.95 | Y | Y | Noise at 34,000 lb; failed in TL EJ at 19.6 ft (100%), thru 2d lam to EJ failure in 3d lam at 19.8 ft (100%). |
| 6-3 | 5.00 | 23.48 | 11 | 1,300 | 6:32 | 36,000 | 7,193 | 2.00 | Y | Y | Noise at 32,000 lb; failed in TL EJ at 23.9 ft (100%), thru 2d lam EJ at 22.5 ft (100%). |
| 6-4 | 5.03 | 23.44 | 11 | 1,290 | 7:42 | 41,500 | 8,245 | 2.09 | Y | Y | Failed in TL EJ at 19.5 ft 100%), thru 2d to 4th lams at 19.5 ft-10 ft, COMP in top lam at left loadhead at 37,500 lb. |
| 6-5 | 5.03 | 23.44 | 10 | 1.350 | 5:20 | 31,850 | 6,366 | 2.06 | Y | Y | Noise at 25,006 lb; failed in TL EJ at 23.9 ft (100%), thru 2d lam EJ (25%) at 21.9 ft, thru core. |
| 6-6 | 5.00 | 23.38 | 11 | 1,300 | 6:55 | 38,500 | 7,749 | 2.03 | Y | Y | Noise at 38,000 lb; failed in TL EJ (100%) at 23.5 ft. |
| 6-7 | 5.03 | 23.38 | 11 | 1,280 | 6:18 | 32,800 | 6,579 | 1.92 | Y | Y | Noise at 31,000 lb; failed in TL EJ at 24.6 ft (100%), thru 2d to 4th lams. |
| 6-8 | 5.03 | 23.38 | 11 | 1,300 | 4:50 | 25,500 | 5,147 | 1.97 | Y | Y | Failed in TL EJ at 15.2 ft (100%), glue failed—2d/3d at 20-30 ft. |
| 6-9 | 5.03 | 23.44 | 11 | 1,200 | 6:55 | 36,500 | 7,258 | 1.93 | Y | Y | Noise at 34,000 lb; failed in TL EJ at 15.9 ft (100%), thru 2d and 3d lam to end of beam. |
| 6-10 | 5.03 | 23.38 | 11 | 1,270 | 7:58 | 41,100 | 8,208 | 1.90 | Y | Y | Noise at 39,000 lb; failed in TL EJ at 20.5 ft (100%), failed thru 2d and 3d lams to core. |
| 6-11 | 5.03 | 23.31 | 11 | 1,200 | 6:12 | 31,750 | 6,398 | 1.91 | Y | Y | Noise at 23,000 lb; failed in TL EJ at 14.6 (100%), thru knot in 2d lam at 15.3 ft. |
| 6-12 | 5.03 | 23.41 | 11 | 1,300 | 5:52 | 32,130 | 6,432 | 2.00 | Y | Y | Noise at 31,000 lb; failed in TL EJ at 24.7 ft (100%), thru 2d and 3d lams. |
| 6-13 | 5.00 | 23.31 | 11 | 1,100 | 7:04 | 36,100 | 7,292 | 2.01 | Y | Y | Noise at 28,400 lb; failed in TL EJ at 14.7 ft (100%), thru 2d and 3d lams, thru core. |
| 6-14 | 5.06 | 23.47 | 12 | 1,100 | 8:24 | 39,500 | 7,765 | 1.76 | Y | N | Noise at 32,000 lb; failed in TL (lumber) at 20 ft, thru 2d to 4th lams, thru core. |
| 6-15 | 5.00 | 23.31 | 11 | 1.400 | 6:56 | 35,240 | 7,153 | 1.92 | Y | Y | Noise at 22,500 lb; failed in TL EJ at 15.9 ft (100%), thru EJ in 2d lam at 12.7 ft (100%), |
| 6-16 | 5.03 | 23.42 | 12 | 1,200 | 6:25 | 35,200 | 7,015 | 1.90 | Y | Y | Noise at 29,500 lb; failed in TL EJ at 16.5 ft (100%), thru 2d to 4th lams. |
| 6-17 | 5.00 | 23.38 | 11 | 1,300 | 9:01 | 46,400 | 9,310 | 2.00 | Y | Y | Noise at 40,500 lb (sliver popped at 13 ft), failed TL (lumber) at 20 ft, thru EJ in 2d lam at 16 ft (100%). |
| 6-18 | 5.03 | 23.38 | 11 | 1,250 | 8:48 | 45,200 | 9,011 | 1.96 | Y | Y | Noise at 35,000 lb; failed in TL EJ at 24.7 ft (20%), thru 2d to 5th lams. |
| 6-19 | 5.06 | 23.50 | 12 | 1,270 | 5:22 | 28,500 | 5,637 | 1.94 | Y | Y | Noise at 26,500 lb; failed in TL EJ at 18 ft (100%), thru 4th lam. |
| 6-20 | 5.03 | 23.44 | 12 | 1,270 | 6:13 | 32,670 | 6,517 | 1.93 | Y | Y | Failed in TL EJ at 21 ft (100%), thru 4th lam. |

[a] See footnotes a, b, and c to Table B-1.

[b] Beam 6-2 excluded from analysis as a result of substandard EJ in TL.

# Appendix C—Results of Tension Tests

**Table C-1—Results of tension tests on end-jointed lumber (lognormal distribution)**

| Lumber grade and size | Sample size[a] | Tensile strength Average (lb/in$^2$) | COV (%) | 0.05 point estimate | 0.05 at 75% tolerance |
|---|---|---|---|---|---|
| 2.3E | | | | | |
| 2 by 4 | 0 | – | – | – | – |
| 2 by 6 | 30 | 6,790 | 17.2 | 5,050 | 4,860 |
| No. 1D | | | | | |
| 2 by 4 | 29 (32) | 6,680 | 22.7 | 4,500 | 4,280 |
| 2 by 6 | 28 (29) | 6,100 | 18.9 | 4,400 | 4,210 |
| No. 2M | | | | | |
| 2 by 4 | 9 (21) | 4,280 | 34.5 | 2,330 | 1,970 |
| 2 by 6 | 14 (23) | 3,900 | 23.2 | 2,610 | 2,400 |

[a] Numbers in parentheses indicate original sample size. Sample sizes and statistics reported correspond to specimens with failures associated with end joints.

# Appendix D-Glulam Beam Failure Maps and Lumber Properties

Lumber properties shown on beam maps are in the form $X(Y)Z$,

where

$X$ is modulus of elasticity [$10^6$ lb/in$^2$],

$Y$ specific gravity, and

$Z$ moisture content (during beam manufacture) (percent).

The critical moment (>85 percent maximum moment) region is defined as the area between 8 and 16 ft for the 10-lamination beams, and the area between 12 and 28 ft for the 17-lamination beams.

The lowline strength characteristics are also mapped,

where

SOG is slope-of-grain,

CK center knot,

EK edge knot, and

GD grain deviation.

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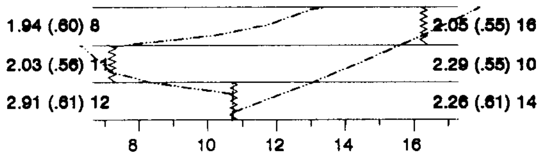

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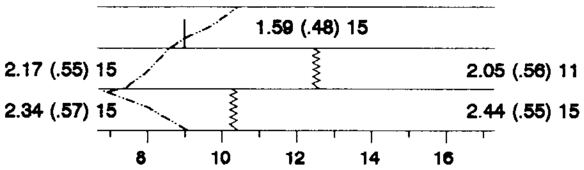

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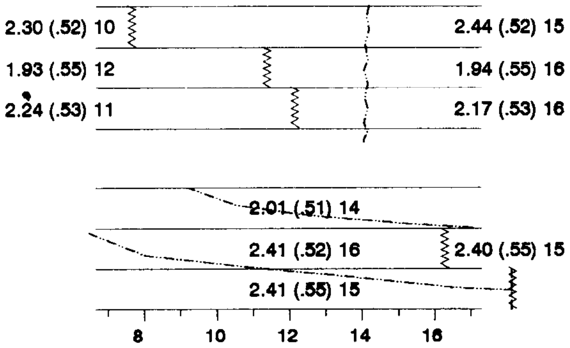

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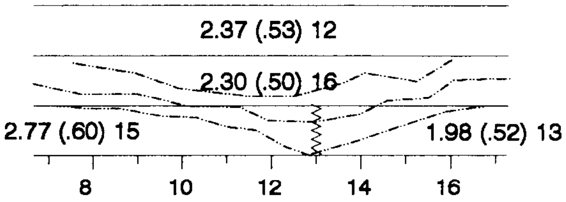

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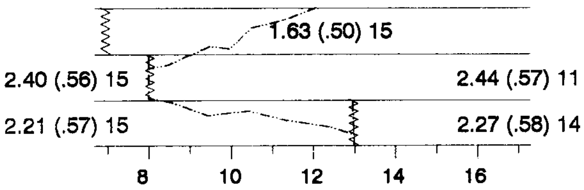

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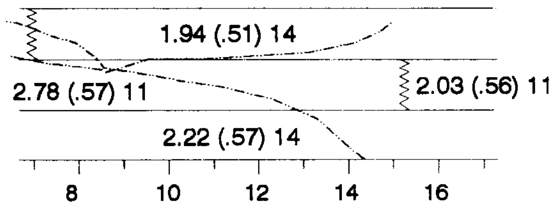

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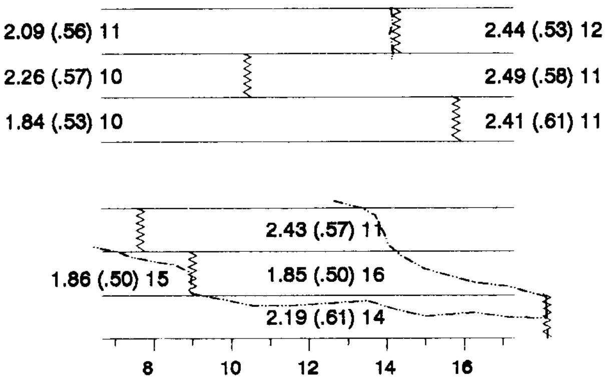

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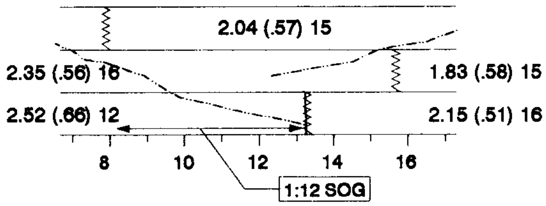

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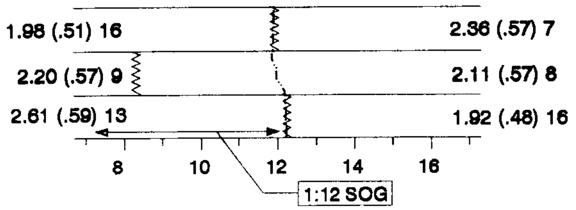

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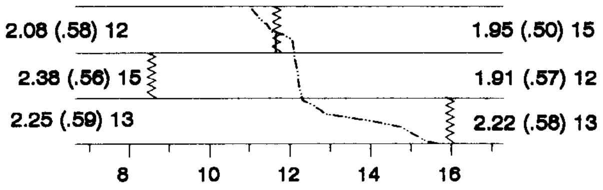

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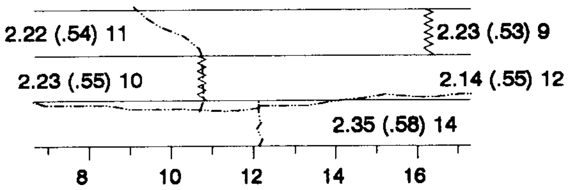

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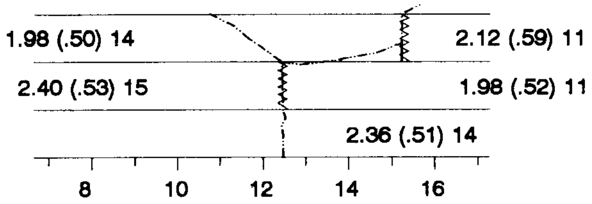

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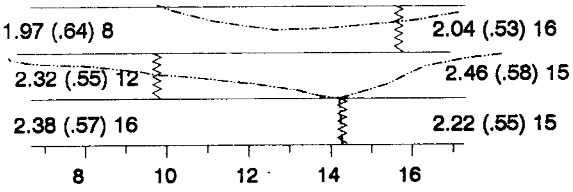

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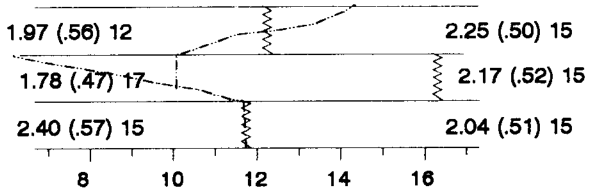

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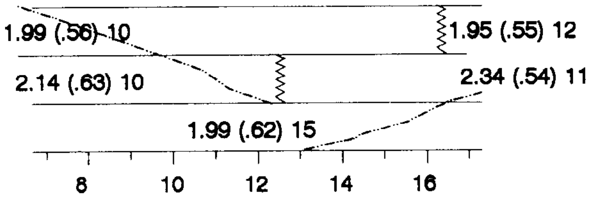

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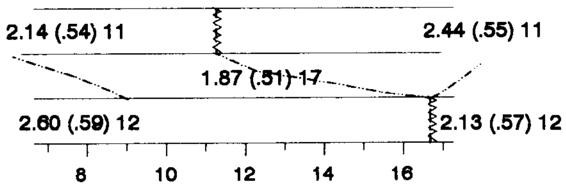

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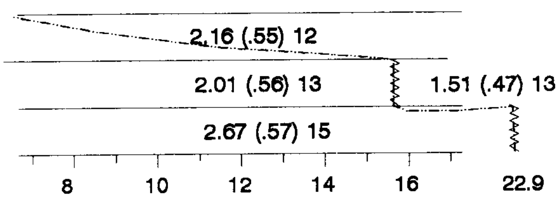

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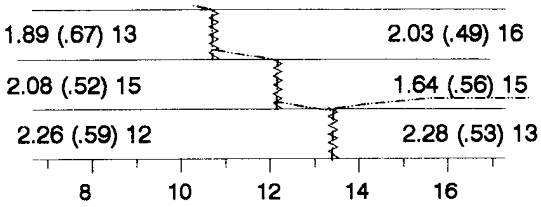

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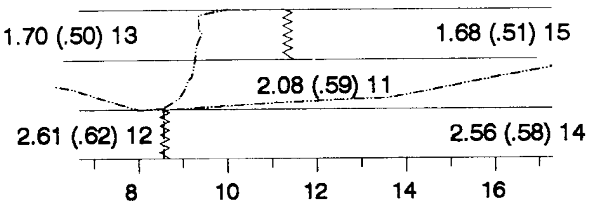

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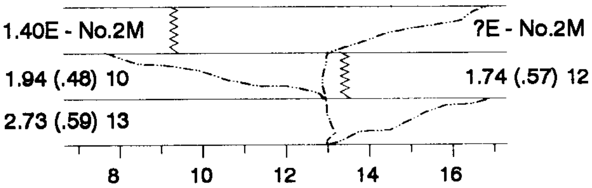
This beam was excluded from the research project



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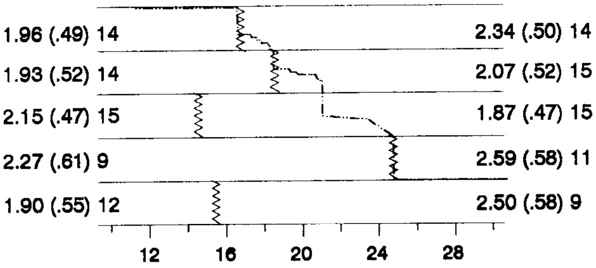

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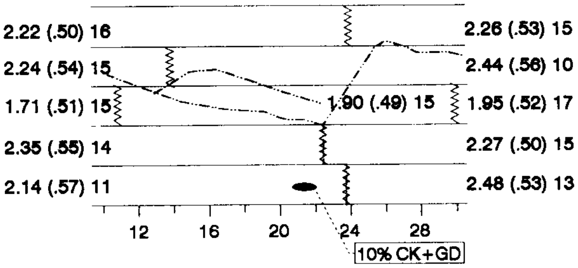

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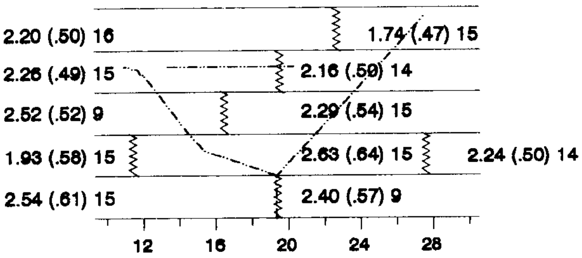

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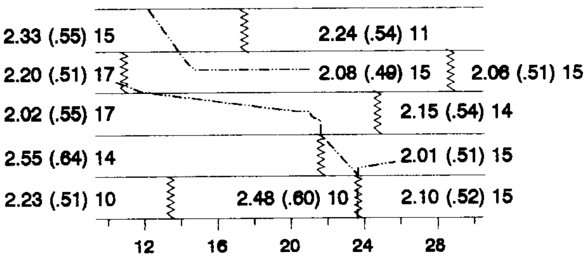

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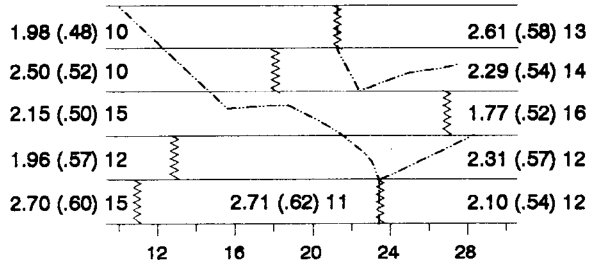

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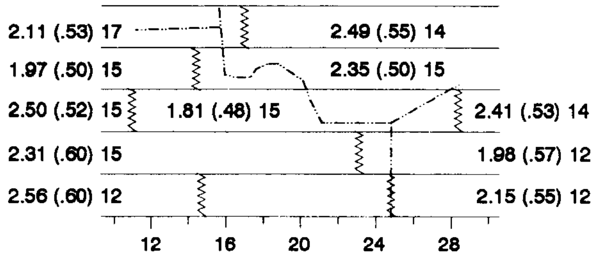

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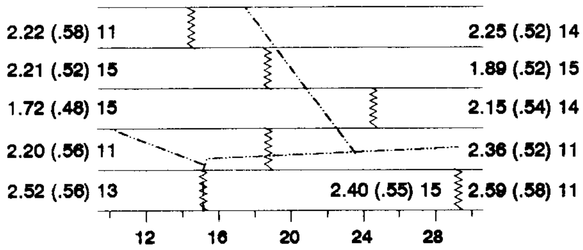

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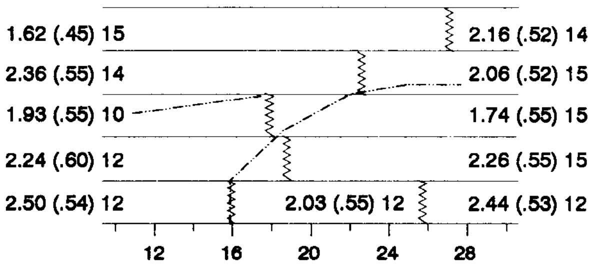

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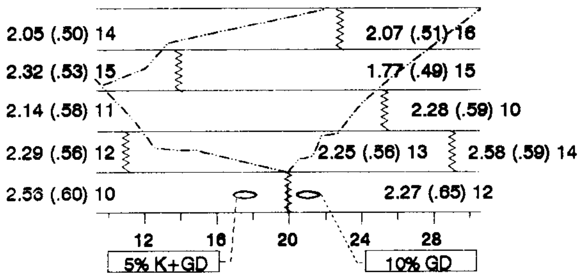

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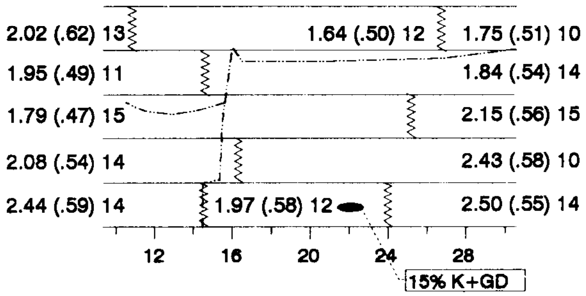

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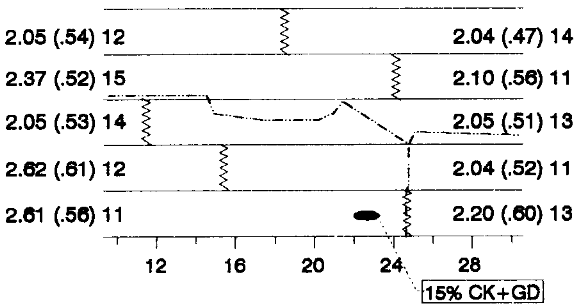

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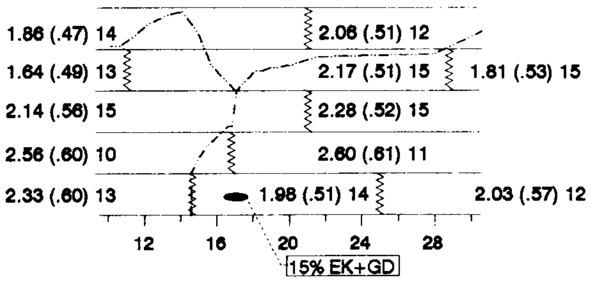

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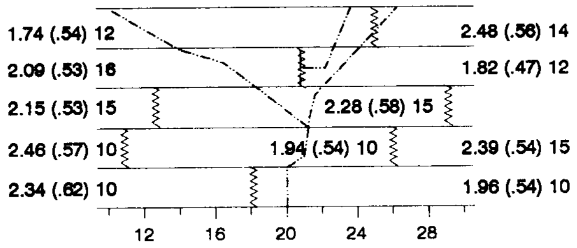

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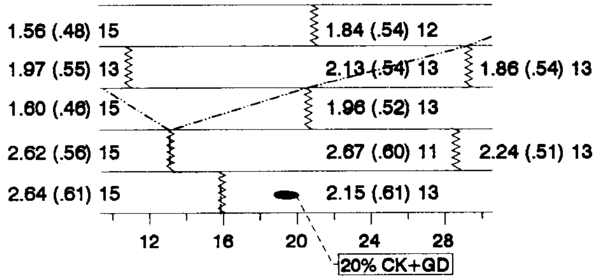

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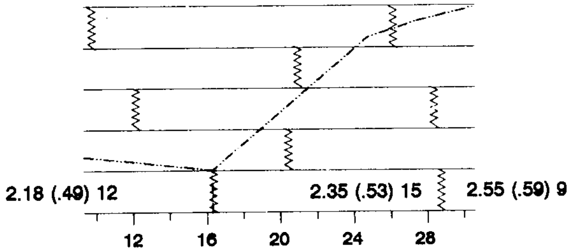

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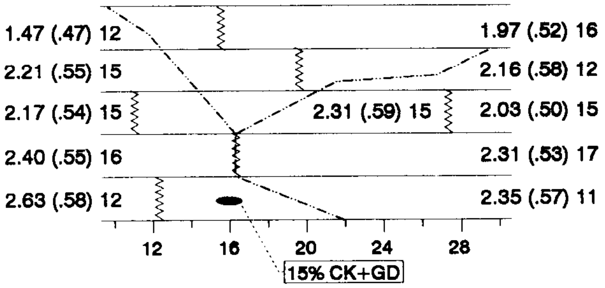

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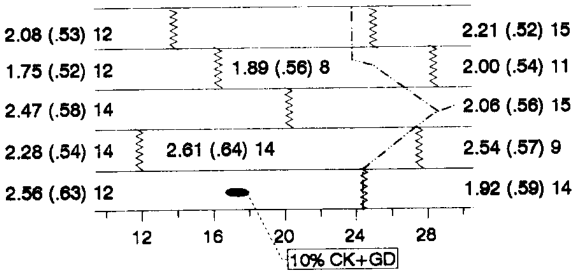

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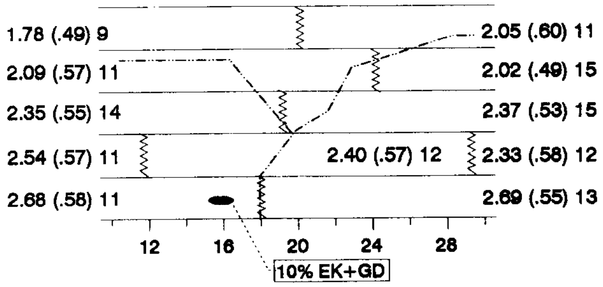

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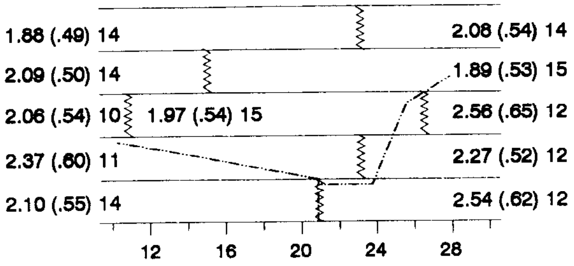

Beam No. 6-2

This beam was excluded from the research project