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Fiber Stress Values for Design of Glulam Timber Utility Structures

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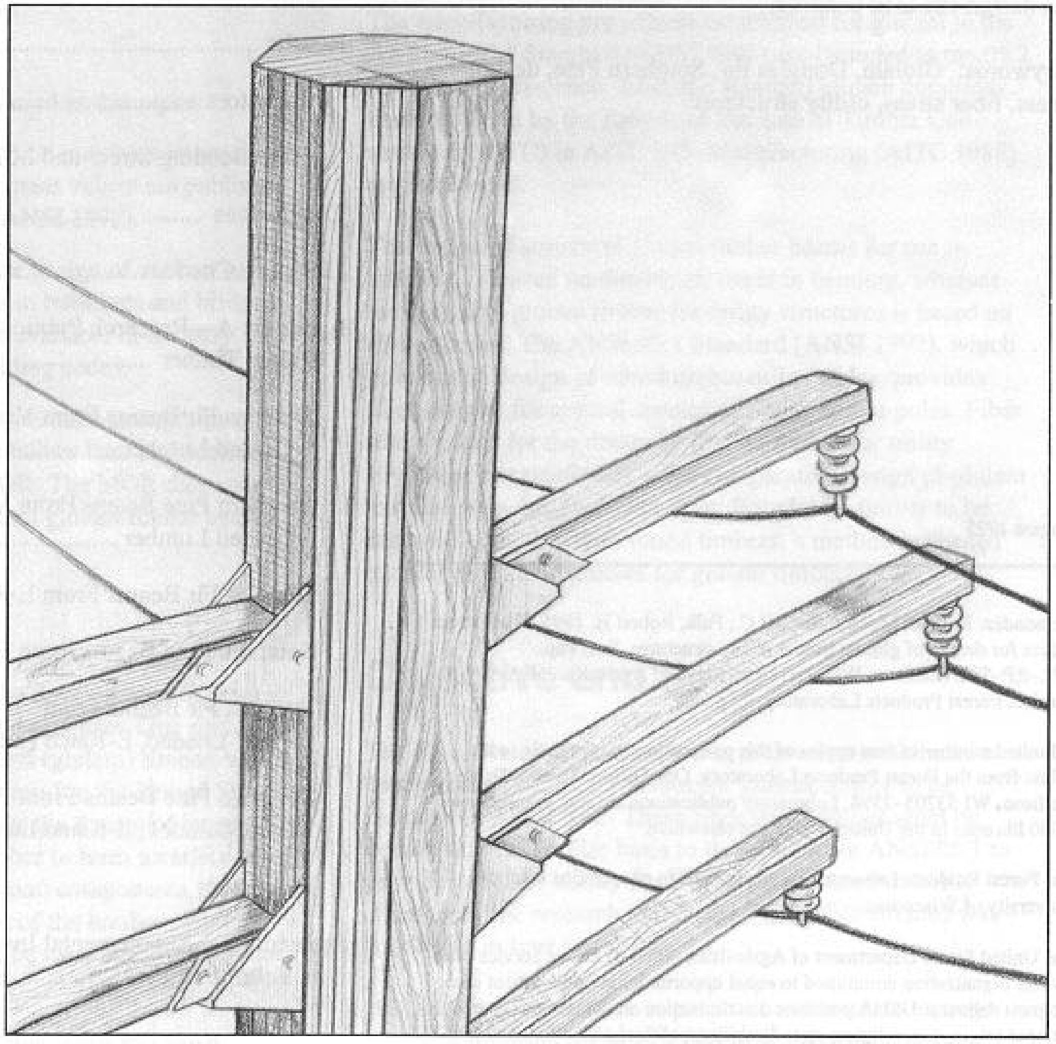

Abstract

In this study, we developed a simple equation to calculate average fiber stress values for design of glued-laminated (glulam) timber utility structures as a function of design bending stress. We took design stress in bending values specified by the American Institute of Timber Construction (AITC) for various combinations of glulam timber, applied appropriate end-use adjustments, and determined an appropriate factor to obtain average modulus of rupture. Fiber stresses for glulam were then determined from the average modulus of rupture values using the relationship between these values and the fiber stress values for round timber poles. To verify this relationship, a data base was compiled that contained bending strength results of glulam timber beams manufactured following the design combinations established by the AITC. Results indicate that the proposed equation can be used to calculate fiber stresses for all glulam beams manufactured with visually graded or E-rated lumber. For bending members less than 50 ft (15.24 m) long, the average fiber stress was found to be approximately 2.7 times the design stress in bending.

Keywords: Glulam, Douglas Fir, Southern Pine, design stress, fiber stress, utility structures

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Introduction

Definitions

For clarity, we define some terms used in this report:

Fiber stress: basis for design of wood members in bending used in utility applications. Fiber stress values are published in ANSI O5.1 for round timbers (ANSI 1992).

Design stress in bending: basis for design of various types of wood members for applications in buildings and bridges, commonly denoted F_b. Values are available in industry literature and through various building codes.

Modulus of rupture: measure of ultimate strength in bending calculated using ultimate failure load and section properties, commonly denoted MOR. The MOR data used in this report are from tests of structural glulam timber beams.

Background

The decreased availability of large timbers for use in structural applications has led to the development of several types of engineered structural wood products. One such product is structural glued-laminated (glulam) timber, which was developed in Europe and first used in the United States in the 1930s. Glulam timber permits the design of large members using nominal-sized lumber to form a variety of lengths, sizes, and shapes of structural components. Also, glulam allows for better utilization of the lumber resource because low-strength material can be used in areas subjected to low stresses.

Glulam timber can replace both round poles and sawn timbers in utility structures. The American National Standards Institute (ANSI) establishes requirements for the manufacture, marking, coding, testing, inspection, quality control, storage, and shipping of all glulam products used for utility structures in the ANSI 05.2 Standard (ANSI 1983). The manufacturing procedures established for glulam in the ANSI A190.1 Standard (ANSI 1992) are included in the 05.2 Standard by reference. Also, the standard glulam combinations provided by the American Institute of Timber Construction (AITC) in AITC 117–Manufacturing (AITC 1988) are referenced.

The design of structural glulam timber beams for use in buildings is based on the design stress in bending, whereas the design of glulam timber for utility structures is based on fiber stresses. The ANSI 05.1 Standard (ANSI 1992), which governs the design of round timber utility poles, provides fiber stresses for several species of round timber poles. Fiber stress values for the design of glulam timber for utility structures that would allow the comparative design of glulam to round pole design do not exist. For glulam timber to be designed equitably with round timbers, a method is needed to determine fiber stresses for glulam timbers.

Objective and Scope

The objective of this research was to develop a method for determining fiber stress values for glulam timber to be included in ANSI 05.2. These fiber stress values must be developed on a similar basis to those found in ANSI 05.1 to provide equal reliability for glulam timber used in utility structures. The research to develop these fiber stresses was conducted in four parts:

1. A simple equation was proposed to calculate average glulam beam MOR as a function of both the design stress in bending for glulam combinations in AITC 117–Manufacturing (AITC 1988) and several end-use factors in AITC 117–Design (AITC 1987).

2. A data base of glulam beam tests using AITC 117–Manufacturing (AITC 1988) glulam beam combinations was compiled for validating the proposed equation.
3. An actual relationship between design stress in bending and average MOR was determined using results from the data base.
4. Published fiber stress for round poles was related to average MOR for round poles so that the relationship for glulam was consistent with the relationship that forms the basis for round poles in ANSI 05.1 (ANSI 1992).

Procedures

Design Stress in Bending and Average Bending Strength

Each glulam timber combination provided in AITC 117–Manufacturing (AITC 1988) has a specified value for design stress in bending (F_b). The relationship between these F_b values and the actual bending strength of the glulam combinations involves a safety factor, a load duration factor, and several end-use factors. These factors, when applied to the F_b value, relate the specified design stress to the lower fifth percentile of an actual beam bending strength distribution for that particular combination. This relationship is represented by the following equation and illustrated in Figure 1:

$$F_b = \frac{\mathrm{MOR}_{.05}}{2.1C} \tag{1}$$

where

F_b is design stress in bending at normal conditions,

$\mathrm{MOR}_{.05}$ fifth percentile of glulam MOR distribution (75-percent tolerance limit),

2.1 combined factor for safety and load duration, and

C product of all end-use adjustment factors.

The factored F_b values in the AITC 117 Standard (AITC 1988) are related to the fifth percentile of the MOR distribution to obtain the reliability levels required by glulam timber for use as main load-carrying members.

To arrive at the relationship between F_b and average MOR for glulam, another factor, not shown in Equation (1), has to be considered. The variability, or coefficient of variation (COV), of MOR directly affects the relationship between $\mathrm{MOR}_{.05}$ and the average MOR value (MOR_{avg}). If Equation (1) is rewritten, the following relationship for the normal distribution and large sample sizes is used:

$$\mathrm{MOR}_{.05} = \mathrm{MOR}_{avg}\,(1 - 1.645\ \mathrm{COV})$$

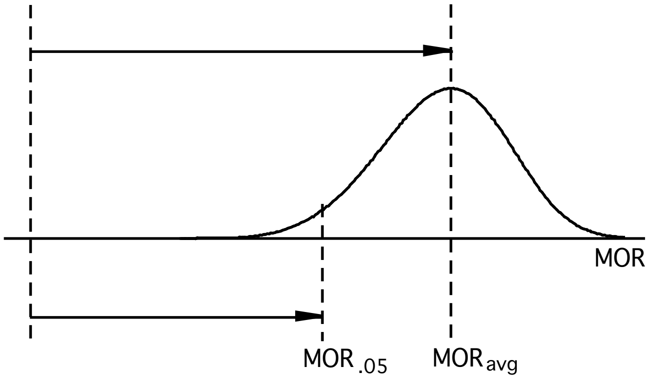

Figure 1—Relationship between design bending stress and actual modulus of rupture (MOR).

Equation (1) becomes

$$F_b(2.1C) = \mathrm{MOR}_{avg}\,(1 - 1.645\ \mathrm{COV}) \tag{2}$$

By dividing both sides of the equation by MOR_{avg} and solving for MOR_{avg},

$$\mathrm{MOR}_{avg} = \frac{F_b(2.1C)}{1 - 1.645\,\mathrm{COV}} \tag{3}$$

Equation (3) relates the F_b value (factored for safety, load duration, end-use, and MOR variability) to MOR_{avg}.

Safety, Load Duration, and Variability Factors

Combining the safety, load duration, and variability components into a single factor K gives (also shown in Fig. 1)

$$\mathrm{MOR}_{avg} = F_b K C \tag{4}$$

where

$$K = \frac{2.1}{1 - 1.645\,\mathrm{COV}} \tag{5}$$

The factor K is dependent on the COV of the glulam beam bending strength, which normally ranges from 15 to 20 percent. For COV ranging from 15 to 20 percent, calculated K ranges from 2.79 to 3.13, respectively.

End-Use Factors

In glulam beam design, end-use factors are applied to the published design bending stress values to account for various conditions of use. The conditions of use directly affect the bending strength performance of the glulam timber. The following sections describe the end-use factors for tension lamination, volume, loading, and moisture content.

Tension Lamination: Past research has shown that special provisions are required for the tension lamination of a glulam beam to achieve the specified design bending strength levels. Strength reduction factors must be incorporated in determining bending strength if a special tension lamination is not included in the beam combination. Tension lamination factors (C_t), which can be found in the ASTM Standard D3737 (ASTM 1991), have the following values:

C_t = 1.00 for special tension laminations per AITC 117

= 0.85 without tension laminations and for depth ≤15 in. (≤380 mm)

= 0.75 without tension laminations and for depth >15 in. (≥380 mm)

Volume: The volume factor (C_v) accounts for an observed reduction in strength when length, width, and depth of structural members increase. This strength reduction is due to the higher probability of occurrence of strength-reducing characteristics, such as knots, in higher volume beams. This volume factor adjustment is given in AITC Technical Note 21 (AITC 1991) in the form

$C_v = (12/d)^{0.10} (5.125/w)^{0.10} (21/L)^{0.10}$ Douglas Fir
$\quad = (12/d)^{0.05} (5.125/w)^{0.05} (21/L)^{0.05}$ Southern Pine

where

d is depth (in.),
w is width (in.), and
L is length (ft).

Loading: An adjustment for the type of loading on the member is also necessary because the volume factors were derived assuming a uniform load. For MOR values derived using loading conditions other than uniform, the values must be adjusted using the following method of loading factors (C_L) recommended in AITC Technical Note 21 (AITC 1991):

C_L = 1.08 for center-point loading on simple span

= 1.00 for uniform loading on simple span

= 0.97 for third-point loading

= 0.92 for constant stress over full length

For other loading conditions, an approximate C_L factor can be determined by calculating the proportion of the beam length subjected to ≥83 percent of the maximum stress, L_0, and

$C_L = (0.408/L_0)^{0.1}$ (Moody and others 1988)

Moisture Content: The moisture content factor (C_m) accounts for the reduction in strength as moisture content increases. The following moisture content factors are listed in both the ASTM D3737 Standard (ASTM 1991) and AITC 117–Design (AITC 1987):

C_m = 1.0 for ≤16 percent moisture content

= 0.8 for >16 percent moisture content, as in ground contact and other exterior conditions

Equation for All End-Use Factors: By applying all the end-use factors to Equation (3), the following is obtained:

$$\mathrm{MOR_{avg}} = \frac{F_b(2.1 C_t C_v C_L C_m)}{1 - 1.645\,\mathrm{COV}} \tag{6}$$

where $C = C_t C_v C_L C_m$ (see Eq. (3))

Glulam Data Base

To verify if the relationship between MOR and F_b presented in Equation (6) is feasible, test data of glulam beams manufactured using standard AITC 117-Manufacturing (AITC 1988) combinations were compiled. The glulam beam test results were obtained from past research reports as well as recent laboratory tests. The beam tests were divided into two species groups, Douglas Fir and Southern Pine, and each species group was further divided into horizontally and vertically laminated combinations. The horizontally laminated combinations were separated into three groups that represented the use of (a) visually graded lumber, (b) E-rated lumber, and (c) both E-rated and tension-proof-loaded laminations. Data on critical features, such as beam dimensions, moisture content, MOR, and use of tension laminations, were compiled for analysis. These data are available through the National Technical Information Service (Hernandez and others 1995). Each research report is described in detail in Appendix A. Table 1 lists the sample sizes associated with the data base compilation.

Table 1—Sample sizes for glulam beam data base

Laminating stock	Douglas Fir	Southern Pine	Combined
Horizontally laminated			
Visually graded lumber	372	262	634
E-rated lumber	53	80	133
Tension-proof-loaded end-joints	105	48	153
Vertically laminated			
Visually graded lumber	272	126	398

Determination of *K*-Factor From Actual Test Results

To determine the actual *K*-factors for each beam discussed in the section on compiling the glulam data base, Equation (5) was substituted into Equation (6) and solved for *K*. The resulting equation was applied individually to the MOR value of each beam:

$$K = \frac{\mathrm{MOR}}{C_t C_v C_L C_m F_b} \qquad (7)$$

A supplemental investigation was also conducted to determine if the volume effect factor C_v should be applied for beam depths shallower than 12 in. (30.48 cm). Currently, the AITC 117–Design Standard (AITC 1987) specifies that any beam with a depth shallower than 12 in. (30.48 cm) should not be adjusted by C_v. Therefore, the effects of limiting C_v to 1.0 for shallower depths, as opposed to using the calculated C_v across all depths, were addressed (Appendix B).

Fiber Bending Stress and MOR

The MOR values of round timbers were examined and related to the fiber stresses published in ANSI 05.1 (ANSI 1992). This comparison may provide the basis for determining fiber stresses for glulam to be published in ANSI 05.2 (ANSI 1983). The basis for these values should be similar to that for the fiber stress values published for round timbers in ANSI 05.1.

Results

Data from individual tests are available through the NTIS (Hernandez and others 1995). In this section, we discuss overall volume effects, *K*-factors calculated from all data, and the relationship between fiber bending stress values and MOR values.

K-Factors

Based on results given in Appendix B, we determined that the *K*-factor analysis should be conducted by applying C_v, over all depths, to glulam beams. The *K*-factor analysis of horizontally laminated Douglas Fir and Southern Pine beams manufactured with visually graded lumber are illustrated in Figures B2 and B4, respectively. The *K*-factor analyses of the Douglas Fir beams manufactured with E-rated lumber and tension-proof-loaded laminations are illustrated in Figures 2 and 3, respectively. Similar analyses for the Southern Pine beams are shown in Figures 4 and 5. Figures 6 and 7 show the results obtained for the vertically laminated combinations for Douglas Fir and Southern Pine, respectively. Table 2 summarizes the findings for the *K*-factor analysis for all beam groups.

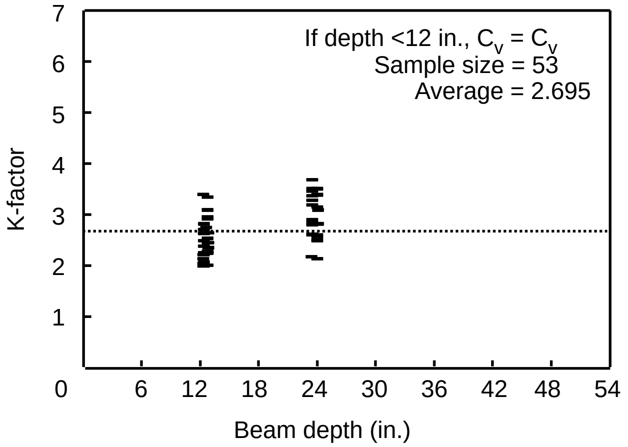

Figure 2—Calculated K-factors for horizontally laminated Douglas Fir beams made from E-rated lumber. (Volume effect factor applied to all depths.)

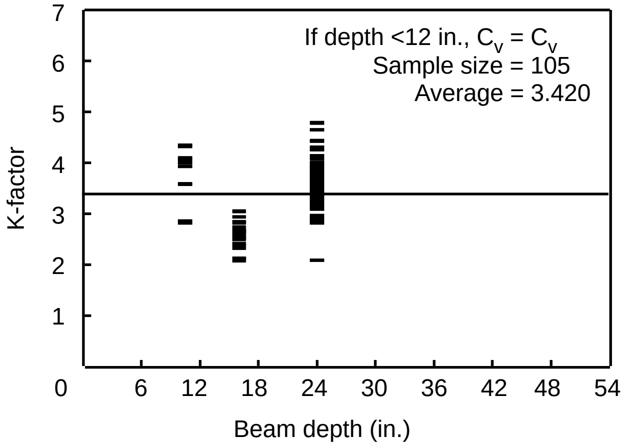

Figure 3—Calculated K-factors for horizontally laminated Douglas Fir beams made from proof-loaded lumber.

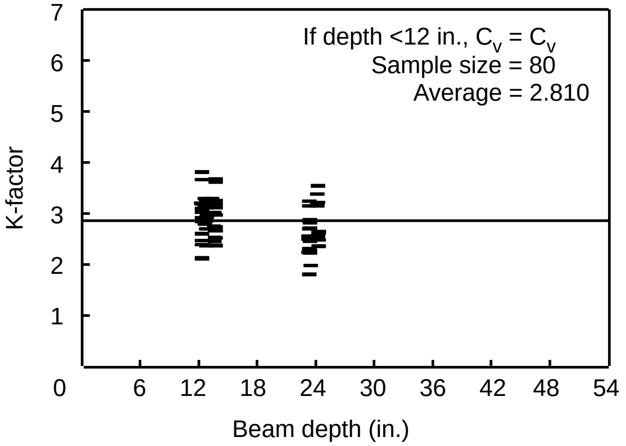

Figure 4—Calculated K-factors for horizontally laminated Southern Pine beams made from E-rated lumber.

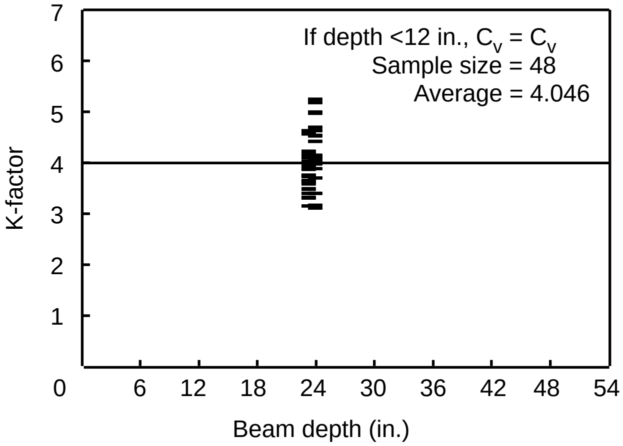

Figure 5—Calculated K-factors for horizontally laminated Southern Pine beams made from proof-loaded lumber.

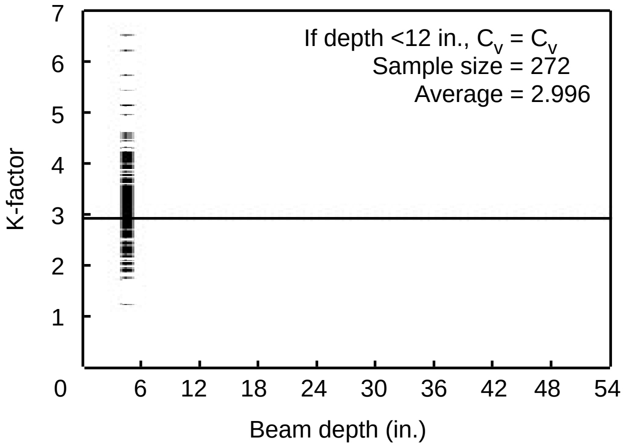

Figure 6—Calculated K-factors for vertically laminated Douglas Fir beams made from visually graded lumber.

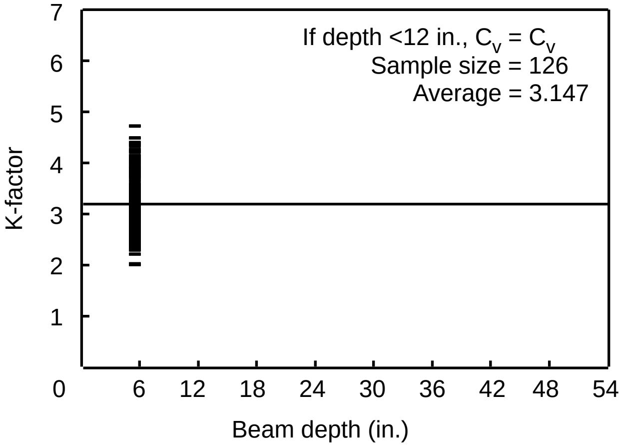

Figure 7—Calculated K-factors for vertically laminated Southern Pine beams made from visually graded lumber.

Table 2—*K*-factor results for all glulam beam groups[a]

Laminating stock	Douglas Fir		Southern Pine		Combined	
	Avg.	COV	Avg.	COV	Avg.	COV
Horizontally laminated						
Visually graded lumber	2.985	22.8	2.902	21.5	2.951	22.3
E-rated lumber	2.695	17.5	2.810	14.6	2.759	15.9
Tension-proof-loaded end joints	3.420	17.3	4.046	12.7	3.616	17.3
Vertically laminated						
Visually graded lumber	2.996	24.6	3.147	19.7	3.044	23.2
Combination[b]	2.967	23.4	2.930	20.1	2.952	22.1

[a] Volume effect equation used throughout all beam depths. COV values are percent.

[b] Combination of horizontally and vertically laminated stock, excluding the tension-proof-loaded end joints.

The results in Table 2 indicate that the calculated *K*-factors are similar to those calculated with Equation (5) using the experimental COV values. Results for glulam beams fabricated with visually graded lumber were similar to those for beams with E-rated lumber, for both Douglas Fir and Southern Pine; this includes beams tested in both the horizontal and vertical orientations. However, tension proof loading the laminations prior to fabricating the beams apparently resulted in a significantly higher *K*-factor.

As the visually graded, E-rated, and vertically laminated groups gave similar results, the *K*-factors calculated from a combination of these groups are shown in Table 2. The calculated *K*-factor of 2.95 for all combinations of Douglas Fir and Southern Pine combined (excluding those with tension-proof-loaded laminations) is based on results of 1,165 beam tests. This result corresponds to a value predicted with Equation (5) using a COV between 17 and 18 percent.

To further examine the proposed relationship for calculating the *K*-factor (Eq. (5)), the beam data were grouped by differing number of laminations. This procedure permitted us to examine the effect of number of laminations on the COV of glulam timber MOR. All beam groups were included: Douglas Fir and Southern Pine, visually graded and E-rated lumber, and vertical and horizontal orientations. Only beams fabricated with proof-loaded tension laminations were excluded.

Results shown in Table 3 and Figure 8 indicate a trend of decreasing COV with increasing number of laminations; however, the differences in COV were small. For the three groups of beams with ≤15 laminations, the *K* values

Table 3—Evaluation of COV of modulus of rupture for various beam sizes

Number of laminations	Sample size	Average *K*-value	COV (%)	Predicted *K*-value
2 to 5	596	3.031	23.4	3.422
6 to 10	300	2.947	22.3	3.313
11 to 15	73	2.672	19.5	3.088
16 to 20	158	2.858	17.0	2.913
≥21	38	2.938	16.1	2.857
All[a]	1,165	2.952	22.1	3.300

[a] Combining data across all depths will underestimate the COV for shallow beams and overestimate the COV for deep beams.

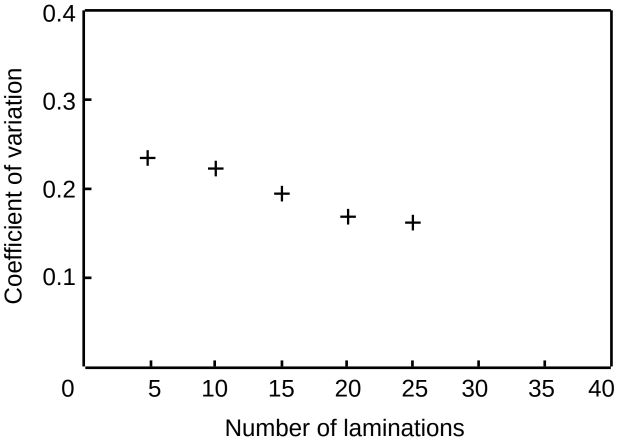

Figure 8—Decrease in coefficient of variation with increase in laminations.

predicted using Equation (5) and a COV ≥ 19.5 percent were significantly higher than the *K* values determined from the data base. Thus, it would be unconservative to predict the MOR of shallow beams using these COV values and Equation (5). Beams with ≥16 laminations had COV values of 16 or 17 percent, and the predicted and actual *K* values were quite close. Overall, the *K* values of all groups were close to that predicted using a COV of 17.5 percent. The COV values reported in Table 3 are for results of glulam tests from several different studies; expected COV values from one source would be slightly lower.

Fiber Bending Stress and MOR

The *K* values calculated previously relate design stress in bending to MOR. Next, the relationship between the published fiber stress values for round timber and the results of round timber tests was examined using data from Appendix C of the ANSI 05.1 Standard (ANSI 1992). Results are compiled in Table 4.

Table 4—Ratio of actual pole strength to published fiber stress[a]

Lumber species	Sample size	Mean MOR (lb/in^2)	Fiber stress (FS) (lb/in^2)	Ratio of MOR/FS
Poles <50 ft long				
Northern white-cedar	28	4,100	4.0	1.025
Western redcedar	387	6,310	6.0	1.052
Pacific silver fir	51	6,380	6.6	0.967
Douglas Fir				
Coastal	118	9,620	8.0	1.202
Coastal[b]	118	8,660	8.0	1.082
Interior	99	8,020	8.0	1.002
Western hemlock	154	7,530	7.4	1.018
Western larch	48	10,000	8.4	1.190
Western larch[b]	48	9,000	8.4	1.071
Jack pine	189	7,300	6.6	1.106
Lodgepole Pine	218	6,700	6.6	1.008
Red pine	231	6,350	6.6	0.962
Southern Pine	143	10,190	8.0	1.274
Southern Pine[c]	143	8,660	8.0	1.082
White spruce	56	5,520	6.6	0.836
Weighted average				1.086
Poles >50 ft long				
Southern Pine	120	8,430	8.0	1.054
Southern Pine[c]	120	7,170	8.0	0.896
Douglas Fir				
Coastal	165	7,860	8.0	0.982
Coastal[b]	165	7,070	8.0	0.884
Western redcedar	100	5,200	6.0	0.867
Weighted average				1.048

[a] Actual results and published values obtained from ANSI 05.1 (ANSI 1992). 1 lb/in^2 = 6.895 ×10^3 Pa. 1 ft = 0.3048 m.
[b] Considers common practice of Boultonizing.
[c] Considers common practice of steam conditioning for Southern Pine.

The results in Table 4 indicate that actual pole strength generally exceeded the fiber stress value; the ratio between actual pole strength and the published fiber stress in ANSI 05.1 (ANSI 1992) was 1.086 for poles <50 ft (<15.24 m) long and 1.048 for poles >50 ft (>15.24 m) long.

Therefore, calculating average MOR with Equation (6) would result in the following equations for relating design bending stress:

Glulam members <50 ft (<15.24 m) long

$$\text{Fiber stress} = \frac{F_b(2.1 C_t C_v C_L C_m)}{1.086(1 - 1.645\,\text{COV})} \tag{8}$$

Glulam members >50 ft (>15.24 m) long

$$\text{Fiber stress} = \frac{F_b(2.1C_t C_v C_L C_m)}{1.048(1-1.645\,\text{COV})} \qquad (9)$$

As an example, consider members less than <50 ft (<15.24 m) long and the COV of 17 percent, which was found to be applicable across a range of sizes of glulam. Using Equation (8), the relationship becomes

$$\text{Glulam fiber stress} = 2.68F_b \qquad \text{(predicted)}$$

Using the previously calculated average *K*-factor of 2.952 based on the data, the relationship would be

$$\text{Glulam fiber stress} = 2.72F_b \qquad \text{(actual)}$$

for members <50 ft (<15.24 m) long.

Using Equation (9), for members >50 ft (>15.24 m) long, the *K*-factor is 2.82.

Conclusions

In this study, we developed a simple relationship for deriving average glulam beam fiber stress based on design bending stresses published in AITC 117. A data base of glulam beam data was also compiled and analyzed to determine this relationship between average fiber stress and design bending stress, referred to as the *K*-factor. In analyzing the glulam data base, we noted the following:

- Volume effect adjustments should be applied to all depths of glulam.
- Calculated *K*-factors were similar for glulam manufactured with visually graded and E-rated lumber.
- Calculated *K*-factors were similar for glulam manufactured with Douglas Fir and Southern Pine lumber.
- Calculated *K*-factors were similar for glulam manufactured as horizontally and vertically laminated members.
- Proof loading the tension lamination or laminations of a glulam beam resulted in a higher calculated *K*-factor.
- Coefficient of variation in glulam modulus of rupture decreased slightly as the number of laminations increased.

In addition, to determine a possible adjustment to the developed equation that would relate the average fiber stress values to published fiber stress values, results of actual pole tests were studied. Based on this analysis of the pole data, the following results were noted:

- Fiber stress values applicable for glulam beams <50 ft (<15.24 m) long would be approximately 2.7 times the design stress in bending.
- Fiber stress values applicable for glulam beams >50 ft (>15.24 m) long would be approximately 2.8 times the design stress in bending.

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Appendix A—Research Publications on Glulam Timber

This appendix contains a description of all beams included in the glulam data base by research study. Six groups of data are presented:

- Douglas Fir beams from visually graded lumber
- Southern Pine beams from visually graded lumber
- Douglas Fir beams from E-rated lumber
- Southern Pine beams from E-rated lumber
- Douglas Fir beams from E-rated and proof-loaded lumber
- Southern Pine beams from E-rated and proof-loaded lumber

The beams were generally tested following ASTM D198 Standard (ASTM 1991) using a 5- to 10-min ramp loading to failure. Ultimate load plus dead load stress was used with actual dimensions to calculate modulus of rupture (MOR). Unless otherwise stated, the beams were manufactured using nominal 2- by 6-in. (standard 38- by 140-mm) lumber (2 by 6 lumber) and evaluated under dry-use conditions with a moisture content near 12 percent. Lumber was graded following rules in effect at the time of manufacture, published by either the West Coast Lumber Inspection Bureau (1991) or Western Wood Products Association (1991) for Douglas Fir, and the Southern Pine Inspection Bureau (SPIB 1970) for Southern Pine.

Glulam made with Douglas Fir and Southern Pine visually graded and E-rated lumber was assigned design stresses based on a comparison of similar combinations in the current AITC 117-Manufacturing Standard (AITC 1988). If necessary, some criteria in the ASTM D3737 Standard (ASTM 1991) was applied. Applicable design stresses for E-rated and proof-loaded lumber could not be related to present standards. Thus, the design stresses were taken from results of the research reports in which lumber for the tension side was proof loaded to between 1.1 and 1.5 times the stress in the laminations at design load. Table A1 summarizes the findings of the research studies in terms of minimum proof-load levels for the various design stresses. Applicable design stresses were determined using these criteria.

Douglas Fir Beams From Visually Graded Lumber

Bohannan (1966)

The beams, shown in Figure A1, were made of 21 laminations using nominal 2- by 10-in. (standard 38- by 235-mm) lumber (2 by 10 lumber). Although six beams were evaluated, only the three structural beams were included.

Table A1—Results of research on required proof-load levels for various design stresses of Douglas Fir and Southern Pine[a]

Design stress (lb/in^2)	Minimum tension proof-load factor (tensile stress (lb/in^2))			
	Douglas Fir		Southern Pine	
2,200	1.1	(2,420)	1.2	(2.64)
2,400	1.1	(2,640)	1.3	(3.12)
2,600	1.3	(3,380)	1.5	(3.90)
2,800	1.4	(3,920)	1.5	(4.20)
3,000	—	—	1.5	(4.50)

[a] 1 lb/in^2 = 6.89 kPa.

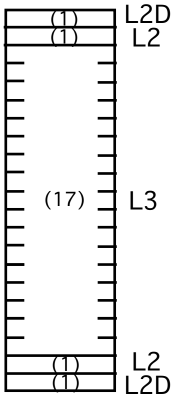

Figure A1—Specifications for Douglas Fir beams made from visually graded lumber in study by Bohannan (1966). For this and other figures, 1 lb/in^2 = 6.89 kPa; 1 in. = 25.4 mm; and 1 ft = 0.3048 m. F_b is design stress in bending.

This layup closely resembles the 20F-V3 layup of AITC 117, which has a design stress of 2,000 lb/in^2 (13.8 MPa). Calculations using ASTM D3737 procedures confirm this design stress. This design bending stress is further reduced by a factor of 0.75 because of the absence of a special tension lamination. Thus, a design stress of 1,500 lb/in^2 (10.3 MPa) was selected for the layup.

Johnson (Marx and Moody 1981a)

Results of research by Johnson were published in the appendix of FPL Research Paper 380 (Marx and Moody 1981a) and included beams manufactured with five types of lumber having knot sizes of 10, 20, 30, 40, or 50 percent of the cross section. Four sizes of beams having 2, 4, 6, or 8 laminations were evaluated (Fig. A2). Each lamination of each beam used the same grade of lumber with a limiting characteristic near mid-length, and each type-size category had five replications. Thus, the experiment was a 5 × 4 × 5 design with a total of 100 beams.

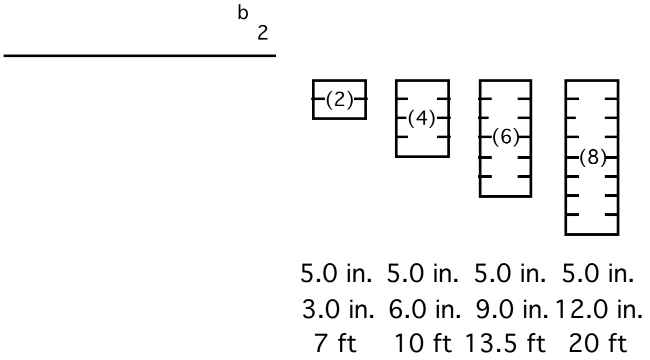

Figure A2—Specifications for Douglas Fir beams made from visually graded lumber in study by Johnson (1969).

Beams with knot sizes of 10 and 20 percent of the cross section were assumed to be of L1 grade, those with 30 percent of L2 grade, and those with 40 and 50 percent of L3 grade. The design bending stresses were obtained from table 2 of AITC 117-Design (AITC 1987) for configurations without special tension laminations.

Bohannan and Moody (1969)

Bohannan and Moody (1969) studied two beam configurations: one with 15 laminations and the other with 21 laminations (Fig. A3). For the 15-lamination beams, beams 1 to 5 were manufactured with a 301-67 special tension lamination and beams 6 to 10 were manufactured with a 301+ special tension lamination. Three 21-lamination beams (21 to 23) were manufactured with 2 by 10 lumber and with a 301-67 special tension lamination. The criteria for the 301-67 special tension lamination are different than those currently used and allow a 1:16 slope-of-grain and a maximum knot size of 25 percent of the cross section. The criteria for the 301+ special tension lamination allow a 1:16 slope-of-grain and a maximum knot size of 20 percent of the cross section.

According to the design standard in effect at the time of manufacture, the design bending stress value for all these configurations was 2,600 lb/in^2 (17.9 MPa).When the layups are compared with those in current standards (AITC 1988), most were found to have a design bending stress of 2,400 lb/in^2 (16.6 MPa). An exception was one of the 15-lamination beams (No. 5) that had a tension lamination with a 1:10 slope-of-grain, which did not meet the tension lamination requirements for this design stress. Using current standards, the design stress on this beam would be reduced to 1,800 lb/in^2 (12.4 MPa) using a 0.75 factor.

Moody and Bohannan (1970a)

Ten 16-lamination beams were evaluated in this study, five of each layup are shown in Figure A4. According to the 1970 standards, these beams had a design stress of 2,600 lb/in^2 (17.9 MPa). Using current standards, the design stress would be 2,400 lb/in^2 (16.6 MPa).

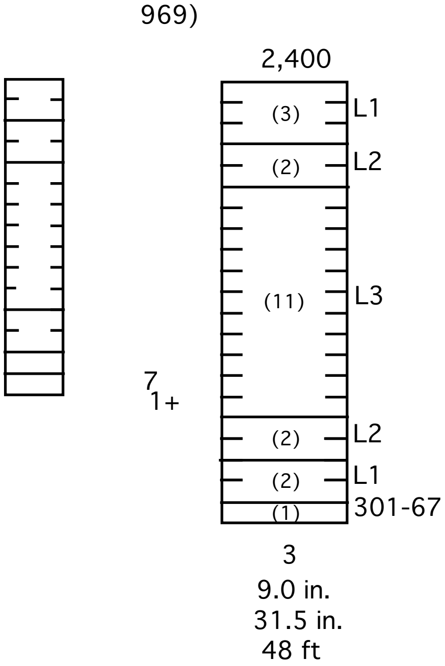

Figure A3—Specifications for Douglas Fir beams made from visually graded lumber in study by Bohannan and Moody (1969). The 301-67 grade is a special tension lamination grade.

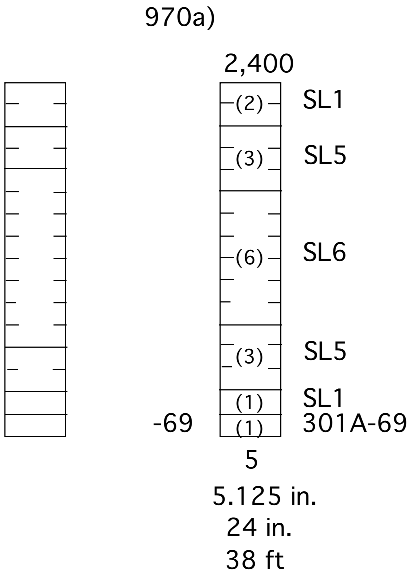

Figure A4—Specifications for Douglas Fir beams made from visually graded lumber in study by Moody and Bohannan (1970a).

Moody (1974a)

The three beam configurations evaluated in this study each had 16 laminations; lodgepole pine lumber was used for the inner laminations (Fig. A5). Five beams each of the 16F (1,600 lb/in^2) and 20F (2,000 lb/in^2) layups and 10 beams of the 24F (2,400 lb/in^2) layup were evaluated. A comparison with current standards confirmed that the design stresses would be 1,600, 2,000, and 2,400 lb/in^2 (11, 13.8, and 16.6 MPa), respectively.

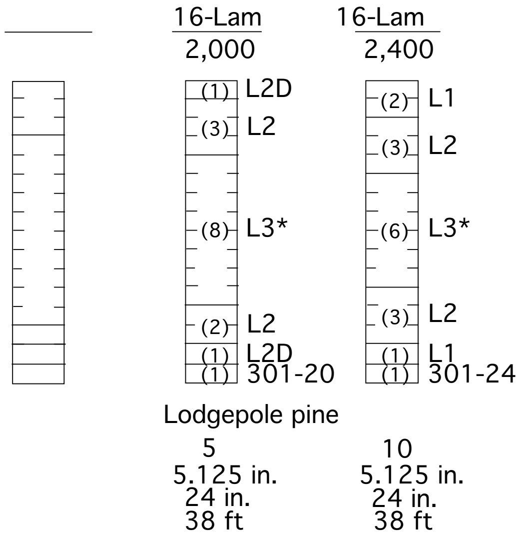

Figure A5—Specifications for Douglas Fir beams made from visually graded lumber in study by Moody (1974a).

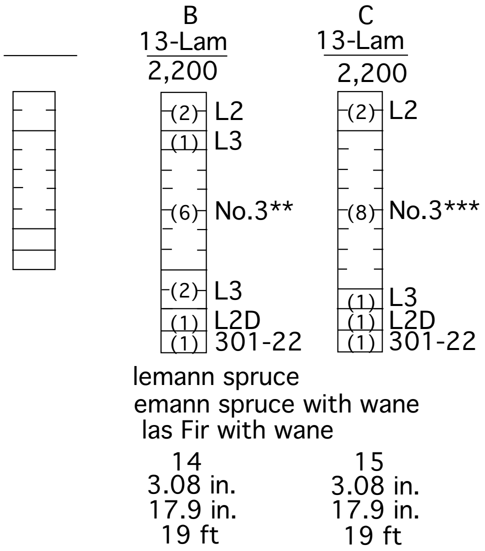

Figure A6—Specifications for Douglas Fir beams made from visually graded lumber in study by Moody (1977).

Moody (1977)

Three beam configurations were made with nominal 2- by 4-in. (standard 38- by 89-mm) lumber (2 by 4 lumber) (Fig. A6). Engelmann spruce was used for the inner laminations of layups A and B; inner laminations of layups B and C had significant amounts of wane.

Using current standards, layup A was determined to have a design bending stress of 2,000 lb/in^2 (13.8 MPa); both layups B and C had a design bending stress of 2,200 lb/in^2 (15.2 MPa).

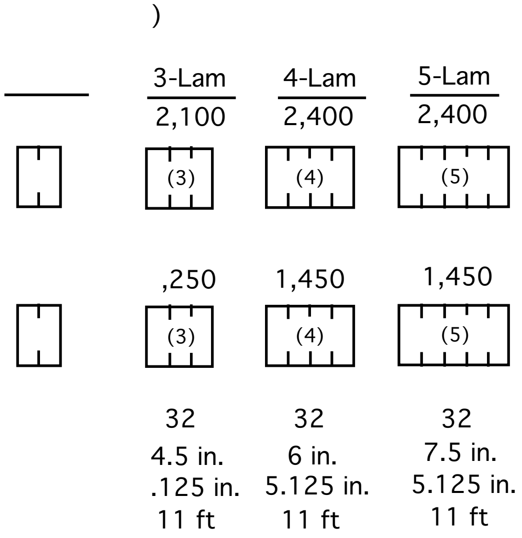

Figure A7—Specifications for Douglas Fir beams made from visually graded lumber in study by Wolfe and Moody (1979).

Wolfe and Moody (1979)

Vertically laminated beam groups were made of either L1 or L3 lumber and were fabricated with 2 to 5 plies (Fig. A7). Forty replicates were included for the 2-Lam samples and 32 replicates for each of the 3-, 4-, and 5-Lam groups. The applicable design stresses from table 2 of AITC 117 are as follows:

	Design stress (lb/in^2 (MPa))		
Grade	2 Lam	3 Lam	4 and 5 Lam
L1	1,800 (12.4)	2,100 (14.5)	2,400 (16.6)
L3	1,000 (6.9)	1,250 (8.6)	1,450 (10.0)

Marx and Moody (1981a)

Three sizes of shallow beams using either L1 or L3 lumber were evaluated. Beam sizes were 2, 4, or 6 laminations deep, and the beams were made of uniform-grade material (Fig. A8). The design stresses for each beam size from table 2 of AITC 117 are as follows:

L1 2,200 lb/in^2 (15.2 MPa)

L3 1,250 lb/in^2 (8.6 MPa)

Marx and Moody (1981b)

Six beam configurations using the 24F-V4 layup of AITC 117 were evaluated, including three sizes of beams made using the layups shown in Figure A9. Ten beams were included for each size-layup combination. For each beam size, the design stress for those beams with special tension laminations was 2,400 lb/in^2 (16.6 MPa). The design stress of beams with the L1 grade tension lamination was reduced by 15 percent (2,040 lb/in^2 (14.1 MPa)) (ASTM D3737).

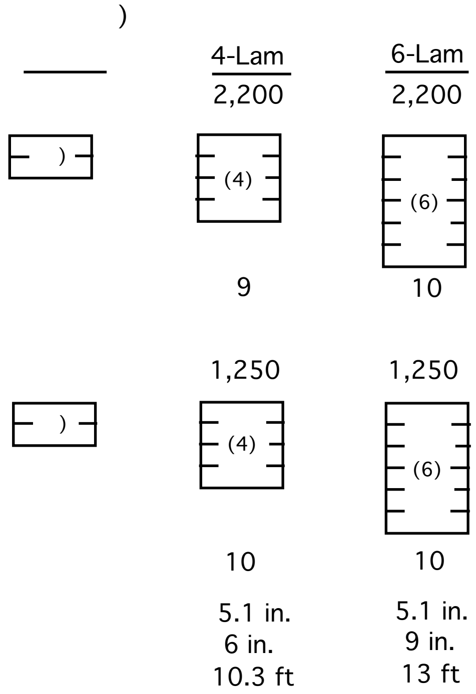

Figure A8—Specifications for Douglas Fir beams made from visually graded lumber in study by Marx and Moody (1981a).

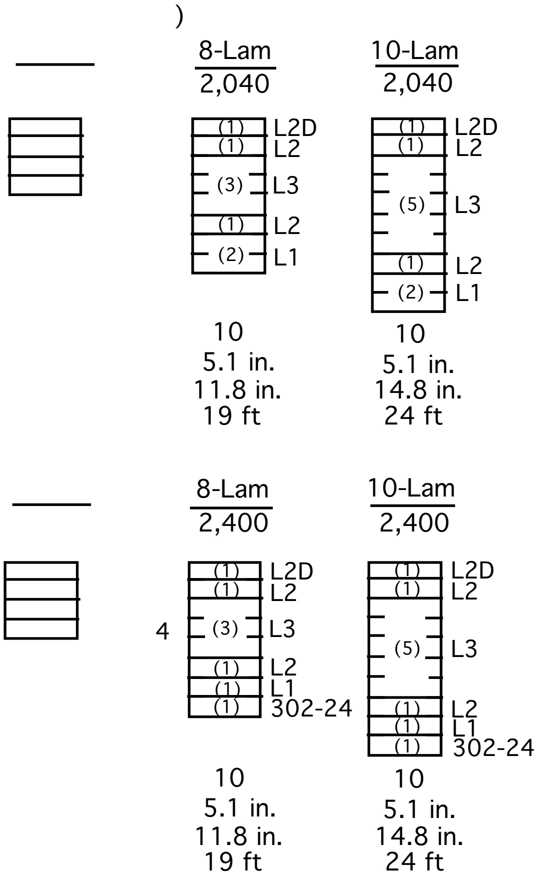

Figure A9—Specifications for Douglas Fir beams made from visually graded lumber in study by Marx and Moody (1981b).

Schaffer and Others (1986)

Three versions of the 24F-V4 layup were evaluated with seven beams of each version (Fig. A10). Different thicknesses of tension laminations were used to simulate the effect of charring of lumber during a fire. The three beam layups were intended to represent the same beam at different times during a fire; thus, layups B and C were narrower than layup A (Fig. A10). Layups A and B would qualify for a design stress of 2,400 lb/in^2 (16.6 MPa), but layup C would require a 15-percent reduction in design stress.

Moody and Others (1990)

Two sizes of the 24F-V4 layup, one with 16 laminations and the other with 32 laminations, were evaluated using the layups shown in Figure A11. The study included thirty 16-lamination beams made of 2 by 6 lumber, and fifteen 32-lamination beams made of 2 by 10 lumber. Results of tests on 16-lamination beams were published by Moody and others (1990). Results of tests on the 32-lamination beams are available from the American Institute of Timber Construction (AITC) but have not been published.

Southern Pine Beams From Visually Graded Lumber

Bohannan and Moody (1969)

Two beam configurations were studied: one with 15 laminations and the other with 21 laminations (Fig. A12). For the 15-lamination beams, five beams were manufactured with a 301-67 special tension lamination and another five beams were manufactured with a 301+ special tension lamination. Three 21-lamination beams were manufactured with 2 by 10 lumber and with the 301-67 special tension lamination. The criteria for the 301-67 special tension lamination are different than those currently used and allow a 1:16 slope-of-grain and a maximum knot size of 25 percent of the cross-section. The criteria for the 301+ special tension lamination allow a 1:16 slope-of-grain and a maximum knot size of 20 percent of the cross-section.

According to the design standard in effect at the time of manufacture, the design bending stress for all of these configurations was 2,600 lb/in^2 (17.9 MPa). However, when the layups were compared with those in current standards (AITC 117), most were found to have a design bending stress of 2,200 lb/in^2 (15.2 MPa). Five beams from the 15-lamination groups were exceptions because they contained tension laminations that did not meet current standards because of their pith-associated wood. Thus, their design stress was reduced 25 percent to 1,650 lb/in^2 (18.8 MPa), according to ASTM D3737 and AITC 117.

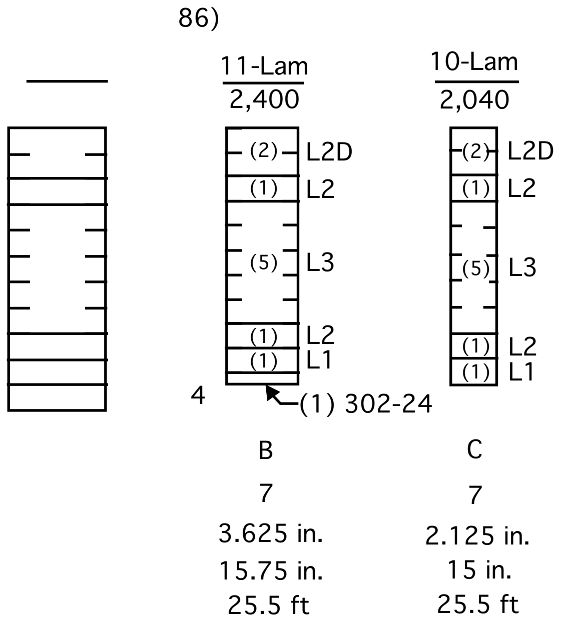

Figure A10—Specifications for Douglas Fir beams made from visually graded lumber in study by Schaffer and others (1986).

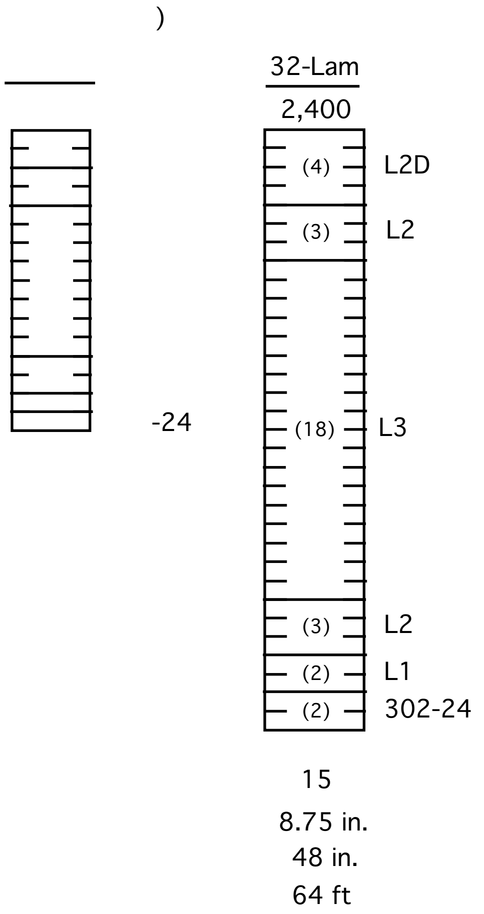

Figure A11—Specifications for Douglas Fir beams made from visually graded lumber in study by Moody and others (1990).

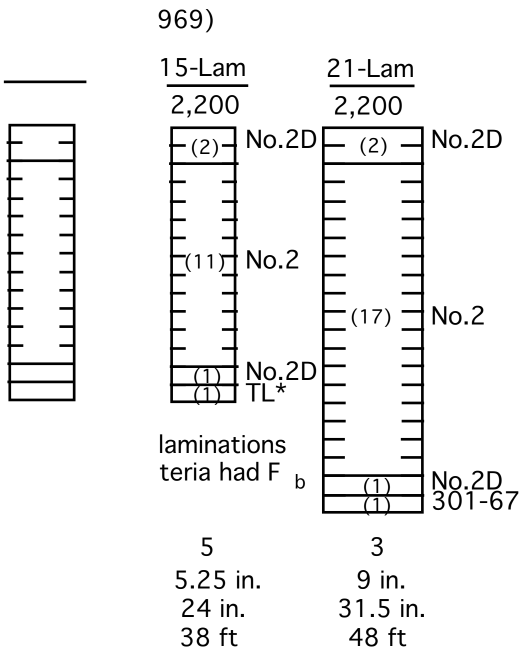

Figure A12—Specifications for Southern Pine beams made from visually graded lumber in study by Bohannan and Moody (1969).

Moody and Bohannan (1970b)

Five 16-lamination beams were evaluated with the layup shown in Figure A13. According to the 1970 standards, these beams had a design stress of 2,600 lb/in^2 (17.9 MPa). Using current standards, the design stress would be 2,400 lb/in^2 (16.6 MPa).

Moody and Bohannan (1971)

Ten beams were manufactured using the same layup as that used in a previous study by these authors (Moody and Bohannan 1970b) (Fig. A14). Five beams were manufactured with no finger joints near the midlength of the tension lamination. For another five beams, specific gravity criteria, in addition to the visual criteria, were used to position laminations. All 10 beams had an applicable design bending stress of 2,400 lb/in^2 (16.6 MPa) by current standards.

Moody (1974b)

Two different 15-lamination beams were evaluated, with 10 beams in each group, using the layups shown in Figure A15. Combination I was determined to be comparable to a layup with a 1,600 lb/in^2 (19 MPa) stress in the current standard. Combination II compared to a layup with a design stress of 2,200 lb/in^2 (15.2 MPa).

Wolfe and Moody (1979)

Vertically laminated beams made of No. 2D lumber and 1 to 5 laminations were evaluated (Fig. A16). The data for beams with 2 to 5 laminations were included in the data set. Thirty-six replicates were included for the 2-Lam samples and

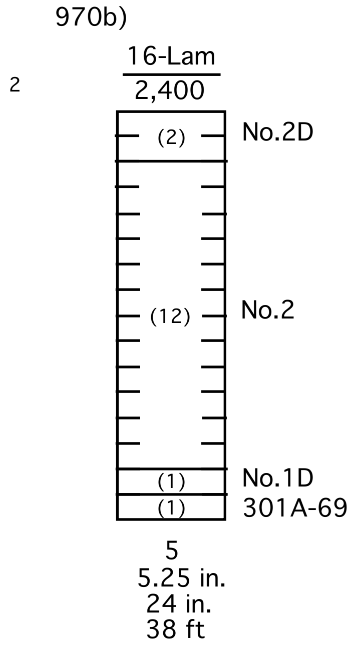

Figure A13—Specifications for Southern Pine beams made from visually graded lumber in study by Moody and Bohannan (1970b).

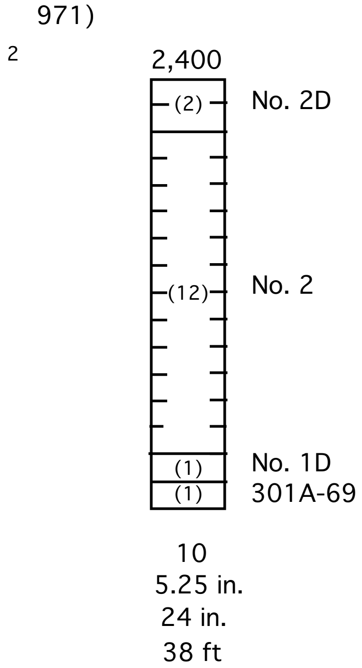

Figure A14—Specifications for Southern Pine beams made from visually graded lumber in study by Moody and Bohannan (1971).

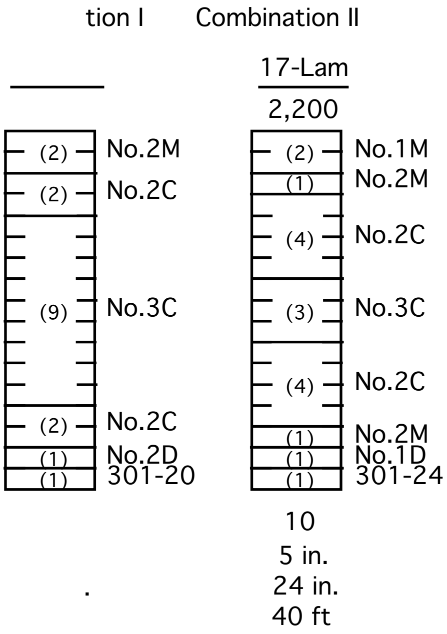

Figure A15—Specifications for Southern Pine beams made from visually graded lumber in study by Moody (1974b).

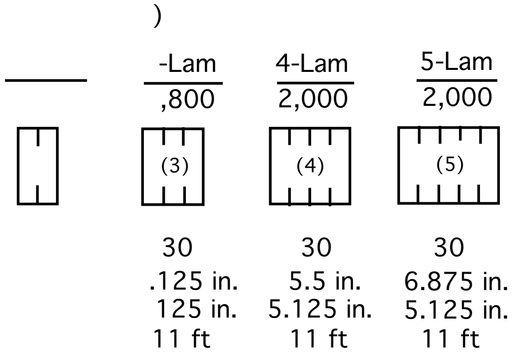

Figure A16—Specifications for Southern Pine beams made from visually graded lumber in study by Wolfe and Moody (1979).

30 replicates for each of the 3-, 4-, and 5-Lam groups. The applicable design stresses from table 2 of AITC 117 are as follows: for 2-Lam beams, 1,500 lb/in^2 (10.3 MPa); 3-Lam, 1,800 lb/in^2 (12.4 MPa); and 4- and 5-Lam, 2,000 lb/in^2 (13.8 MPa).

Marx and Moody (1981a)

Three sizes of shallow beams using No. 2D lumber were evaluated (Fig. A17). The beams were made of uniform-grade material. The design stress for each beam size was from table 2 of AITC 117 (1,600 lb/in^2 (18.8 MPa)).

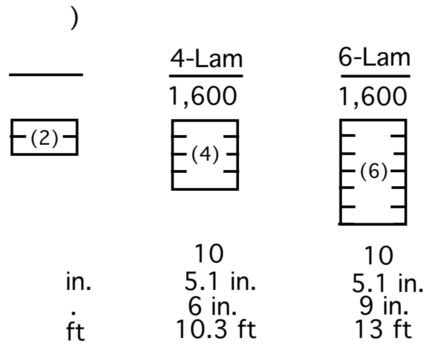

Figure A17—Specifications for Southern Pine beams made from visually graded lumber in study by Marx and Moody (1981a).

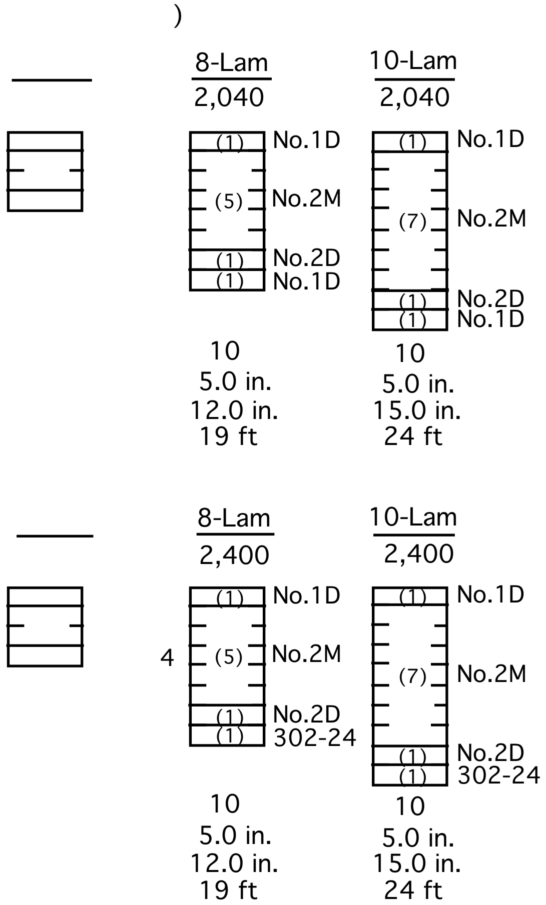

Figure A18—Specifications for Southern Pine beams made from visually graded lumber in study by Marx and Moody (1981b).

Marx and Moody (1981b)

Six beam configurations were evaluated: three beam sizes of the 24F-V2 combination from AITC 117–Manufacturing Standard (1988) and three beam sizes of the same combination without a special tension lamination (Fig. A18). The initial study plan included 10 beams of each size-layup combination. When the beams were evaluated, the authors found that the finger joints did not meet the ANSI A190.1 standard for a 2,400 lb/in^2 (16.6 MPa) design stress, but would meet the standard for a lower design stress (2,040 lb/in^2 (14.1 MPa)). Thus, another complete set of 10 beams for each size-layup combination was manufactured and evaluated. For the analyses in this study, the beams that contained special tension laminations from the initial set were removed from the data base because of the inadequacy of the finger joints. Therefore, the beams from the initial set that did not have special tension laminations as well as the entire second set were included.

For each beam size, the design stress for those beams with special tension laminations would be 2,400 lb/in^2 (16.6 MPa). Beams with the No. 1D grade tension laminations would have a design stress reduced by 15 percent or 2,040 lb/in^2 (14.1 MPa) (ASTM D3737).

Marx and Moody (1982)

All the beams in this study were made with four laminations and complemented the beams in a previous study (Marx and Moody 1981b). One set of beams was made with an intermediate grade of 2 by 6 tension lamination lumber, and three sets were made with 2 by 10 lumber. The sets made with 2 by 10 lumber had three grades of tension laminations: No. 1D, 302-20, and 302-24 (Fig. A19).

The design bending stress for the beams with either the 302-20 or 302-24 tension laminations was 2,400 lb/in^2 (16.6 MPa); the design stress for the beams with No. 1D tension laminations was 2,040 lb/in^2 (14.1 MPa).

Gopu (1991)

The study evaluated fifteen 35-lamination beams of the 24F-V3 layup (Fig. A20). The beams were made with 2 by 10 lumber and the design stress was 2,400 lb/in^2 (16.6 MPa).

Soltis and Rammer (1994)

Two sizes of beams made with the 24F-V5 layup were evaluated, using 20 beams of each size (Fig. A21). The 8-Lam beams were made from 2 by 4 lumber and the 16-Lam beams were made from 2 by 6 lumber. The design stress was 2,400 lb/in^2 (16.6 MPa).

Douglas Fir Beams From E-Rated Lumber

Johnson (1969a)

A total of 11 beams were manufactured from E-rated lumber similar to the visually graded lumber used to manufacture the beams studied by Bohannan and Moody (1969). For the layup shown in Figure A22, the 15-lamination beams were targeted to have a design stress in bending of 2,600 lb/in^2 (17.9 MPa). The standard (AITC 117) does not provide layups for this design stress for E-rated Douglas Fir. However, the layup (Fig. A22) would qualify for a design stress of 2,600 lb/in^2 (17.9MPa) using the criteria of ASTM D3737. Thus, this design stress was used.

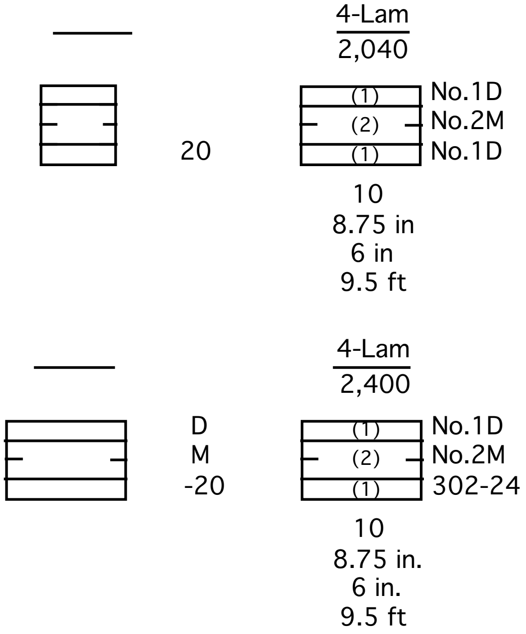

Figure A19—Specifications for Southern Pine beams made from visually graded lumber in study by Marx and Moody (1982).

Two layups were evaluated, with six beams in each group (Fig. A23). The 16-lamination beams closely paralleled the layups in the current standard for a 2,200 lb/in^2 (15.2 MPa) or 2,400 lb/in^2 (16.6 MPa) design stress in bending. Layups for 2,600 lb/in^2 (17.9 MPa) are not given for E-rated Douglas Fir in AITC 117. However, the 26F layup would qualify for this design stress value using the criteria of ASTM D3737. Thus, this design stress was used for the 26F layup.

Moody (1977)

A total of 15 beams were manufactured from E-rated 2 by 4 lumber using the layup shown in Figure A24. The lumber met the requirements of layup 24F-E5, so the applicable design stress was 2,400 lb/in^2 (16.6 MPa).

Wolfe and Moody (1978)

The Douglas Fir beam combination used for this study was the same as the combination in the study by Moody (1977) (Fig. A24). The beams were immersed in water for several weeks and then tested to failure in bending to determine the effect of high moisture content. This beam combination was assigned a 2,400 lb/in^2 design stress in bending, as was the group E combination from Moody (1977). Reduction in design bending stress resulting from high moisture content was accounted for by the 0.8 end-use factor for moisture content (C_m), which reduced the design bending stress to 1,920 lb/in^2.

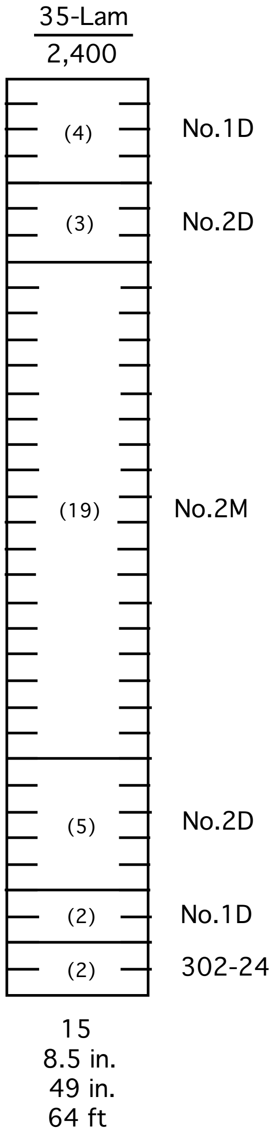

Figure A20—Specifications for Southern Pine beams made from visually graded lumber in study by Gopu (1991).

Southern Pine Beams From E-Rated Lumber

Johnson (1969b)

Two layups were evaluated, with six beams in each group (Fig. A25). The 16-lamination beams closely paralleled the current layups in AITC 117 for a 2,200 lb/in^2 (15.2 MPa) or 2,400 lb/in^2 (16.6 MPa) design stress in bending. Layups for 2,600 lb/in^2 (17.9 MPa) are not given for E-rated Southern Pine in AITC 117. However, the 26F layup would qualify for a design stress of 2,600 lb/in^2 (17.9 MPa) using the criteria of ASTM D3737. Thus, this design stress was used.

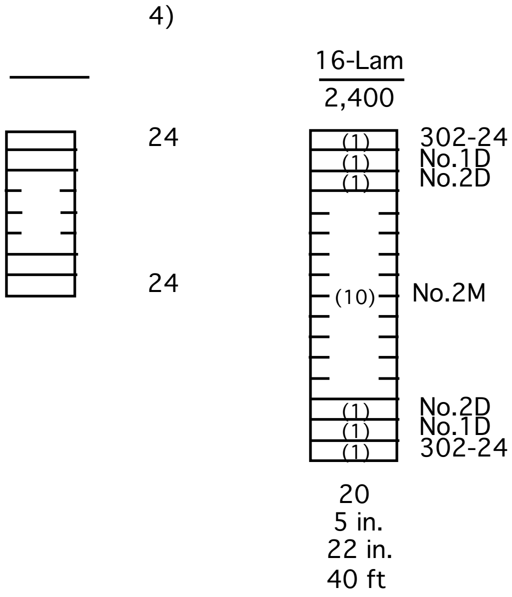

Figure A21—Specifications for Southern Pine beams made from visually graded lumber in study by Soltis and Rammer (1994).

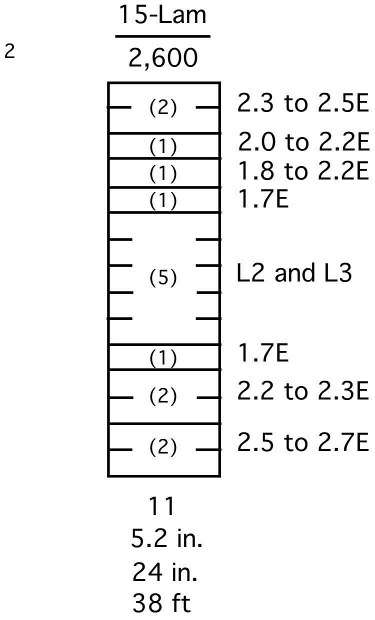

Figure A22—Specifications for Douglas Fir beams made from E-rated lumber in study by Johnson (1969a).

Moody (1977)

A total of 15 beams were manufactured from E-rated 2 by 4 lumber using the layup shown in Figure A26. The lumber used in the beams closely approximated the requirements of layup 22F-E2 of AITC 117, so the applicable design stress was 2,200 lb/in^2 (15.2 MPa).

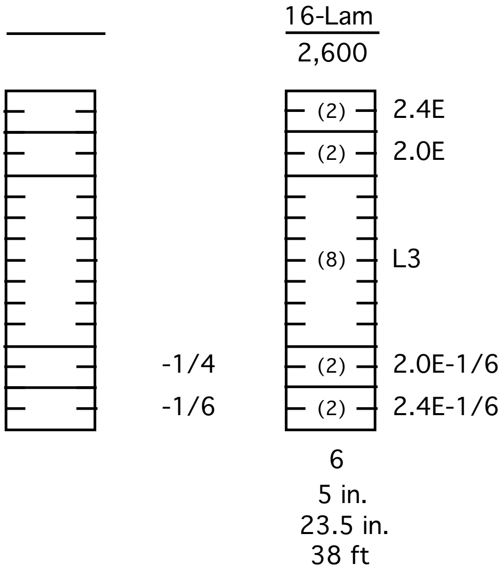

Figure A23—Specifications for Douglas Fir beams made from E-rated lumber in study by Johnson (1969b).

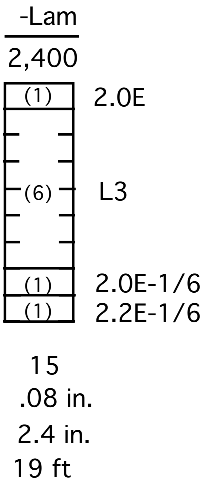

Figure A24—Specifications for Douglas Fir beams made from E-rated lumber in study by Moody (1977).

Hernandez and Moody (1992)

The beam configurations were new layups with a target design bending stress of 3,000 lb/in^2 (20.7 MPa) and design modulus of elasticity (MOE) of 2,000,000 lb/in^2 (13.8 GPa) (Fig. A27). The 2.3E material was sorted for stiffness from a population of visually graded No. 1D material. The No. 1D material used in manufacture of the beams was sorted to assure that it had an average MOE of 2,000,000 lb/in^2 (13.8 GPa) to correspond with the industry design value for this grade. Twenty beams of each configuration were evaluated.

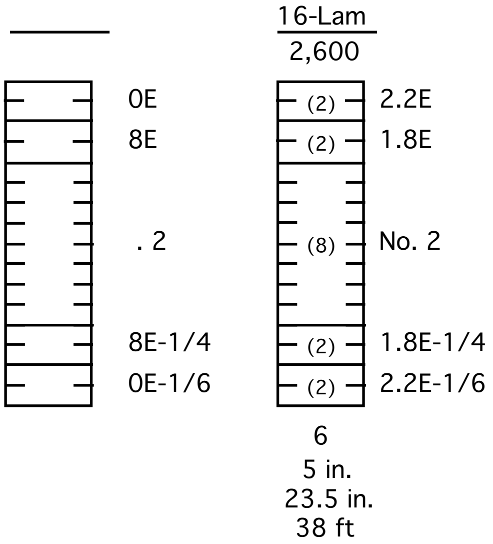

Figure A25—Specifications for Southern Pine beams made from E-rated lumber in study by Johnson (1969b).

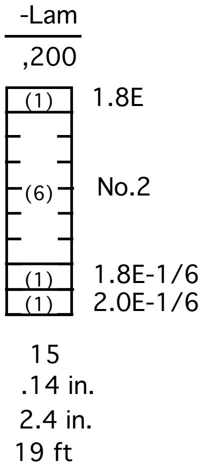

Figure A26—Specifications for Southern Pine beams made from E-rated lumber in study by Moody (1977).

Wolfe and Moody (1978)

The Southern Pine beam combination used for this study was the same as the combination in the study by Moody (1977) (Fig. A26). The beams were immersed in water for several weeks and then tested to failure in bending to determine the effect of high moisture content. This beam combination was assigned a 2,000 lb/in^2 (13.8 MPa) design stress in bending, as was the group F combination from Moody (1977). Reduction in design bending stress resulting from high moisture content was accounted for by the 0.8 end-use factor for moisture content (C_m), which reduced the design bending stress to 1,760 lb/in^2 (12.1 MPa).

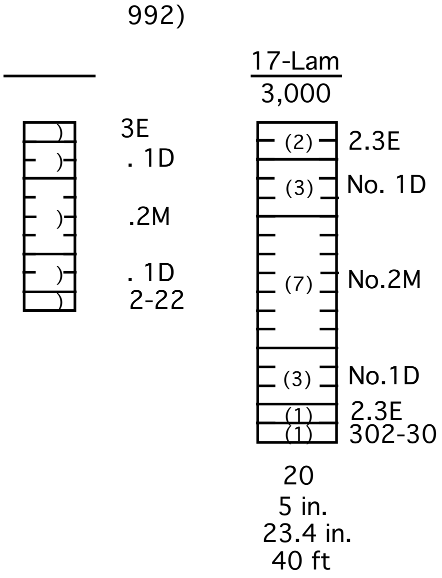

Figure A27—Specifications for Southern Pine beams made from E-rated lumber in study by Hernandez and Moody (1992).

Douglas Fir Beams From Proof-Loaded, E-Rated Lumber

Pellerin and Strickler (1971)

Three beams each of three 7-lamination layups were evaluated (Fig. A28). The layups differed in the stiffness of lumber selected for the L1 and L2 zones and were designated as 2200f, 2400f, and 2600f. Before beam manufacture, the two outer laminations on the tension side were proof-loaded in tension to 1.4 times their nominal stress at the design load. Findings of this and later studies, summarized in Table A1, suggest that the applicable design stresses for the 2200f, 2400f, and 2600f layups should be 2.4, 2.6, and 2.6×10^3 lb/in^2 (16.6, 17.9, and 17.9 MPa), respectively.

Strickler and Pellerin (1971)

Six beams each of three layups were evaluated (Fig. A29). The layups differed in the stiffness of lumber selected for the L1 and L2 zones and were designated as L, M, and H. Before beam manufacture, the four outer laminations on the tension size were proof-loaded in tension. Findings of this and later studies, summarized in Table B1, suggest that the applicable design stresses for the L, M, and H layups should be 2.4, 2.6, and 2.6×10^3 lb/in^2 (16.6, 17.9, and 17.9 MPa), respectively.

Pellerin and Strickler (1972)

Six beams each of four layups were evaluated (Fig. A30). The lumber was arranged with stiffer lumber in the outer zones. The layups differed in the stiffness of lumber selected for the various zones and in the proof-load level used.

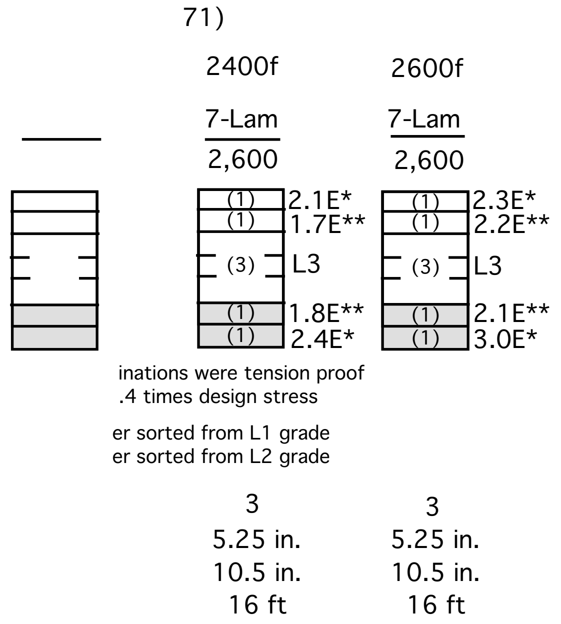

Figure A28—Specifications for Douglas Fir beams made from proof-loaded, E-rated lumber in study by Pellerin and Strickler (1971).

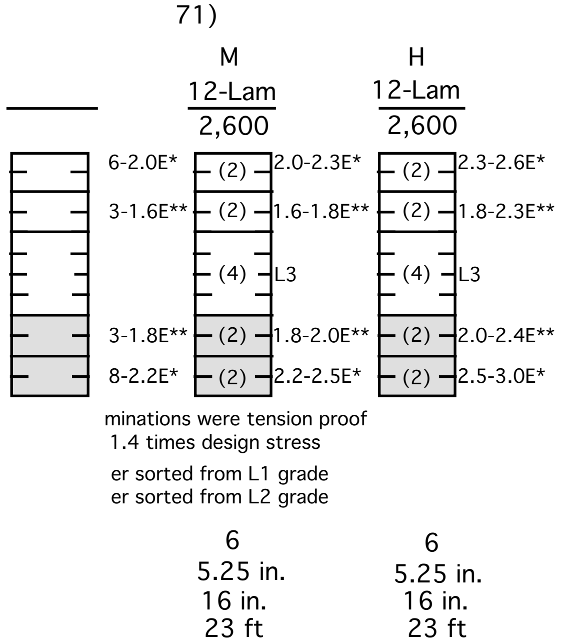

Figure A29—Specifications for Douglas Fir beams made from proof-loaded, E-rated lumber in study by Strickler and Pellerin (1971).

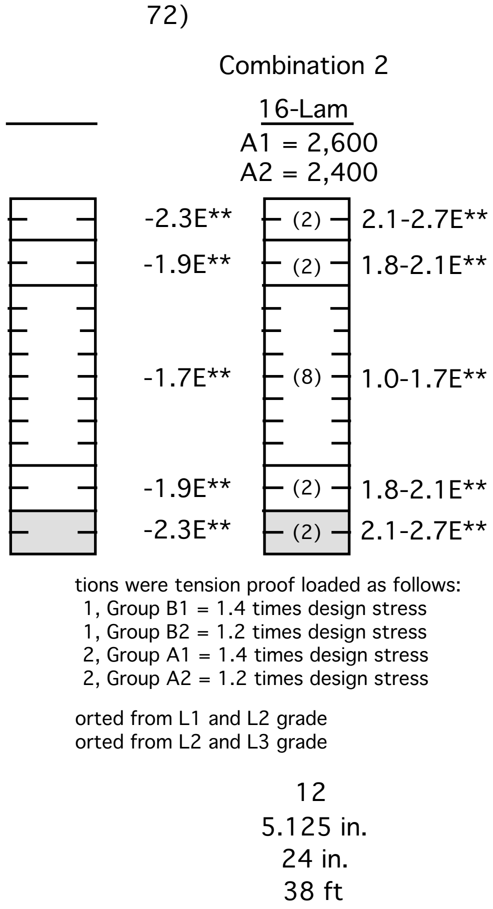

Figure A30—Specifications for Douglas Fir beams made from proof-loaded,E-rated lumber in study by Pellerin and Strickler (1972).

Layups B1 and B2 were designed for 2.2×10^3 lb/in^2 (15.2 MPa); layups A1 and A2 were designed for 2.6×10^3 lb/in^2 (17.9 MPa). The outer two laminations on the tension side were proof-loaded in tension prior to beam manufacture. A proof-load level of 1.4 times the nominal stress at design load was used for layups A1 and B1. For layups A2 and B2, the level was 1.2 times the nominal stress at design load. Findings of this and later studies, summarized in Table B1, suggest that the applicable design stresses for the layups are 2.6×10^3 lb/in^2 (17.9 MPa) for layup A1 and 2.4×10^3 lb/in^2 (16.6 MPa) for the other three layups.

Strickler and Pellerin (1974)

Six beams each of nine layups were evaluated (Fig. A31). The visual grades of the layups followed one of two 16-lamination layups, and the lumber was arranged with stiffer lumber in the outer zones. The layups differed in the stiffness of lumber selected for the various laminations, in the proof-load level used, and in the number of proof-loaded laminations. Four layups (A3, A6, B3, and B4) were similar to those from the research reported by these authors in 1972 except that the outer three laminations on the tension side, rather than two laminations, were proof loaded. One layup (A7) had four proof-loaded laminations. Proof-loads different from those used in earlier studies were used for two layups (A4 and A5), and higher stiffness lumber was used for another two layups (C1 and C2). Findings of this and later studies suggest that the applicable design stresses for the layups are as follows: A3, A7, B3, and B4, 2,400 lb/in^2 (16.6 MPa); A4, A5, A6, and C1, 2,600 lb/in^2 (17.9 MPa); and C2, 2,800 lb/in^2 (19.3 MPa).

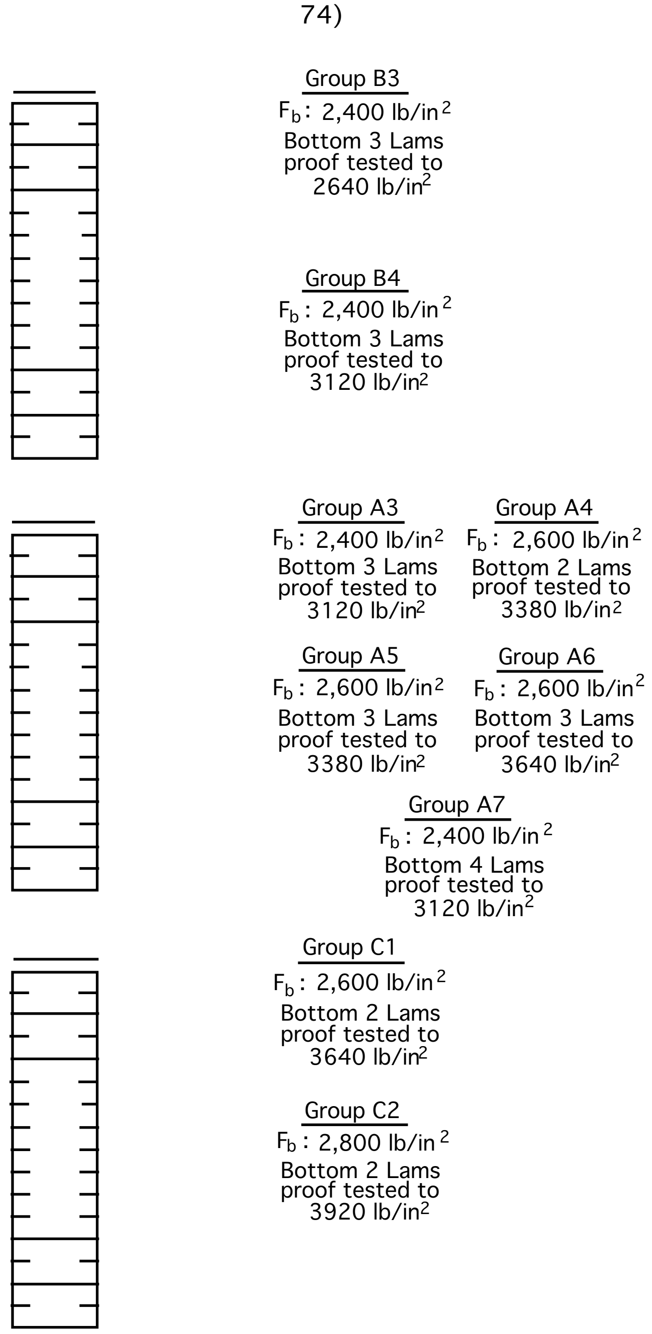

Figure A31—Specifications for Douglas Fir beams made from proof-loaded, E-rated lumber in study by Strickler and Pellerin (1974).

Southern Pine Beams From Proof-Loaded, E-Rated Lumber

Strickler and Pellerin (1976)

Six beams each of four layups, designated X1, Y1, Y2, and Z1, were evaluated (Fig. A32). The lumber was arranged with stiffer lumber in the outer zones. The layups differed in the stiffness of lumber selected for the various zones and in the proof-load level used. The outer three laminations on the tension side were each proof-loaded in tension to different levels for each layup. Using the results of this and the following study, which are summarized in Table B1, the design stresses for X1, Y1, Y2, and Z1 were 2,200, 2,400, 2,400, and 2,600 lb/in^2 (15.2, 16.6, 16.6, and 17.9 MPa), respectively.

Pellerin and Strickler (1977)

Six beams each of four layups, designated X2, Y3, Y4, and Z2, were evaluated (Fig. A33). The lumber was arranged with stiffer lumber in the outer zones. The layups differed in the stiffness of lumber selected for the various zones and in the proof-load level used. The outer three laminations on the tension side were each proof-loaded in tension prior to beam manufacture. Using the results of this and the previous study given in Table A1, the design stresses for X2, Y3, Y4, and Z2 were 2,400, 2,600, 2,800, and 3,000 lb/in^2 (16.6, 17.9, 19.3, and 20.7 MPa), respectively.

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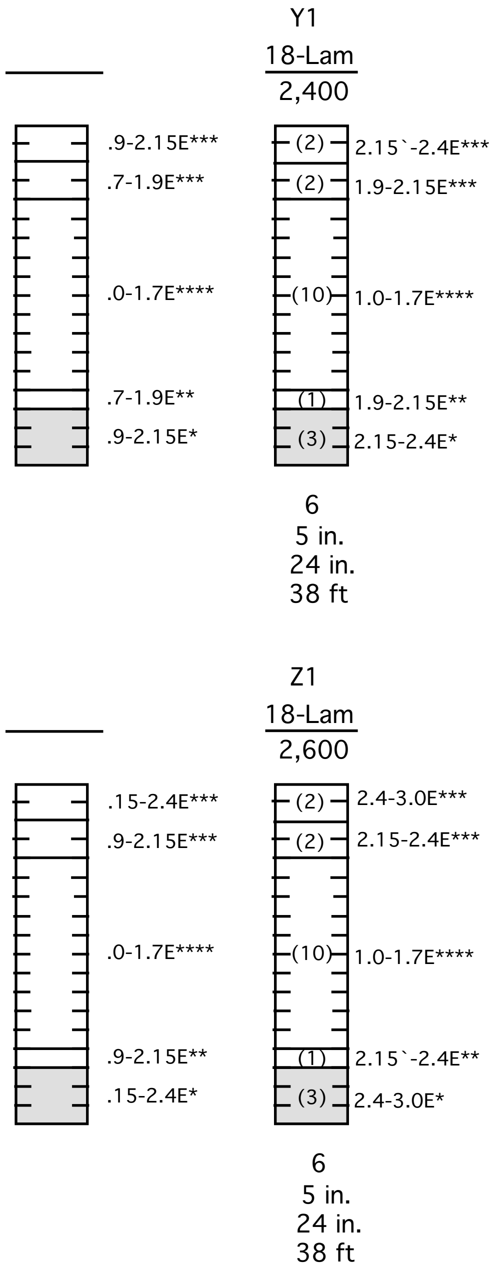

s were tension proof loaded as follows:
times design stress
times design stress
times design stress
times design stress

ed from No. 1 grade
ed from No. 2 grade
ed from No. 3 and Better grade
ed from No. 3 grade

Figure A32—Specifications for Southern Pine beams made from proof-loaded, E-rated lumber in study by Strickler and Pellerin (1976).

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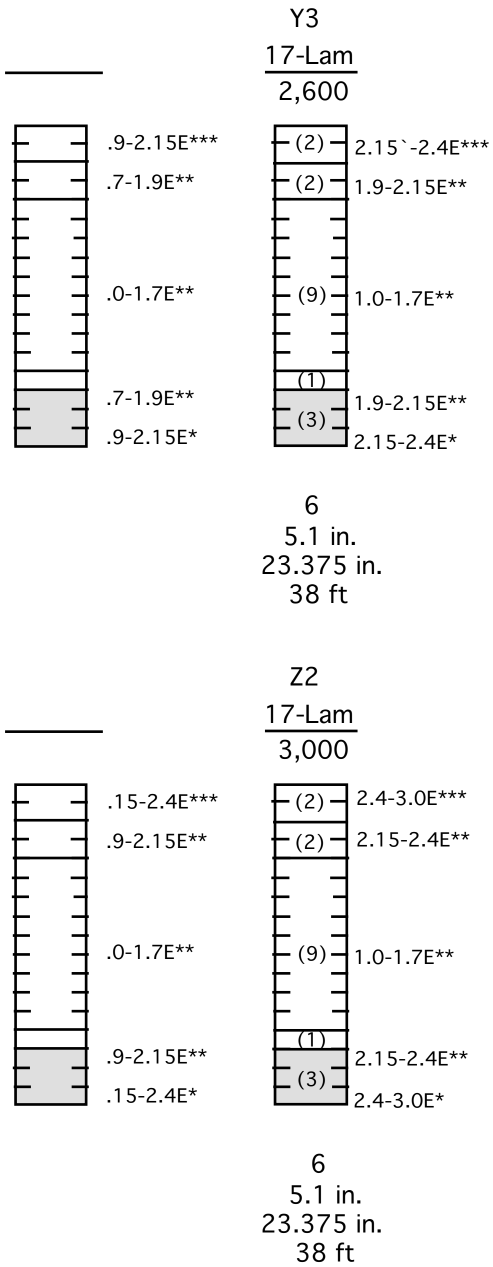

tension proof loaded to 1.5 times design stress

ed from No. 1 grade
ed from No. 2 grade
ed from No. 2 and Better grade

Figure A33—Specifications for Southern Pine beams made from proof-loaded, E-rated lumber in study by Pellerin and Strickler (1977).

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Appendix B—Supplemental Investigation on Volume Effects

As noted, AITC currently specifies that the end-use factor C_v should be used for all depths greater than 12 in. (30.48 cm). For depths shallower than 12 in. (30.48 cm), the C_v is limited to a maximum value of 1.0. The issue of limiting C_v values to 1.0 for shallow beams is addressed first. Figures A1 and A2 show calculated *K* values for the Douglas Fir beams fabricated with visually graded lumber. Figure A1 applies the current AITC rule ($C_v = 1.0$) for beam depths shallower than 12 in. (30.48 cm) and Figure A2 applies the calculated volume factors throughout all depths. Similar plots for Southern Pine beams made from visually graded lumber are illustrated in Figures A3 and A4; Figure A3 shows $C_v = 1.0$, and Figure A4 shows C_v applied throughout all depths. Table A1 summarizes the calculated *K* values for these beam groups.

The results from this initial analysis indicated that when thevolume effect factor was applied throughout all beam depths, the average *K* value for each beam depth remained fairly constant in relation to the overall mean *K* value of the group. When the current AITC rule for shallow beams was applied ($C_v = 1.0$), the calculated *K* values for the shallower beams were significantly greater. As a result of applying the AITC rule, average *K* values for each beam depth were highly scattered around the overall mean of the group; the average *K* values were approximately 6 percent higher for both species compared with groups in which C_v was applied throughout all depths. The results of this analysis suggest that all beams be analyzed by applying C_v over all depths; this was done for all remaining analyses.

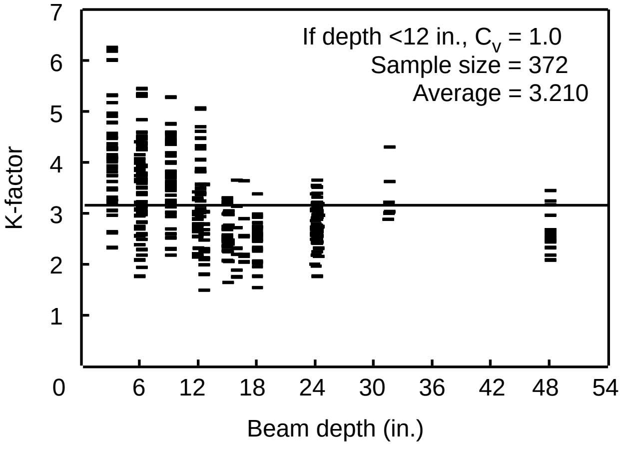

Figure B1—Calculated K-factors for horizontally laminated Douglas Fir beams made from visually graded lumber. (Volume effect factor equal to 1.0 for beams ≤12 in. deep.)

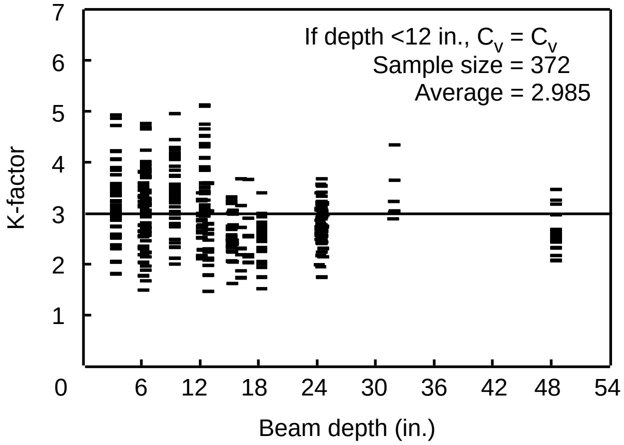

Figure B2—Calculated K-factors for horizontally laminated Douglas Fir beams made from visually graded lumber. (Volume effect factor applied to all depths.)

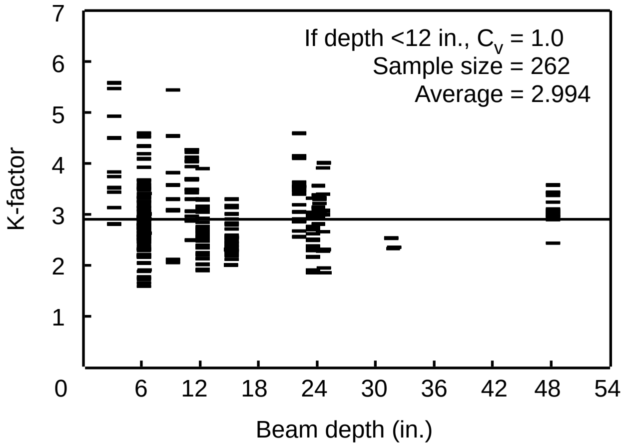

Figure B3—Calculated K-factors for horizontally laminated Southern Pine beams made from visually graded lumber. (Volume effect factor equal to 1.0 for beams ≤12 in. deep.)

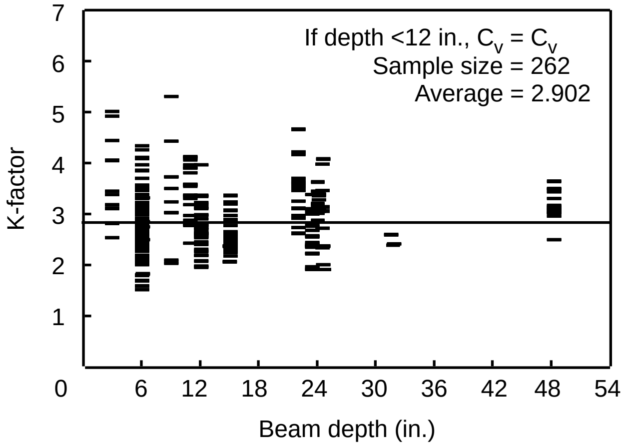

Figure B4—Calculated K-factors for horizontally laminated Southern Pine beams made from visually graded lumber. (Volume effect factor applied to all depths.)

Table B1—*K*-factor results for volume effect study[a]

	Douglas Fir		Southern Pine		Combined	
Volume factor	Avg.	COV	Avg.	COV	Avg.	COV
C_V = 1.0 for $d < 12$ in.[b]	3.210	26.7	2.994	22.6	3.121	25.5
C_V applied at all depths[c]	2.985	22.8	2.902	21.5	2.951	22.3
Difference between average values (%)	7.5		3.2		5.8	

[a] All beams were horizontally laminated with visually graded lumber. COV is coefficient of variation (%).

[b] The AITC rule was applied for depths shallower than 12 in. (30.48 cm).

[c] The volume effect factor was used for all depths.