In: Sugiyama, Hideo, ed. Proceedings of the 1990 International timber engineering conference; 1990 October 23–25; Tokyo. Tokyo: Steering Committee of the International Timber Engineering Conference: 1990: 176–182. Vol. 1.

# STRENGTH OF GLULAM BEAMS-VOLUME EFFECTS

Russell Moody
Supervisory Research Engineer
Robert Falk
Research Engineer
USDA Forest Service, Forest Products Laboratory[1]
Madison, Wisconsin USA

Thomas Williamson,
Vice-president Technical Operations
American Institute of Timber Construction
Vancouver, Washington USA

## Abstract

A volume-effect relationship for use in the design of glued laminated (glulam) timber beams was developed based on an analysis of the bending strength of more than 500 Douglas-& and Southern Pine test beams having depths up to 31-1/2 in. (0.80 m) and spans up to 48 ft (14.6 m). Proposed for adoption as a provision of an American Society of Testing and Materials standard, this design factor has a significant effect in determining the allowable design bending stresses for "large" beams. A glulam beam testing program recently completed by the American Institute of Timber Construction (AITC) provides additional data for evaluating the applicability of this design factor. Two groups totaling 45 Douglas-fir beams were commercially manufactured by AITC-member laminators and tested in bending. Fifteen beams from one group were 8-3/4 by 48 in. (222 mm by 1.22 m) in cross-section with a span of 64 ft (19.5 m)–believed to be the largest glulam beams ever tested. Mean bending strength values and 5% tolerance limits were determined for these two test groups. Results from the AITC tests compared closely to those predicted both from a previous study and from presently assigned design stresses as adjusted using the proposed volume effect.

## Introduction

### Definition and Use of Glulam

Glued laminated timber, commonly referred to as glulam, is an engineered stress-rated product produced by structurally bonding individual lumber laminations. The thickness of individual laminations may not exceed 2 in. (50 mm) net. Shorter lengths of commercially available lumber are structurally end jointed with adhesives to produce the required full-length laminations. In the United States, glulam is manufactured under the provisions of ANSI/AITC A190.1–83 "Structural Glued Laminated Timber" (5) and designed using the "Timber Construction Manual" (1).

Glulam is used in a wide variety of applications, ranging from headers or support beams in residential framing to major structural elements in roof framing of domed stadiums that span more than 500 ft (150 m). Glulam may be produced in any size and shape desired, ranging from large, long-span straight beams to complex curved-arch configurations. With the introduction of wet-use or durable adhesives about 50 years ago, glulam became a viable construction material for diverse uses such as utility structure crossarms, lighting standards, electric transmission line towers, and vehicular, nonvehicular, or railroad bridge structures.

The most common design application for glulam timber is as a bending member with the primary design loads applied perpendicular to the wide face of the laminations. To more effectively utilize the available lumber resource and to enhance the competitive position of glulam in the marketplace, such bending members are produced using engineered layups or combinations, incorporating a range of species and structural grades of lumber. In these engineered layups, the highest quality material is positioned in the member where the service loading will create the highest stress. Conversely, lower grade laminatiom are positioned in areas or zones where the stress will be lower.

The lumber grades used in the U.S. manufacture of glulam timber include special laminating grades, conventional visually stress-rated lumber grades, and machine-stress-rated (MSR) or E–rated lumber grades. Table 1 illustrates the use of the special Douglas-fir laminating grades, or L grades, as positioned in the engineered layups used for the manufacture of the test beams discussed later:

In some design applications, it may be desirable to apply the load parallel to the wide face of the laminations. This is commonly referred to as a vertically laminated member. In addition, glulam may be used as tension members in truss chords or as compression members in columns. In these cases, the stresses are essentially uniform across the entire cross-section of the member, and, as a result, a single grade of lumber is typically specified for all laminations within the member.

### Allowable Stresses for Glulam

The American Institute of Timber Construction (AITC) publishes design stresses for a wide variety of species and layup combinations in AITC 117–Design (2). These published stresses are derived based on the principles set forth in ASTM Standard D3737 (6).

One provision of ASTM D3737 is a requirement to adjust the allowable bending stresses for glulam by using a size-effect factor to account for the varying sizes of members under consideration. Details of the evolution of these procedures are given in other references (4,8,12).

---

[1] The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin. This article was written and prepared by U.S. Government employees on official time, and it is therefore in the public domain and not subject to copyright.

Table 1--Laminating grade combinations for test beams

| | | Number of laminations of each grade[a] in each zone | | | | | |
|---|---|---|---|---|---|---|---|
| | | Outer tension | | Inner tension | Core | Inner compression | Outer compression |
| Group | laminations | 302-24 | L1 | L2 | L3 | L2 | L2D |
| I | 4 | 1[b] | 0 | 1 | 1 | 0 | 1 |
| | 8 | 1[c] | 1 | 1 | 3 | 1 | 1 |
| | 10 | 1[c] | 1 | 1 | 5 | 1 | 1 |
| II | 16 | 1 | 12 | 2 | 8 | 2 | 2 |
| III | 32 | 2 | 23 | 3 | 18 | 3 | 4 |

[a] Douglas-fir grades per AITC 117–Manufacturing (3).

[b] 302-20 grade required.

[c] 302-22 grade required.

## Volume-Effect Factor

In recent years, a proposed change to ASTM D3737 has been to adopt the use of a volume-effect factor to replace the size-effect factor. This proposed factor accounts for all three parameters of volume; that is. depth, width, and length, and was baaed on analysis of results of bending tests of more than 500 Douglas-fir and Southern Pine glulam beams, ranging in depths from 3 to 31-1/2 in. (76 mm to 0.80 m) (11). In that analysis, results indicated species have no apparent effect, and the volume-effect factor was proposed to apply to all species.

A simpilified version of the volume-effect factor (11) can be approximated by the equation (4):

$$C_V = (V_o/V)^{0.102} \qquad [1]$$

where

$C_v$ is volume adjustment factor,

$V_o$ is volume of a standard beam that is assumed to have a width b = 5-1/8 in., a depth d = 12 in., and a length L = 21 ft (130 mm by 305 mm by 6.4 m), and

V is volume of the beam under consideration, b by d by L, where b, d, and L are in the same units as for $V_o$.

To further expand the database related to assignment of allowable bending and stiffness values for glulam beams and to provide further verification of the proposed volume-effect factor, AITC completed in 1988 and 1989 a testing program of two groups of 45 Douglas-fir beams. The objective of this paper is to determine how those results compare to results predicted from a previous study (10) and from presently assigned designed stresses as adjusted using Equation [1].

## Procedures

### Description of Test Beams

Three groups of Douglas-fir test beams identified as I, II, and III were evaluated. Group I consisted of 30 beams with depths of 6, 12, or 15 in. (152, 305, or 380 mm) and were tested in an earlier study (10). Group II consisted of 30 beams, 24 in. (610 mm) deep, and Group III consisted of 15 beams. 48 in. (1.22 m) deep. Groups II and III were those tested by AITC in 1988 and 1989, respectively. All beams were manufactured to meet the requirements of AITC Combination 24F–V4, Western Species in AITC 117–Manufacturing (3). Groups I and II were made using nominal 2- by 6-in. (actual 38- by 140-mm) lumber and group III using nominal 2- by 10-in. (actual 38- by 235-mm) lumber.

All beams had special high-quality tension laminations identified by AITC as a 302–24 grade in at least the outer 5% of the tension zone. For group I beams, this exceeds the requirements in AITC 117–Manufacturing (3) that would permit the use of slightly lower quality lumber in these shallower beams (see Table 1).

The method of selecting the specific lumber for use in the midlength outer-tension zone laminations differed for the groups. For group I, lumber that had near-maximum characteristics (i.e., knots, grain deviation, etc.), permitted by the AITC 302–24 tension lamination grade (3) was selected for that region of the test beams. These tension laminations represent the near-minimum quality permissible for the grade. For groups II and III, lumber was selected such that it represented a range of quality commonly used for the AITC 302–24 grade.

Another difference between the groups is the year in which the test beams were manufactured. Group I beams were manufactured in 1978, whereas groups II and III were manufactured in 1988 and 1989, respectively. All beams were commercially manufactured in accordance with the requirements of the industry standard in effect at the time (Product Standard 56–73 (14) and ANSI/AITC Standard A190.1–83 (5)). One AITC-member laminator manufactured all group I beams, whereas different AITC-member laminators each manufactured approximately one-third of the beams in groups II and III. The layup of the test beams is given in Table 1; a physical description of the beams is given in Table 2.

## Test Method

The beams were tested following ASTM D198 (7) procedures. Two-point loading was used for all tests that subjected approximately 20% of the midspan area of the beams to maximum moment. Test spans are given in Table 2. Group I beams were tested at the Forest Products Laboratory (FPL), Madison. Wisconsin, group II at Oregon State University. Corvallis, Oregon, and group III at Washington State University, Pullman, Washington. For groups I and III, deflections were measured electronically, whereas a stringline and scale were were used to determine the deflection for the beams in group II.

## Data Adjustments

As noted, group I beams used AITC 302–24 grade tension laminations, a grade level that exceeds the minimum quality required by AITC 117–Manufacturing (3); that is, an AITC 302–22 or AITC 302–20 grade depending upon the beam depth. However, group I beams also differed from the other two beam groups in that they were manufactured with tension laminations that had been purposely selected to contain a near-maximum-sized strength reducing characteristic permitted by the grade. Thus, group I beams were considered to be representative of near-minimum quality beams. Also, as previously noted, group II and III beams were made with tension laminations having a range of characteristics permitted within the grade description and were thus considered to be representative of average quality beams.

To account for the relative tension lamination quality differences, group I strength data were adjusted to conditions comparable to those used for groups II and III. In a previous study, the bending strength values of glulam beams manufactured using tension laminations having average strength-reducing characteristics were estimated to be about 10% higher than those of comparable beams produced using tension laminations containing near-maximum allowable defects (10). In that same study, shallow beams with AITC 302–20 tension laminations (permitted for 24F–V4 beams up to 12 in. (305 mm) in depth) had bending strength values about 16% lower than those of comparable beams utilizing AITC 302–24 grade tension laminations. Although similar data are not available for beams with AITC 302–22 tension lamination grades (permitted for 24F–V4beams having depths from 12 to 15 in. (305 mm to 380 mm)), it would be expected that the difference would be about half of 16% or 6%. When manufactured with these grades of material used for the tension laminations, no increase in design stress based on volume effect is permitted for beams shallower than 12 in. (305 mm) (3).

Thus, the net adjustments proposed for group I beams are as follows:

1. For all beams, increase strength values by 10% to adjust to average quality tension laminations.

2. For 6-in.- (152-mm-) deep beams. decrease strength values by 16% to adjust to the use of 302–20 (per AITC 117–Manufacturing) instead of 302–24 tension laminations.

3. For 12- and 15-in.- (305- and 360-mm-) deep beams, decrease strength values by 8% to adjust to the use of 302–22 (per AITC 117–Manufacturing) instead of 302–24 tension laminations.

The net effect of these adjustments is only a few percent for each beam size in group I.

## Analysis Methods

The bending stress introduced by the uniform dead load of the beams was added to the stress induced by the test loads to obtain the overall beam modulus of rupture (MOR). For each group. a 90% confidence interval on the mean value and a 5% tolerance limit, assuming a lognormal distribution, were determined for MOR (13). Using the data from group I, which were available prior to the testing of the other two groups, and the volume-effect reduction recently developed (11), the mean strength values of groups II and II were estimated.

## Results

Average MOR and modulus of elasticity (MOE) values with their corresponding coefficients of variation (COVs) for each group of test beams are given in Table 3. The previously described data adjustments applied to the results of group I beams are also included. The cumulative frequency distributions of individual unadjusted strength values for each set of data are shown in Figure 1.

Using group I beam results as a basis (after normalizing to a standard 12-in.- (305-mm-) deep. 21-ft- (6.4-m-) long beam), the volume-effect factor applicable for group II and III beams was used to predict their MOR values (6,050 lb/in$^2$ (41.7 MPa) and 5,050 lb/in$^2$ (34.6 MPa), respectively). These predicted MOR results for group II and III beams are presented in Table 4 and are those defining the top curve of Figure 2. Thus, the shape of the top curve plotted in Figure 2 was determined by Equation [1], and it was positioned using group I results from Table 4 (9). The bottom curve plotted in Figure 2 is 2.1 times the design stress for beams with a nominal 2,400 lb/in$^2$ (16.5 MPa) design stress in bending.

Actual (not predicted) average MOR values for each group of beams are given in Table 5 with the resulting estimates of 5% tolerance limit values from the data. These actual data, along with confidence intervals on the mean. are also shown in Figure 2.

The results of a post-test visual evaluation of the failed beams conducted by the FPL staff for group I and by FPL and AITC staff for groups II and III to determine the most probable primary cause of failure are summarized in Table 6. Also presented in Table 6 is a summary of relative tension lamination quality for all the test beams based on these post-test visual inspections.

## Discussion

As indicated in Figure 1. a significant volume effect is apparent over the range of unadjusted strengths of 6- to 48-in.- (150-mm to 1.22-m-) deep beams. Although it is difficult to discern between the 12-, 15-, and

Table 2--Description of various-sized Douglas-fir beams[a]

| Group | Number of lami-nations | Nominal lumber size (in.) | Nominal lumber size (mm) | Beam size: Width (in.) | Beam size: Width (mm) | Beam size: Depth (in.) | Beam size: Depth (mm) | Beam size: Length (ft) | Beam size: Length (m) | Test condition: Span (ft) | Test condition: Span (m) | Test condition: Load heads[b] (ft) | Test condition: Load heads[b] (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I | 4 | 2 by 6 | (38 by 140) | 5-1/8 | (130) | 6 | (152) | 10 | (3.05) | 9.5 | (2.90) | 2 | (0.61) |
|  | 8 | 2 by 6 | (38 by 140) | 5-1/8 | (130) | 12 | (305) | 20 | (6.10) | 19 | (5.79) | 4 | (1.22) |
|  | 10 | 2 by 6 | (38 by 140) | 5-1/8 | (138) | 15 | (380) | 25 | (7.62) | 24 | (7.32) | 5 | (1.52) |
| II | 16 | 2 by 6 | (38 by 140) | 5-1/8 | (130) | 24 | (610) | 40 | (12.2) | 38 | (11.6) | 8 | (2.44) |
| III | 32 | 2 by 10 | (38 by 235) | 8-3/4 | (222) | 48 | (1,220) | 68 | (20.7) | 64 | (19.5) | 12 | (3.66) |

[a] Manufactured to meet AITC 117 manufacturing requirements for a 24F-V4 layup.

[b] Distance between two symmetric load heads.

Table 3--Results of bending tests on Douglas-fir beams

| Group | Number of lami-nations | Number of tests | Unadjusted modulus of rupture: Average ($\text{lb/in}^2$) | Unadjusted modulus of rupture: Average (MPa) | Unadjusted modulus of rupture: COV (%) | Modulus of rupture (adjusted for tension laminations)[a]: Average ($\text{lb/in}^2$) | Modulus of rupture (adjusted for tension laminations)[a]: Average (MPa) | Modulus of elasticity: Average ($10^6$ $\text{lb/in}^9$) | Modulus of elasticity: Average (GPa) | Modulus of elasticity: COV (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| I | 4 | 10 | 8,200 | 56.5 | 16.1 | 7,650 | 52.7 | 2.03 | 14.0 | 6.2 |
|  | a | 10 | 6,460 | 44.5 | 17.0 | 6,610 | 45.6 | 2.04 | 14.1 | 3.4 |
|  | 10 | 10 | 6,050 | 42.7 | 16.0 | 6,180 | 42.6 | 1.99 | 13.7 | 3.6 |
| II | 16 | 30 | 6,050 | 41.7 | 14.5 |  |  | 2.06 | 14.2 | 4.0 |
| III | 32 | 15 | 4,850 | 33.4 | 14.5 |  |  | 1.72 | 11.9 | 8.6 |

[a] Estimated for random beams meeting requirements of AITC 117-Manufacturing fur 24F-V4 combination.

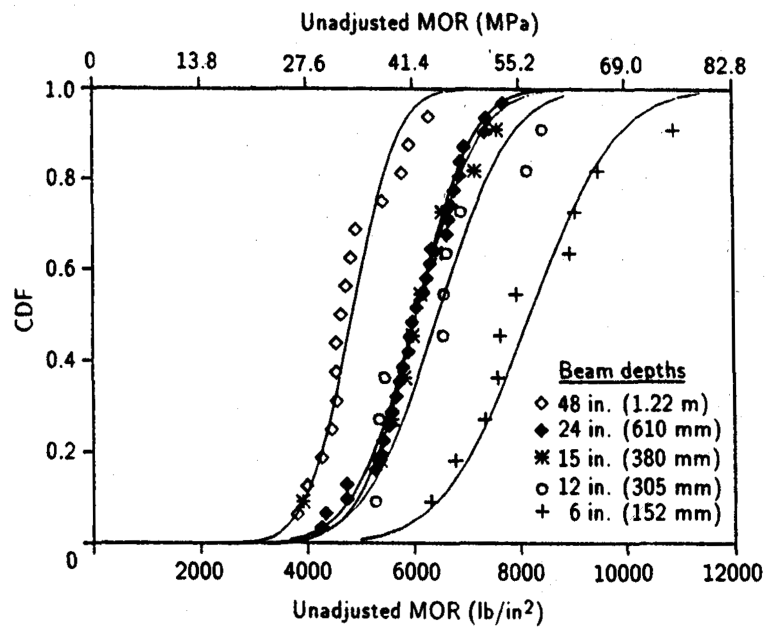

Fig. 1. Cumulative distribution function (CDF) for five sizes of Douglas-fir glulam timber beams manufactured to meet combination 24F–V4of AITC 117–Manufacturing. Group I beams were 6, 12, and 15 in. (152, 305, and 380 mm) deep, group II beams 24 in. (610 mm) deep, and group III beams 48 in. (1.22 m) deep.

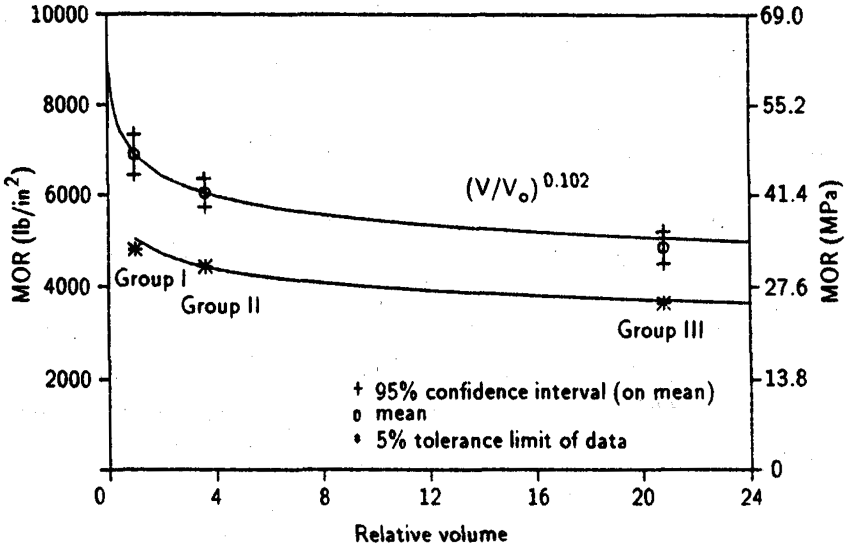

Fig. 2. Effect of volume on strength properties of Douglas-fir glulam timber beams. Mean and fifth percentiles of the data are compared with predicted values.

24-in.- (305-. 380-. and 610-mm-) deep beam strength distributions. it is easy to see a distinct difference between the shallow, medium depth, and deep beams.

After the strength values of group I beams were adjusted for the effect of tension lamination quality. these values were used as a basis for predicting the MOR values of deeper beams (Table 4). Predicted and actual strength values of the deeper beams are compared in Figure 2. The actual values of mean strength for group II and III beams (6,040 lb/in$^2$ (41.6 MPa) and 4.850 lb/in$^2$ (33.4 MPa). respectively) with corresponding confidence bounds are shown in Figure 2 and agree closely with the predicted values. This indicates the ability of the volume-effect factor to accurately account for the reduction in strength as a result of increasing beam size. Also shown in Figure 2 are the 5% tolerance limits (assuming a lognormal distribution and 75% confidence). Note that the volume-effect trend at the fifth percentile parallels that at the mean.

Allowable design stresses for glulam beams are targeted to have values 1/2.1 times the fifth percentile of the actual strength distribution from tests: therefore. these fifth percentile values can be compared to the applicable beam design stresses for the layups of the tested beams. Table 5 indicates that the ratio of fifth percentile values to design stress is very close to the targeted 2.1 values. This indicates both that the developed volume-effect relationship is applicable and that the design stresses are appropriate for the combinations tested.

Table 6 shows that group I beams tended to have tension laminations of lower relative quality than the other groups, whereas group II and III beams tended to have a wider range of tension lamination qualities. Knots were involved in many of the failures of group I beams, whereas finger joints in the outer-tension laminations were the primary cause of failure in group II and III beams. With the higher quality tension laminations and the greater number of highly stressed finger joints in group II and III beams, the higher frequency of failures initiating at finger joints would be expected.

## Conclusions

The presented beam test results adjusted by appropriate factors to account for tension lamination quality indicate that the developed volume-effect factor works well in accounting for strength reduction in large glulam beams. Although this verification has been applied only to the available Douglas-fir beam test results. previous results showed that species have no significant effect (11).

## References

1. American Institute of Timber Construction. "Timber Construction Manual." John Wiley and Sons. New York. N.Y.. 1985.
2. American Institute of Timber Construction. "Standard Specifications of Structural Glued Lamianted Timber of Softwood Species." AITC 117-87-Design. AITC. Vancouver. Wash.. 1987.
3. American Institute of Timber Construction, "Standard Specifications of Structural Glued Laminated Timber of Softwood Species." AITC 117-88-Manufacturing. AITC. Vancouver, Wash.. 1988.
4. American Institute of Timber Construction. "Use of a Volume Effect Factor in Design of Glued Laminated Timber Beams." AITC Technical Note No. 17. AITC. Vancouver. Wash.. 1990.
5. American National Standards Institute. "Structural Glued Laminated Timber." ANSI/AITC A190.1, AITC. Vancouver, Wash., 1983.
6. American Society of Testing and Materials, "Standard Method for Establishing Stresses for Structural Glued Laminated Timber (Glulam)." ASTM D3737-89, ASTM. Philadelphia. Pa., 1989.
7. American Society of Testing and Materials. "Standard Methods of Static Tests of Timbers in Structrual Sizes." ASTM D198-84. ASTM. Philadelphia, Pa.. 1989.
8. Bohannan, B., "Effect of Size on Bending Strength of Wood Members." FPL-RP-56, U.S. Department of Agriculture. Forest Service, Forest Products Laboratory, Madison, Wis., 1966.
9. Marx. C.M., and Moody, R.C., "Strength and Stiffness of Small Glued-Laminated Beams with Different Qualities of Tension Laminations," FPL-RP-381, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wis., 1981.
10. Marx, C.M. and Moody, R.C., "Effect of Lumber Width and Tension Lamination Quality on the Bending Strength of Four-Ply Laminated Beams," Forest Products Journal, Vol. 32, No. 1, 1982, pp. 45-52.
11. Moody, R.C., Dedolph, C., and Plantinga, P.L., "Analysis of Size Effect for Glulam Beams." Vol. 1, The 1988 International Timber Engineering Conference, Sept. 1988. Seattle, Wash.. Forest Products Research Society. Madison. Wis.. 1988, pp. 892-898.
12. Moody, R.C.. and Falk. R.H.. "Development of Design Stresses for Glulam Timber in the United States." Proceedings, 2d Pacific Timber Engineering Conference. Aug. 28-31, 1989. Auckland. New Zealand, Auckland Centre for Continuing Education, University of Auckland. 1989, Vol. 2. pp. 309-313.
13. Natrella, M.G.. "Experimental Statistics." National Bureau of Standards Handbook 91. U.S. Department of Commmerce. Washington, D.C.. 1963.
14. U.S. Department of Commerce. "Voluntary Product Standard PS 56-73 for Structural Glued Laminated Timber." U.S. Department of Commerce. Washington, D.C., 1973.

Table 4--Predicted modulus of rupture for groups II and III

| Group | Number of laminations | Applicable volume-effect factor | Modulus of of rupture (adjusted for tension laminations and volume)[a] (lb/in$^2$) | (MPa) | Predicted modulus of rupture (lb/in$^2$) | (MPa) |
|---|---|---|---|---|---|---|
| I | 4 | 1.000 | 7.650 | 52.7 | -- | -- |
|  | 8 | 1.000 | 6.610 | 45.6 | -- | -- |
|  | 10 | 0.966 | 6,400 | 44.1 | -- | -- |
|  | Average |  | 6.880 | 47.4 | -- | -- |
| II | 16 | 0.879 | -- | -- | 6,050 | 41.7 |
| III | 32 | 0.734 | -- | -- | 5,050 | 34.8 |

[a] From Table 3 and further adjusted to standard beam 12 in. (305 mm) deep with a span to depth ratio of 21:l and uniformly loaded.

Table 5--Confidence intervals and tolerances limits[a]

| Group | Number of beams | Average modulus of rupture (lb/in$^2$) | (MPa) | 95% confidence interval on mean | Tolerance limit (5%, 75% confidence lognormal) (lb/in$^2$) | (MPa) | Applicable design stress[b] (lb/in$^2$) | (MPa) | Tolerance limit to design stress ratio |
|---|---|---|---|---|---|---|---|---|---|
| I | 30 | 6.000 | 47.4 | ± 6.5% | 4,000 | 33.1 | 2,400 | 16.5 | 2.00 |
| II | 30 | 6,040 | 41.6 | ± 5.1% | 4,430 | 30.5 | 2,110 | 14.5 | 2.10 |
| III | 15 | 4,050 | 33.4 | ± 7.2% | 3,640 | 25.1 | 1,760 | 12.1 | 2.07 |

[a] For beams meeting requirements of Douglas-fir combination 24F-V4 of AITC 117-Manufacturing.

[b] Volume-effect factor applied to 2,400 lb/in$^2$ (16.5 MPa) for groups II and 111.

Table 6--Comments on visual inspection of test beams

|  | Number of beams in each group |  |  |
|---|---|---|---|
|  | I | II | III |
| Relative quality of 302-24 grade midlength outer-tension lamination: |  |  |  |
| Near minimum | 23 | 9 | 7 |
| Average | 7 | 10 | 5 |
| High | 0 | 11 | 3 |
| Post-test visual evaluation of most probable cause of failure: |  |  |  |
| Knots in outer-tension lamination | 13 | 7 | 3 |
| Finger joints in one or more of three outer-tension laminations | 5 | 14 | 12 |
| Knots and finger joints in combination | 8 | 9 | 1 |
| Compression zone failure | 4 | 0 | 0 |

Printed on recycled paper