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DEVELOPMENT OF DESIGN STRESSES FOR GLULAM TIMBER IN THE UNITED STATES

R. C. Moody **R. H. Falk**

USDA Forest Service, Forest Products Laboratory[1]
One Gifford Pinchot Drive, Madison, Wisconsin 53705-2398 U.S.A.

ABSTRACT

In North America, glued-laminated (glulam) timber beams are used as major structural elements in many buildings and bridges. The engineering design of these important structural members requires a knowledge of their engineering properties on which to base design stresses.

A changing timber resource base demands a better characterization of strength properties for glulam timber. Consequently, reviews of established design stresses are necessary. New and emerging design procedures, incorporating reliability-based design methodologies, will also require the establishment of strength and stiffness distributions.

This paper presents an overview of the current method of assigning design stresses for glulam beams and the research underway that is directed towards characterizing the engineering properties of glulam beams. Research is summarized in the areas of (1) reanalysis of allowable clear wood stresses for design. (2) formulation of equations to represent the volume effect in glulam bending members, and (3) the use of mathematical models for strength and stiffness predictions.

INTRODUCTION

Clued-laminated (glulam) timber beams are a highly engineered wood product used in a variety of structural and architectural applications. Structural uses in North America range from 15-cm-deep window and door headers to 2.5-a-deep main load carrying members in large-span stadium structures and bridges. These members represent a relatively small, though vital, portion of lumber produced in the United States. Over 0.25 x 10^9 board feet (600,000 m^3) of lumber are used annually in the manufacture of glulam timber.

The engineering design of these important structural members follows industry standards that specify design stresses for a variety of species and grade combinations of lumber. These design stresses are developed from nationally recognized standards that are aimed at maximizing the efficient use of the timber resource while maintaining acceptable safety levels.

The objective of this paper is to review the current methods of assigning design stresses for glulam timber in the United States and discuss current research efforts that are directed toward Improving the characterization of glulam strength properties.

REVIEW OF CURRENT METHODS

Design stresses for glulam timber are published by the American Institute of Timber Construction (AITC). an organization representing most of the U.S. manufacturers of glulam timber. To justify published design stresses, the manufacturing standard ANSI/AITC A190.1 (ANSI 1983) must be followed. This standard sets minimum requirements for production, inspection, testing, and certification of glulam timber.

The AITC selects specific target design stresses for bending and optimizes combinations of softwood lumber grades to meet these target levels. These levels are 1.600, 2.000, 2.200. and 2,400 lb/in^2 (11.0. 13.8, 15.2. and 16.5 MPa) (AITC 1987). In some instances, specific modulus of elasticity (MOE) values are also targeted. Other design stresses, such as those for axial loading and shear, are generally of secondary concern and do not influence the development of the grade combinations.

To develop the listed design values. AITC uses the American Society for Testing and Materials standard ASTU-D3737 (ASTM 1988) to develop the combinations of lumber in their manufacturing specifications (AITC 1988) that meet the required performance. The remainder of this section describes the concepts of ASM-D3737, which forms the basis for assigning design stresses to glulam timber. Most glulam timber is used for bending members; therefore, emphasis is placed on design strength and stiffness in bending.

The approach in ASTM-D3737 to developing design stresses involves a concept of multiplying a clear wood strength value by a strength ratio:

$$MOR = CWS \times SR \qquad (1)$$

where MOR is modulus of rupture, CWS is clear wood strength, and SR is strength ratio.

By developing design stresses appropriate for clear wood. this can be rewritten in a design stress format :

$$F_b = CWDS \times SR \qquad (2)$$

where F_b is design stress in bending and CUDS is clear wood design stress.

Values of SR depend upon the lower of two values calculated, based on the effect of either slope of grain or knots. Tables are provided in ASTM-D3737 (ASTM 1988) for slope of grain. The method to

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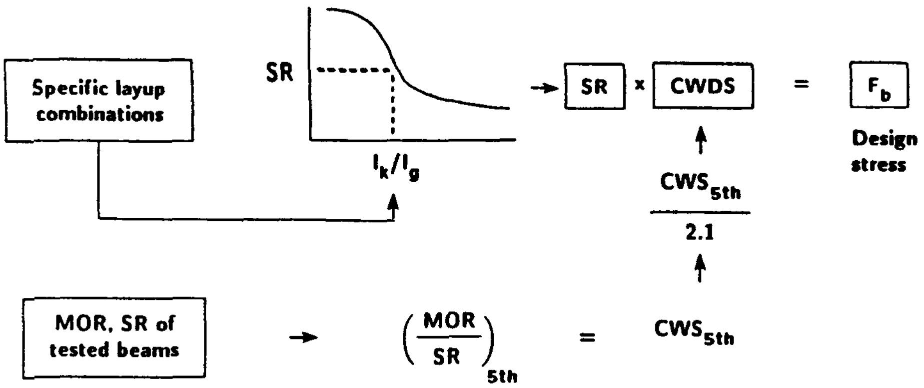

FIG 1: Flowchart to establish F_b, design stress in bending. (ML89 5706)

account for the effect of knots is based on a combination of statistical and empirical techniques (Freas and Selbo 1954). For horizontally laminated beams, these techniques use statistical properties of the knots in the various lumber grades that are used to calculate a value called I_k/I_g for a specific combination of lumber grades. The value is the ratio of the moment of inertia of knots, I_k, in a cross section to the total moment of inertia, I_g. This I_k/I_g value, which is a near maximum value, is then empirically related to the strength ratio in bending.

Two options exist for determining the cleanwood design stress, CWDS. One option is to follow the same general procedures used for lumber given in ASTM-D245 (ASTM 1988). The other option. which is used for most of the beams produced in the United States (Douglas Fir, Southern Pine. and Hem-Fir). is based on an analysis of test beams. The method used involves analyzing test beams using a rewritten version of Equation (1):

$$CWS = MOR/SR \qquad (3)$$

and determining

$$CWDS = (CWS)_{5th}/2.1 \qquad (4)$$

where $(CWS)_{5th}$ is the lower 5th percentile of the distribution of CWS for a species calculated from Equation (3). The 2.1 factor is a bending adjustment factor, accounting for duration-of-load and end-use factors with the duration-of-load adjustment from 5 minutes to 10 years. Values of CUDS.based on an analysis of test data from the 1960s and 1970s. are given in ASTM-D3737 (ASTM 1988) for visual grades of Douglas Fir. Southern Pine, and Hem-Fir. In addition. data are also provided for categories of E-rated lumber that has been nondestructively tested to determine its long-span stiffness. Figure 1 is a flowchart of how the design stress in bending is established using the option of analyzing test beams.

An additional requirement of ASTM-D3737 (ASTM 1988) is that certain minimum quality levels must be maintained for laminations on the outer 5 percent of the beams on the side stressed in tension. A review of the beam tests that formed the basis for the I_k/I_g concept reveals that high-quality outer laminations were used on beams with I_k/I_g values of less than about 0.25. which is in the range of today's popular 2.400-lb/in^2 (16.5-HPa) design stress (Fig. 2). Lumber used in the critical outer 5 percent of the tension zone, called tension laminations. has specific grading restrictions to justify assigning the strength ratio values previously calculated. These grading restrictions include limitations on knots, their associated grain deviation, slope of grain. density, specific gravity, and other characteristics. Thus, these tension lamination8 are graded to provide a high-visual grade. An example of the grade used for the 2,400-lb/in^2 (16.5-MPa) design stress level is given in Table 1.

As previously noted, these procedures for developing design stresses are predicated on a level of manufacturing that will result in adequate glue bonds between laminations and an adequate end joint within laminations. Minimum strength levels for these glued joints and quality assurance procedures are prescribed in the American National Standards Institute standard for manufacture of glulam timber, ANSI/AITC A190.1 (ANSI 1983).

Required shear strength of glued joints between laminations must achieve 90 percent of the strength of unglued wood. To glue laminations end-to-end, most U.S. manufacturers use a finger-type of end joint. These joints are about 1.1 in. (2.8 cm) long with 4 fingers per inch. Required tensile strength of these finger joints is related to the design level of the beams, with a required 5th percentile equal to or exceeding 1.67 times the design level in bending.

Experience indicates that end joints lower in strength than required result in test beams with short-term strengths lover than the target minimum of 2.1 times the design level. The ANSI/AITC A190.1 (ANSI 1983) standard is being revised, and a major area of emphasis is being focused on methods of improving the reliability of end joints.

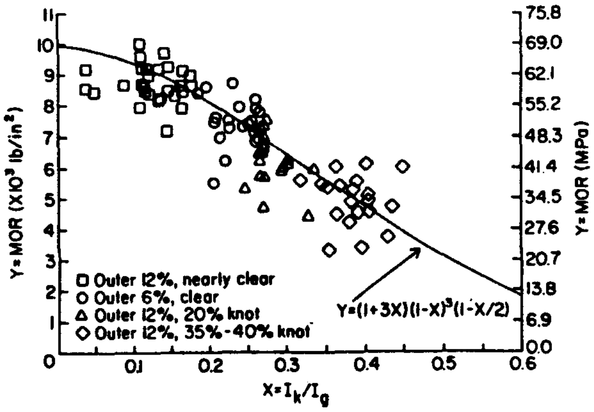

FIG 2: A comparison of MOR and I_k/I_g showing the quality of laminations in the outer zones of the beam groups (Freas and Selbo 1954). (ML89 5707)

Table 1. Example of special tension lamination grading requirements for glulam beams with a design stress of 1,400 lb/in^2 (AITC 1988).

C3. AITC 302–24 TENSION LAMINATION––MEMBERSIN BENDING

C3.l General Provisions. In addition to the basic requirements of the grades tabulated in these specifications. the following limitations shall apply:

C3.l.l A one–foot length of a lamination shall be considered as a cross section.

C3.l.2 Knot shall not occupy more than 1/5 of the cross section.

C3.1.3 Any cross section shall have at least 2/3 clear wood free of strength–reducing characteristics with a slope of grain no steeper than 1:16. (Knots plus associated localized cross grain, or knots plus associated localized cross grain plus localized cross grain not associated with a knot, or localized cross grain not associated with a knot may occupy up to 1/3 of the cross section.)

C3.1.4 Maximum size single strength–reducing characteristics when not in the same horizontal projection must be at least two feet apart measured center to center.

C3.1.5 The general slope of grain shall not exceed 1:16. Where more restrictive slope of grain requirements are required by the laminating combinations. these shall apply.

C3.2 Visually Graded Combinations

C3.2.l In addition to the general provisions in C3.l. the following applies to visually graded combinations.

C3.2.2 Growth rate requirements (including "dense" if required) shall apply to the full length of the piece. Douglas Fir–Larch. Hem–Fir and Southern Pine tension laminations are required to be dense. Pieces shall have near average or above average specific gravity for the species.

C3.2.3 Pieces containing wide–ringed or lightweight pith associated wood at the ends of the piece occupying over 1/8 of the cross section shall be excluded. (The next inch of wood outside the area of the pith associated wood shall meet the growth rate requirements of the grade. including "dense" when dense laminations are required. The line along which measurement of this inch is made shall correspond to the line used in the standard grading rules for rate of growth and percentage of summerwood. If a distance of one inch is not available along this line, the measurement will be made over such lesser portion as exists.)

C3.3 E–Rated Combinations

C3.3.1 Laminations must be visually graded and E–rated in accordance with all of the requirements for the E–rated grade shown for the outer tension lamination. In addition to these, the general grading provisions in C3.l apply.

C3.3.2 Pieces containing wide–ringed or lightweight pith associated wood at the ends of the piece occupying over 1/8 of the cross section shall be excluded. (The next inch of wood outside the area of the pith associated wood shall be of the same rate of growth and density as the remainder of the wood located away from the pith. The line along which measurement of this inch is made shall correspond to the line used in the standard grading rules for rate of growth and percentage of sumerwood. If a distance of one inch is not available along this line, the measurement will be made over such lesser portion as exists.) All wood not included as pith associated wood must be of at least medium grain rate of growth.

ESTABLISHMENT OF CLEAR WOOD DESIGN STRESS

To assure that the design values for glulam beams accurately reflect the properties of the resource base from which they are constructed, material property and component test data must be periodically reviewed. Recently, questions have been raised regarding the validity of the currently used allowable clear wood design stress values for beams manufactured from visually graded and E-rated lamination lumber.

Clear wood design stresses are given in ASTM-D3737 (ASTM 1988) and, as previously mentioned, are based upon an analysis of tested beams. The modulus of rupture of tested beams and a measure of the bending strength ratio for each beam are used in Equation (3) to establish the CUDS. Beans designed with this clear wood stress and tested according to ASTM-D198 (ASTM 1988) (a standard method describing procedures for the testing of timber beams) should yield bending strength values such that the lover 5th percentile will exceed the design bending stress by the factor of 2.1. with 75 percent confidence.

The I_k/I_g method previously described is used to determine the bending strength ratio. As presented by Wilson and Cottingham (1945) and Freas and Selbo (1954). the ratio I_k/I_g accounts for the effects of knots in glulam beams based upon both knot size and position. Moments of inertia are computed for the knots (I_k) and for the gross cross section of the beam (I_g); therefore. this method accounts for the fact that knots located in the outer laminations have a greater affect on strength than knots located in laminations near the neutral axis. This analysis procedure requires information on the layup combinations of the beams. lumber properties (clear wood design stress in bending for the species). and both modulus of elasticity and knot properties for the lamination grades used.

An empirical relationship between the ratio I_k/I_g and the bending strength ratio has been established (Fig. 2). This relationship vas established from analysis of beam test data (Wilson and Cottingham 1945) and indicates the influence of tension lamination grade on the I_k / I_g ratio.

Today's tension lamination requirements evolved from these early indications of tension lamination influence.

The currently used clear wood design stress values were derived using both the results of full-size beam tests and properties of lamination grade lumber data available prior to 1975. The study from which they were derived utilized available Douglas Fir (86 beams) and Southern Pine (28 beams) tests to establish allowable clear wood stresses (Moody 1977). For the Douglas Fir. a statistical analysis indicated a wan clear wood stress of 7.531 lb/in^2 (51.8 MPa) with a coefficient of variation (COV) of 15 percent. Assuming a lognormal distribution, this resulted in a clear wood design stress of 3.500 lb/in^2 (24.0 MPa). An analysis of the Southern Pine beams indicated a higher mean clear wood stress of 10.790 lb/in ^{2} (74.2 MPa) with a COV of 17 percent. Due to the small number of beams available for analysis and the increased COV, a committee decision was made to limit the clear wood design stress for Southern Pine to that of Douglas Fir.

A current study at the U.S. Department of Agriculture. Forest Service. Forest Products Laboratory (FPL) involves the reanalysis of clear wood design stresses to include the results of over 500 Douglas Fir. Southern Pine, and E-rated beams tested between the period from 1967 to 1989. Preliminary analysis results of adjusted CWS as a function of time for Douglas Fir are shown in Figure 3 (adjusted CWS is the clear wood stress of Eq. (3) adjusted for volume effect to a 12-in.- (30.5-cm) deep beam). Although Figure 3 indicates some variation in the wan values of adjusted clear wood stress, there appears to be a slight decrease in the general trend with respect to time. Most of the variation that does exist can be attributed to specific characteristics of the beams constructed for the particular study investigated.

VOLUME EFFECT

The apparent decrease in unit strength as timber beams became larger has been recognized in design standards in the United States for many years. Work by Tucker (1941) resulted in a relationship between beam strength and depth. Bohannan (1966) reviewed the history of the so-called depth effect and proposed a modified version in 1966. This work, which was based on an extensive analysis of clear wood beams of varying sizes, led to the present practice that recognizes both beam depth and length as influencing strength. To differentiate from the previous concept, it was called a size effect.

We have recently completed an extensive reanalysis of the glulam timber data collected during the past 40 years in North America and have proposed yet another technique for accounting for varying strength with increasing size. A new relationship was necessary because the data show a greater effect of both depth and length for structural grades of beams than previously recognized and, in addition. a significant effect of width for beams made with structural grades of lumber. We have chosen to call this most recent method of accounting for decreased beam strength a volume effect.

Last year, we reported on the results of the data analysis and the progress toward standardization of a proposed volume effect (Moody and others 1988). This standardization effort is still underway in the form of a proposed change to the ASM-D3737 (ASTM 1988) standard and. if adopted. would be as follows:

$$R = R_0 K (d_0/d)^{1/10} (w_0/w)^{1/10} (1_0/1)^{1/9} \qquad (5)$$

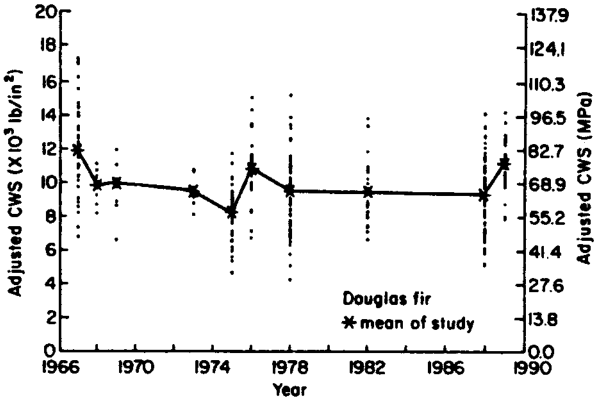

FIG 3: Clear wood stress reanalysis results for visually graded Douglas Fir. (ML89 5708)

where R is strength of beam of dimensions d, w, and 1; R_0 is strength of standard beam of dimensions d_0, w_0, 1_0; and K is a factor to account for method of loading. For constant ratios of depth to width to length, Equation (5) becomes approximately

$$R = R_0 K (V_0/V)^{1/10} \qquad (6)$$

where V is beam volume. A plot of the proposed volume effect and the currently used size effect is shown in Figure 4.

MATHEMATICAL MODELING

Reliability-based design procedures are being proposed for the U.S. wood industry that will require information on the statistical distributions of strength and stiffness properties for a11 materials and components. It is not feasible to develop such data for all grades, sizes, and combinations of materials that can be used for glulam timber; therefore, it is necessary that reliable simulation models be developed and utilized to predict glulam beam performance.

Several computer models have been developed to simulate the strength and stiffness distributions of horizontally laminated beams and tension members (Foschi and Barrett 1980, Bender and others 1985. Ehlbeck and others 1985. Burdzik and others 1988. Govindarajoo 1989). The basic approach of these models is to simulate the material properties of the constituent laminating lumber, after which the ultimate moment carrying capacity of the beam is determined from structural analysis. The analysis techniques used in these models vary in complexity, and model accuracy depends on accurate characterization of the material properties of the constituent lumber and end joints that connect the lumber end-to-end.

The model developed by Foschi and Barrett (1980) uses the finite element method of structural analysis. To predict strength and stiffness, this model requires information on the relationship betwen knot size and lumber strength and between lumber stiffness and lumber strength. Utilizing finite elements to construct a beam whose laminations are discretized into 6-in. (15-cm) cells, knot sizes are assigned to each cell based upon the probability distributions of actual knot occurrences in graded lumber. The model assumes that for each laminating grade tensile tests have been conducted. noting the knot size at the point of failure. These data permit the establishment of a relationship between tensile strength and knot size for a given grade. End joints are accounted for in the model and are randomly allocated according to the lengths of lumber stock available. End joint strength data are based upon limited test data and are represented by a three-parameter Weibull distribution.

The Bender and others (1985) model is not as computationally intensive as the finite element approach utilized by Foschi and Barrett (1980). This model uses a statistical approach to beam strength prediction and utilizes the actual lumber strengths of the lamination grades. Unlike the clear wood adjustment approach used in Foschi's model, no strength-reduction factors are necessary. Using the assumption that failure is initiated in the tension zone, the ultimate moment capacity of the beam can be predicted knowing the tensile strength and stiffness of each lamination. Ultimate moment capacity is calculated by the transformed section method, allowing the analysis of beams of two or more laminations constructed of materials with varying properties.

Govindarajoo (1989) has combined the I_k/I_g method with probabilistic analysis to determine strength and stiffnear frequency distributions for glulam beams. Although the I_k/I_g method is deterministic in nature, the author has modified the method for probabilistic analysis by generating input parameters, such as MOE, clear wood strength, knot infomation. and end joint strength in a prescribed random fashion. Monte Carlo simulations are performed to randomly generate the beam strength and stiffness distributions.

None of these models have been completely verified, but they are currently being evaluated as part of research programs in the United States for use in generating resistance distributions for reliability-based design procedures.

CONCLUDING REMARKS

As the timber resource in North America continues to change, there will be a continued need to monitor the strength and stiffness of lamination grades of lumber for the manufacture of glulam beams. Continued research in mathematical modeling. analysis of perfomance as affected by volume, and allowable clear wood stresses will assure that this resource is efficently utilized to produce safe timber structures.

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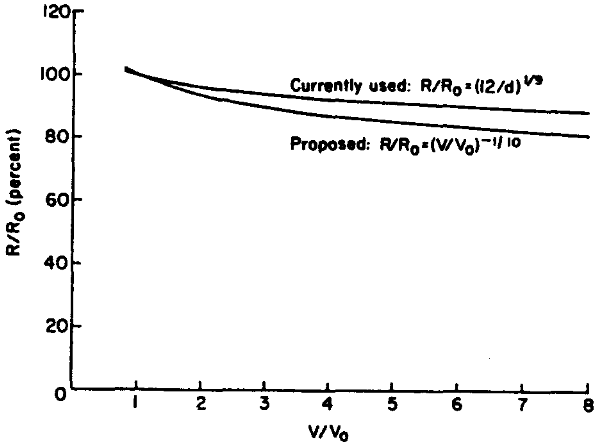

FIG 4: A comparison of currently used size effect and proposed volume effect for glulam beams in bending assuming (1) constant span-depth ratio, (2) constant width for existing size effect. (3) constant width-depth ratio for proposed volume effect, and (4) similar methods of loading. (ML89 5709)

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