PART V: STRUCTURAL GLUED LAMINATED TIMBER

5.1 GENERAL

Background

Glued laminated timber consisting of multiple layers of wood glued together with the grain of all layers approximately parallel began its growth as a significant structural material in the United States in the 1930's. Technology developed in the formulation and use of casein glues to fabricate structural members in wood aircraft during and after World War I was extended to the construction of larger structural framing members used in buildings (62). The resistance of these glues to elevated relative humidities coupled with the use of pressing systems that could provide continuous pressure to all glue lines enabled the manufacture of large beams, arches and other curved shapes with assured durability. The subsequent development of resorcinol and other synthetic resin glues with high moisture resistance expanded the uses of glued laminated timber to bridges, marine construction and other applications involving direct exposure to the weather.

A significant advantage of glued laminated members is the fact they can be made of dry lumber laminations in which the location and frequency of knots and strength reducing characteristics can be controlled. The result is a structural product in which splits, checks and loosening of fasteners associated with drying in service are greatly reduced and relatively high strength is achieved.

The early development of design values for glued laminated timber paralleled that for visually graded lumber (see History at the beginning of the Commentary). The methods published in 1934 in U. S. Department of Agriculture's Miscellaneous Publication 185 for the grading and determination of working stresses for structural timbers (207) were also applied to glued laminated timber. Under these procedures, strength values for small, clear, straight-grained wood were reduced for load duration, variability, size and factor of safety to basic stresses; and then these stresses were further reduced to account for the effects of knots, slope of grain and other characteristics permitted in the grade of lumber being used as laminations. These design values were assigned by the manufacturers to the species and grades of glued laminated timber being produced.

The earliest comprehensive procedures for establishing design values that were specifically developed for glued laminated timber were published in 1939 in U.S. Department of Agriculture Technical Bulletin 691 (208). These procedures provided for the use of lower grades of lumber in the inner laminations than in the outer laminations. A simplified method of establishing design values from basic stresses also was given which was based on use of only two grades of lumber: one allowing knots up to one-fourth the width of the piece and one allowing up to one-eighth the width of the piece.

Design procedures for glued laminated timber were codified as national standards of practice in 1943 as part of the War Production Board's Directive No. 29 (194) and then in 1944 as part of the first edition of the National Design Specification (128). Design values established in the first edition were the same as those for the grade of sawn lumber used (based on the procedures in Miscellaneous Publication 185) except that increases for seasoning were permitted in compression parallel to grain and for all properties except shear parallel to grain when lumber two inches or less in thickness was used. In addition, increases were permitted for constructions in which knot limitations were twice as restrictive as those applicable to inner laminations. The procedures published in 1939 in Technical Bulletin 691 also were allowed as alternative methods.

As a result of research at the Forest Products Laboratory following World War II, new procedures for establishing grades and design values for glued laminated timber were developed (68,209). By closer control and placement of different grades of laminations, the new procedures provided for higher design values than those previously used. Basic design values for both dry and wet service conditions were recommended. Most significantly, a new strength ratio concept of grading laminated members was introduced which has continued in use to the present time. In the case of tabulated bending design values, the relative strength of the member was defined in terms of a near-maximum (99.5 percent exclusion level) I_K / I_G ratio, where I_K is the sum of the moments of inertia about the neutral axis of the full cross section of all knots within a one-foot length of the critical section and I_G is the moment of inertia of the full cross section. In the case of tabulated compression design values parallel to grain and tension design values parallel to grain, relative strength was defined in terms of a near-maximum K/b ratio, where K is the sum of knots in a three-foot length and b is the lamination width. Under this methodology, the larger the I_K/I_G or K/b ratio, the lower the strength ratio for the combination (62).

The regional lumber rules writing agencies used the new Forest Products Laboratory procedures (68) to establish specifications for the design and fabrication of structural glued laminated lumber which provided design values for various species and lamination grade combinations. Design values established by these regional agencies were published in the Specification from 1951 through the 1968 editions.

In 1970, the American Institute of Timber Construction (AITC) assumed responsibility for developing laminating combinations and related design values for glued laminated timber. Beginning with the 1971 edition, the design values established by AITC have been those published in the Specification.

Changes in design values for glued laminated timber over the years largely reflect changes in grades and grade combinations being manufactured. However, certain changes in clear wood property assignments and in lumber design values also were paralleled by changes in related values for glued laminated timber (see Commentary for 4.2.3.2 - Background). One set of changes of note was an approximate 20 percent reduction in tension design values parallel to grain in 1968 and 1971. This adjustment paralleled the establishment of tension strength ratios for visually graded lumber as 55 percent of the corresponding bending strength ratio in 1968. Tension design values parallel to grain for glued laminated timber were further reduced in the 1977 edition on the basis of full-size tension tests of laminated members (36). The additional reduction, up to 37 percent for some species and combinations based on 1971 values, was made at the same time that a further reduction was made in tension design values parallel to grain for the wider widths and lower grades of visually graded lumber (see 4.2.3.2 Commentary).

A second change of note in glued laminated timber design values was the introduction in the 1986 edition of new compression design values perpendicular to grain based on a deformation limit. Previous values for this property were based on proportional limit stresses. A similar change was made in lumber design values in 1982 (see Commentary 4.2.6).

Glued Laminated Timber Product Standard. A national consensus product standard covering minimum requirements for the production of structural glued laminated timber was promulgated as Commercial Standard CS253-63 by the U.S. Department of Commerce in 1963 (189). The standard was revised and repromulgated by the Department as Voluntary Product Standard PS56-73 in 1973 (191). In 1983, the standard was adopted as an American National Standard through American National Standards Institute's (ANSI) consensus process, it is now published as ANSI/AITC A190.1 (9). This product standard includes requirements for sizes, grade combinations, adhesives, inspection, testing and certification of structural glued laminated timber products. Under A190.1, the grade combinations and related design values for glued laminated timber are required to be in conformance to the current editions of two American Institute of Timber Construction specifications: AITC 117 for softwood species (6) and AITC 119 for hardwood species (5).

The provisions of AITC 117 in turn represent implementation of procedures given in ASTM D3737, Standard Test Method for Establishing Stresses for Structural Glued Laminated Timber (24). Procedures embodied in this ASTM standard, first published in 1978, reflect the previously used methodology (68) as modified by data from a succession of more recent full-scale test programs (9). The provisions of AITC 119 for hardwoods are based exclusively on earlier methodology (68).

National Design Specification provisions for glued laminated timber are limited to those products identified as being in conformance with ANSI/AITC A190.1. This consensus standard couples the AITC design and manufacture specifications with the inspection and certification requirements that are necessary to obtain uniform and assured product quality.

5.1.1-Application

5.1.1.1 The design and use of glued laminated timber is similar to that of sawn lumber products. Therefore, the general requirements given in Parts I, II and III of the Specification are applicable to glued laminated timber except where indicated otherwise. Part V of the Specification contains provisions which are particular to glued laminated timber because of the sizes, shapes, moisture content and combinations of grades in a single member employed in the product's manufacture.

The provisions of Part V contain only the basic requirements applicable to engineering design of glued laminated timber. Specific detailed requirements, such as those for curved and tapered members and connection details, are available from the American Institute of Timber Construction (4).

5.1.1.2 Where design values others than those given in Tables 5A, 5B and 5C or as provided in the adjustments and footnotes of these tables are used, it shall be the designer's responsibility to assure that the values have been developed in accordance with all applicable provisions of AITC 117 (6) and AITC 119 (5).

The design provisions in the Specification for glued laminated timber apply only to material certified by an approved agency as conforming to ANSI/AITC A190.1. The local building code body having jurisdiction over the structural design is the final authority as to the competency of the certifying agency and the acceptability of its grademarks.

5.1.2-Definition

The laminations of glued laminated timber usually are made of sawn lumber. Laminated veneer lumber, consisting of graded veneers bonded together with grain parallel longitudinally, and manufactured lumber, lumber of two or more pieces glued together, are occasionally used for tension laminations where high tensile strength is required (9).

Adhesives and glued joints in glued laminated timber members are required to meet the testing and related requirements of ANSI/AITC A190.1.

5.1.3-Standard Sizes

5.1.3.1 Standard finished widths of glued laminated members have been given in the Specification since the 1951 edition. Widths were reduced 1/8 inch for nominal widths of 4 to 6 inches and 1/4 inch for larger widths in the 1971 edition to reflect new dry lumber sizes established in the American Softwood Lumber Standard, PS 20-70 (190). The sizes in the 1971 edition have been continued for western species in the 1991 edition of the Specification except the finished width for nominal 3 inch members which has been increased from 2-1/4 inch to 2-1/2 inch. This change reflects current manufacturing practice wherein laminations of this width are now made by splitting nominal 2 by 6 lumber in half. Also in the 1991 edition, separate smaller finished widths for 4, 6, 10 and 12 inch nominal widths for southern pine members are introduced.

The finished widths of glued laminated timber members are less than the dimensions of surfaced lumber from which it is made in order to allow for removal of excess adhesive from the edges of the laminations and preparation of a smooth surface. This is done by removing from 3/8 to 1/2 inch of the width from the original lumber width by planing or sanding.

Where necessary, other than standard widths can be specified. However, such special widths (for example, 7 inches) will require use of the nominal lumber width (10 inches) associated with the closest larger standard finished size (8-3/4 inches), which results in significant waste. Where appearance is not a factor, larger than standard widths for the smaller sizes can be provided from some manufacturers by use of laminations that have been split or sawn from larger lumber without further edging.

5.1.3.2 The sizes of glued laminated timber are designated by the actual size after manufacture. Depths are usually produced in increments of the thickness of the lamination used. For straight or slightly curved members, this is a multiple of 1-1/2 inches for western species and 1-3/8 inches for southern pine. The faces of southern pine lumber generally are resurfaced prior to gluing, thereby reducing the thickness of this material an additional 1/8 inch. For sharply curved members, nominal 1 inch rather than 2 inch thick lumber is used (4).

When members are tapered, the depth at the beginning and the end of the taper should be designated. In all cases, the length and net cross-section dimensions of all members should be specified.

Glued laminated timbers are usually custom manufactured to the specifications of the user. However, an increasing volume of material is being manufactured as non-custom or stock beams. These members, generally of the smaller widths and depths, are shipped to wholesalers who in turn sell them to builders and other users. The non-custom beams are often shipped in long billets and then cut to the length specified by the end user.

5.1.4-Specification

5.1.4.1 It is the responsibility of the designer to specify the moisture content condition to which the members will be exposed during service (see Commentary for 5.1.5). Although glued laminated timbers are made with dry lumber, the manufacturer needs to know the condition of use in order to select an appropriate adhesive.

Grades of glued laminated timber are specified in terms of laminating combination or the design values required. For members to be loaded primarily in bending about the x-x axis (load applied perpendicular to the wide face of the laminations), combinations given in Table 5A of the Specification should be designated; or the design values associated with those combinations should be cited. For members subject primarily to axial loads (tension or compression), or to bending loads about the y-y axis (loads applied parallel to the wide face of the laminations), combinations given in Table 5B, or associated design values, should be designated.

5.1.4.2 Because laminating grades of hardwood lumber are not generally available, design values for glued laminated members made with hardwood species are established in a different manner than that used to establish values for members made with softwood species. Strength property stress modules for hardwood laminating grades are given in Part B of Table 5C in terms of the ratio of the size of the maximum permitted knot to the finished width of the lamination. These stress modules are multiplied by the species adjustment factors given in Part A of Table 5C to obtain design values for the particular hardwood laminating grade and species being specified. Example C5.1-1 illustrates the application of these adjustment factors.

Example C5.1-1

Consider a hardwood glued laminated member made with 10 laminations of combination B commercial red oak. Design values for the member based on Table 5C are:

Bending:	770 x 2.80 = 2156 or 2160 psi
Tension parallel to grain:	500 x 2.80 = 1400 psi
Compression parallel to grain:	920 x 2.05 = 1886 or 1890 psi
Modulus of elasticity:	1,000,000 x 1.6 = 1,600,000 psi
Horizontal shear:	230 psi
Compression perpendicular to grain:	800 psi

5.1.5-Service Conditions

5.1.5.1 When the equilibrium moisture content of members in service is less than 16 percent, the dry service design values tabulated in Tables 5A, 5B and 5C apply. The dry service condition for glued laminated timber was first defined in the 1951 edition as moisture contents of less than 15 percent. This was changed to less than 16 percent in the 1962 edition and has remained unchanged since that time.

A dry service condition for glued laminated timber prevails in most covered structures. However, members used in interior locations of high humidity, such as may occur in certain industrial operations or over unventilated swimming pools, may reach an equilibrium moisture content of 16 percent or more. In such conditions, wet service factors should be applied to tabulated design values.

5.1.5.2 Glued laminated members used in exterior exposures that are not protected from the weather by a roof, overhang or eave are generally considered wet conditions of use. Bridges, towers and loading docks represent typical wet service applications. Uses in which the member is in contact with the ground should be considered wet use for those portions of the member that will attain a moisture content of 16 percent or more.

Design values for wet service conditions are obtained by adjusting tabulated design values in Tables 5A, 5B and 5C by the wet service factors, C_M, given in these tables. Where wet service conditions apply, the susceptibility of the member to decay and the need for preservative treatment (see Commentary for 2.3.5) should be considered.

5.2-DESIGN VALUES

5.2.1-Tabulated Values

The history of glued laminated timber design values published in the Specification is given in the Commentary for 5.1.

Softwood Species. Design values in Tables 5A and 5B are for members made with softwood species. Values in Table 5A are for laminating combinations that have been optimized for members stressed in bending about the x-x axis (loads applied perpendicular to the wide face of the laminations). Values in Table 5B are for laminating combinations that have been optimized for stresses due to axial loading or to bending about the y-y axis (loads applied parallel to the wide face of the laminations). Because of the mixing of grades to provide maximum efficiency and the necessity of having special tension laminations, values for a given property may vary with orientation of the loads on the member.

Table 5A. Values in this table apply to members having 4 or more laminations and are divided into western species/visually graded, western species/E-rated, southern pine/visually graded and southern pine/E-rated. The combination symbol in the first column designates a specific combination and lay-up of grades of lumber. For example, 16F-V1 under western species indicates a combination with a bending design value, F_b, of 1600 psi (column 3 - tension zone stressed in tension) made with visually graded lumber (V) and is the first such combination listed for western species. In the same format, 24F-E3 under southern pine indicates an F_b of 2400 psi (column 3 - tension zone stressed in tension) made with E-rated lumber and is the third such combination listed for southern pine.

The second column of Table 5A gives a two letter code indicating the species used for the outer laminations and for the core laminations of the member. For example, DF/WW indicates Douglas fir-Larch is used for the outer laminations and any western softwood species or Canadian softwood species is used for the core laminations. The symbol N3 preceding the core lamination species indicates a No. 3 Structural Joist and Plank or Structural Light Framing grade is used.

Design values in columns 3 through 7 of Table 5A apply when the members are loaded perpendicular to the wide face of the laminations. A higher grade of lumber is required in the tension zone of bending members compared to the compression zone, thus a lower grade of lumber is often used in the latter zone of most combinations. Column 3 of Table 5A gives the F_b value for use when the member is loaded as a simple beam with the tension zone in tension. When the combinations of Table 5A are used as simple beams with short overhangs that create tension on the top side of the beam over the support, F_b values in column 4 for the case of the compression zone in tension apply. The compression zone is distinguished from the tension zone of the member by the word "TOP" that is marked on all members except curved members where the top of the member is self evident.

When glued laminated members are used as cantilevered or continuous beams, those combinations which have the same F_b design values in columns 3 and 4 for tension and compression zones stressed in tension generally should be used.

Tabulated compression design values perpendicular to grain, $F_{c\perp}$, depend on the density of the lumber used for the outer laminations. Columns 5 and 6 of Table 5A indicate the applicable $F_{c\perp}$ value for the tension and compression faces of the member respectively.

Tabulated shear design values parallel to grain, F_v, given in column 7 of Table 5A are based on the species of lumber used as the core laminations.

Tabulated modulus of elasticity, E, given in column 8 of Table 5A represent the average value for the combination. These values are considered to have a shear deflection component equivalent to that occurring in a rectangular beam on a span-depth ratio of 21 under uniformly distributed load (see Commentary for 3.5.1). The coefficient of variation of E for glued laminated timber decreases as the number of lamination increases. The approximate coefficient of variation of E is 0.10 for members of 6 or more laminations.

Design values in columns 9 through 13 of Table 5A apply when members are loaded in bending parallel to the wide face of the laminations. The F_b values in column 9 for bending about the y-y axis are lower than those in column 3 for bending about the x-x axis because of the influence of the lower grade core and compression zone laminations and the lower strength species used in the core laminations of some combinations.

Tabulated compression design values perpendicular to grain, $F_{c\perp}$, given in column 10 of Table 5A represent the lowest species and grade value applicable to any lamination used in the combination.

Tabulated shear design values parallel to grain, F_v, given in column 11 represent the average value of all laminations in the combination reduced by the possibility of an accumulation of seasoning checks that could occur through the wide faces of the laminations.

Tabulated shear design values parallel to grain given in column 12 apply to members manufactured with multiple piece laminations that are not edge glued. For example, a nominal 6-inch wide piece of lumber (5-1/2 net) may be placed beside a nominal 8-inch wide piece (7-1/2 net) to form a lamination 12-3/4-inches wide which eventually is surfaced to a 12-1/4-inch finished width. The nominal 6-inch and 8-inch wide pieces are alternated in the assembly so that the openings between the pieces are not aligned. When the edges between the pieces are not glued, as is the usual practice, only one-half the cross-section is effective in resisting shear parallel to grain. The design values in column 12 reflect this reduced shear area.

Tabulated modulus of elasticity values for bending about the y-y axis in column 13 are lower than those for bending about the x-x axis because of the greater influence of the species and lower grade laminations in the core.

Tabulated tension design values parallel to grain, F_t, and compression design values parallel to grain, F_c, given in columns 14 and 15 of Table 5A are strongly influenced by the lower strength species and grades of lumber used in the core laminations. The combinations given in Table 5B provide more efficient values for these properties.

Although there is a slight difference in the modulus of elasticity in bending about the y-y axis and that in axial loading, axial load E values given in column 16 have been set equal to the y-y bending design values in column 13 for purposes of simplicity.

Table 5B. Design values in this table are for combinations intended primarily for resisting axial loads or for bending about the y-y axis. Each combination consists of a single grade of one species of lumber. The grade associated with each numbered combination can be obtained from the referenced AITC specification (6).

Compression design values parallel to grain, bending design values and shear design values parallel to grain vary with the number of laminations. Differences reflect the relative probability of maximum permitted knots occurring in the same critical section of each lamination or the probability of an accumulation through the member of checks occurring across the wide face of the laminations. Shear design values parallel to grain for members with multiple piece laminations reflect the absence of edge gluing between such pieces (see Table 5A discussion in Commentary for 5.2.1).

Tabulated bending design values, F_b, in column 15 are for members up to 15 inches deep made of 2 or more laminations. Values are for members without tension grade laminations. Bending design values in column 16 for members with 4 or more laminations apply when tension grade laminations are used. If such laminations are not used, tabulated values should be reduced 25 percent.

Table 5C. Hardwood lumber laminating grades are not generally available and therefore design values for combinations of such grades have not been established. Design values for glued laminated members made with hardwood lumber are determined by multiplying stress modules for a specific knot size to lamination width ratio in Part B of Table 5C times the applicable species strength factors given in Part A of the table (see Commentary for 5.1.4.2).

5.2.2-Radial Tension, F_{rt}

Because of undetectable ring shake and checking and splitting that can occur as result of drying in service, very low tension design values perpendicular to grain can be encountered in commercial grades of lumber. For this reason, design values for this property are not published in the Specification (see Commentary for 3.8.2).

Radial tension stresses, however, are induced in curved and pitched and tapered glued laminated timber members when bending loads tend to flatten out the curve or increase the radius of curvature. These stresses must be accounted for in design.

Glued laminated timber beams are made of dry material which is controlled for quality, including seasoning defects, during manufacture. The Specification has provided limiting stresses for actual radial tension in glued laminated members since the 1944 edition. The earliest editions limited allowable radial tension design values perpendicular to grain to a maximum of 2-1/2 percent of the applicable sawn lumber tabulated bending design value for softwoods and 4 percent of this value for hardwoods. For softwood lumber grades available at the time, this provision resulted in maximum radial tension design values perpendicular to grain of approximately 30 to 60 psi.

In the 1951 edition of the Specification, the limiting radial tension design value perpendicular to grain was established as 1/3 the corresponding shear design value parallel to grain for all species. This provision was based on strength data for small, clear specimens free of checks and other seasoning defects (20). As a result of field experience, the radial tension design value perpendicular to grain for Douglas fir-Larch under other than wind and earthquake loading was limited to 15 psi in the 1968 edition. For wind and earthquake loads for this species group and all loadings on other species, the limit on allowable radial tension design value perpendicular to grain of 1/3 the shear design value parallel to grain was retained. Also in the 1968 edition, a provision was added that waived all design value limits when mechanical reinforcement was designed to carry all actual radial tension stress.

In 1977, the general waiver for mechanical reinforcement was eliminated. However, when mechanical reinforcement or all vertical grain laminations was used, allowable radial tension design values perpendicular to grain of 1/3 the shear design value parallel to grain was allowed for Douglas fir-Larch under all types of loading. These radial tension design value provisions were carried forward through the 1986 edition.

In the 1991 edition, the vertical grain alternate for Douglas fir-Larch was discontinued because of the reduced availability of vertical grain material. The previous provisions limiting radial tension design values perpendicular to grain for Douglas fir-Larch under loads other than wind and earthquake to 15 psi, or the use of mechanical reinforcement for such loads up to 1/3 the shear design value parallel to grain (see 5.4.1.2

of Specification), have been extended to all western softwood species. For Southern Pine under all types of loading, and for all other softwood species under wind and earthquake loading, radial tension design values perpendicular to grain continue to be limited to 1/3 the shear design value parallel to grain. The allowable radial tension design value provisions in the 1991 edition are supported by both test results (30,155) and experience.

In calculating values of F_{rt}', the appropriate tabulated F_v value obtained from Tables 5A and 5B is to be modified by all adjustment factors specified in Table 2.3.1 that are applicable to glued laminated timber.

5.2.3-Other Species and Grades

(See Commentary on designer responsibility under 5.1.1.2)

5.3-ADJUSTMENT OF DESIGN VALUES

5.3.1-General

All adjustment factors specified in Table 2.3.1 of the Specification are applicable to one or more of the design values for glued laminated timber given in Tables 5A, 5B and 5C except size factor, C_F, repetitive member factor, C_r, and buckling stiffness factor, C_T.

5.3.2-Volume Factor, C_V

Background

Size or depth adjustment of bending design values for glued laminated timber members has been a provision of the Specification since the 1957 edition (see Commentary for 4.3.2.2). From the 1957 through the 1968 editions, this adjustment for beams over 12 inches deep was made by the following relationship:

$$C_F = 0.81\left(\frac{d^2 + 143}{d^2 + 88}\right) \qquad \text{(C5.3-1)}$$

The size equation was changed in the 1971 edition to

$$C_F = \left(\frac{12}{d}\right)^{1/9} \qquad \text{(C5.3-2)}$$

This revised equation, based on tests of beams one inch to 32 inches deep (33) and introduced into ASTM D245 in 1968 (14), was continued unchanged through the 1986 edition. Adjustments from the equation were applicable to a simply supported beam, uniformly loaded on a span/depth ratio of 21.

In 1973, loading coefficients for modifying the size adjustment of design values for glued laminated beams to concentrated and third point loading conditions were introduced. The coefficients, derived from the bending moment diagrams associated with each condition and the relative span lengths subject to the highest moment levels, were of the order 1.00 uniform, 1.08 concentrated and 0.97 third point. These loading coefficients also were carried forward to the 1986 edition.

1991 Provisions. The volume factor adjustment for glued laminated beams in the 1991 edition includes terms for the effects of width and length as well as depth. The volume factor (C_V) equation, based on recent research involving tests of beams 5-1/8 and 8-3/4 inches wide, 6 to 48 inches deep and 10 to 68 feet in length (118), is

$$C_V = K_L(21/L)^{1/x}(12/d)^{1/x}(5.125/b)^{1/x} \le 1.0 \qquad \text{(C5.3-3)}$$

in which:

K_L = loading condition coefficient
L = length of bending member between points of zero moment, feet
d = depth of bending member, inches
b = width (breadth) of bending member, inches. For multiple piece width layups, b = width of widest piece used in the layup. Thus, $b \le 10.75"$.
x = 20 for southern pine
= 10 for all other species

The foregoing equation is based on the volume effect equation given in ASTM D3737 (24) except that the width effect exponent for other species was changed to 1/10 from 1/9 for simplicity and to reflect the accuracy of the data, and a separate coefficient of 1/20 was established for southern pine based on recent large beam tests of that species (7).

As indicated by the equation, tabulated F_b values given in Tables 5A, 5B and 5C apply to members that are 5-1/8 inches wide, 12 inches deep and 21 feet long. When any other sizes are used, tabulated values are to be adjusted by multiplying by the volume factor, C_V.

The loading condition coefficients of 1.09 for concentrated load at mid span and 0.96 for two equal loads at the third points given in the 1991 edition are slightly different than the comparable values given in previous editions as a result of a change in the method of calculation of these values (7).

As indicated in footnote 1 to Table 2.3.1, the volume factor, C_V, is not applied simultaneously with the beam stability factor, C_L. The smaller of the two adjustment factors applies. This provision is a continuation of the practice introduced in the 1968 edition of the Specification of considering stability and size modifications separately. The practice is based on design experience and the position that beam buckling is associated with stresses on the compression side of the beam whereas bending design values and the effect of volume on such values are related primarily to the properties of the laminations stressed in tension.

5.3.3-Flat Use Factor, C_{fu}

Adjustment of bending design values for glued laminated beams loaded parallel to the wide face of the laminations when the wide face of the laminations is less than 12 inches was a footnote provision to Table 5B in the 1982 and 1986 editions of the Specification. Now tabulated as flat use factors, C_{fu}, in the front of both Tables 5A and 5B, the adjustments are based on equation C5.3-2, which is the 1/9 power size equation of ASTM D245.

5.3.4-Curvature Factor, C_c

When the individual laminations of glued laminated timber members are bent to shape in curved forms, bending stresses are induced in each lamination that remain after gluing. In addition, the distribution of stresses about the neutral axis of curved members is not linear. The curvature factor, C_c, is an adjustment of tabulated bending design values, F_b, to account for the effects of these two conditions.

The curvature factor equation given in 5.3.4 is based on early tests (208) and has been a provision of the Specification since the 1944 edition. The limits on the ratio of lamination thickness to radius of curvature of 1/100 for southern pine and hardwoods and 1/125 for other softwood species are imposed to avoid overstressing or possible breaking of the laminations.

Radii of curvature used in practice generally are larger than those allowed by the specified minimum thickness/radius of curvature ratios. For nominal 1 inch thick material, 3/4 inch net, radii of curvature of 7 feet and 9.3 feet are typically used with southern pine and other softwood species, respectively. For nominal 2 inch material, 1.5 inches net, a radius of curvature of 27.5 feet commonly is used for all species.

5.4-SPECIAL DESIGN CONSIDERATIONS

5.4.1-Radial Stress

5.4.1.1 The equation for determining actual radial stress in a curved member of constant rectangular cross section, which is based on research published in 1939 (208), has been a provision of the Specification since the 1951 edition. Although limited to members of constant rectangular cross section, subsequent design practice was to employ the same equation for calculating actual stresses in tapered cross sections. However, new research showed that actual radial stresses in curved tapered members had to be determined by different procedures (67). Such new methodology for curved members having variable cross section was introduced in the 1973 edition and continued through the 1986 edition. This methodology consisted of applying a modification factor, derived from the ratio of member depth to radius of curvature and the slope of the upper edge of the member, to the actual stress based on the constant cross section equation.

More recent research has shown that additional modification factors are needed to establish bending design values and deflection as well as radial tension design values perpendicular to grain of pitched and tapered bending members (80). It was concluded that the design procedures required were too complex for inclusion in the Specification. Thus design methodology for radial stresses in curved bending members of varying cross section has been removed from the 1991 edition. Complete design procedures for such members are available from other authoritative sources (4).

5.4.1.2 When the bending moment acts to reduce curvature, the actual radial stress is to be checked against the allowable radial tension design value perpendicular to grain, F_{rt}', which includes all adjustment factors applicable to tabulated shear design values parallel to grain. (See Commentary for 5.2.2 for background on allowable radial tension design values perpendicular to grain and mechanical reinforcement requirement.)

5.4.1.3 Actual radial stress is checked against the allowable compression design values perpendicular to grain when the bending moment acts to increase beam curvature. As shown by the tabulated design values for this property in Tables 5A and 5B, actual radial compression stress seldom controls design when it occurs.

5.4.2-Lateral Stability for Glued Laminated Timber

5.4.2.1 Bending design values, F_b, given in Tables 5A, 5B and 5C are based on members having a compression edge supported throughout its length or having a depth to breadth ratio of one or less. When these conditions do not exist, F_b values are to be adjusted by the beam stability factor, C_L, calculated in accordance with the procedures of 3.3.3. As the tendency of the compression portion of the beam to buckle is a function of beam stiffness about the y-y axis (bending due to loading parallel to the wide face of the laminations), all glued laminated beam stability factor calculations are to be made with values of modulus of elasticity for bending about the y-y axis, E_{yy}, modified by all applicable adjustment factors.

In determining the adequacy of lateral support, decking or subflooring applied directly to a beam with two or more fasteners per piece is acceptable edge restraint for a beam loaded through such decking or subflooring. Rafters, joists or purlins attached two feet or less on center to the side of a beam and stabilized through the attachment of sheathing or subflooring are acceptable edge restraint for a beam that is loaded through such rafters, joists or purlins. Recent research has shown that the bottom edges of rafters, joists or purlins attached to the sides of beams by strap hangers or similar means do not have to be fixed to provide adequate lateral support to the beam if their top edges are restrained (205, 206).

5.4.2.2 The depth to breadth limitations for laterally supported arches have been a provision of the Specification since the 1977 edition. These rules are good practice recommendations based on field experience over many years.

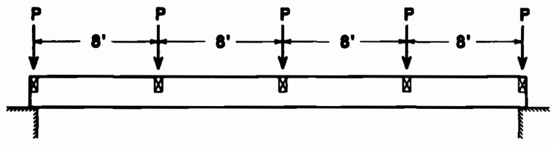
5.4.3-Deflection

(See Commentary for 3.5 and 5.2.1 - Table 5A, modulus of elasticity.)

Example C5.4-1 illustrates the use of design procedures outlined in the Specification for design of a glued laminated timber member.

Example C5.4-1

Design a simple beam spanning 32 ft, with 5000 lb loads (1000 lb DL + 4000 lb SL) applied by purlins at 8 ft on center (1/4 points plus ends). Member has lateral support at the ends and on the compression edge by the purlins. Beam supports are 6 in. long. Assume dry service conditions. Temperature is less than 100°F but occasionally may reach 150°F. Use 24F-V1 Southern Pine glued laminated timber.



$C_D = 1.15$ $C_M = 1.0$ $C_t = 1.0$ (Table 5A and 2.3.1)

$F_b = 2400$ psi $F_v = 200$ psi $F_{c\perp\ compression} = 560$ psi

$F_{c\perp\ tension} = 650$ psi $E_{yy} = 1{,}500{,}000$ psi

$E_{xx} = 1{,}700{,}000$ psi

Bending (3.3.3, 5.3.2)

$F_b^* = F_b C_D C_M C_t = (2400)(1.15)(1.0)(1.0) = 2760$ psi

$\ell_u = 8$ ft

$\ell_e = 1.54\ell_u = 1.54(8) = 12.32$ ft (Table 3.3.3)

The slenderness factor, R_B, must be determined. Since dimensions are unknown a trial design will be estimated and modified as needed. Try a 5 × 30-1/4 beam, $S_{xx} = 762.6$ in^3

Beam Stability Factor, C_L

$$R_B = \sqrt{\frac{\ell_e d}{b^2}} = \sqrt{\frac{(12.32)(12)(30.25)}{(5)^2}} = 13.375$$

$$K_{bE} = 0.609$$

$$F_{bE} = \frac{K_{bE}E'}{R_b{}^2} = \frac{(0.609)(1{,}500{,}000)}{(13.375)^2} = 5107 \text{ psi}$$

$$C_L = \frac{1+(F_{bE}/F_b^*)}{1.9} - \sqrt{\left[\frac{1+(F_{bE}/F_b^*)}{1.9}\right]^2 - \frac{F_{bE}/F_b^*}{0.95}}$$

$$= \frac{1+5107/2760}{1.9} - \sqrt{\left[\frac{1+5107/2760}{1.9}\right]^2 - \frac{5107/2760}{0.95}}$$

$$= 0.950$$

Volume Factor, C_V

$$C_V = K_L(21/L)^{1/x}(12/d)^{1/x}(5.125/b)^{1/x} \leq 1.0$$

Assume $K_L = 1.0$; load condition approaches uniform load

x = 20 for Southern Pine

(cont.)

Example C5.4-1 (cont.)

$C_V = (1.0)(21/32)^{1/20}(12/30.25)^{1/20}(5.125/5)^{1/20} = 0.936$

$C_V < C_L$, therefore C_V applies

Allowable Bending Design Value, F_b' (Table 2.3.1)

$$F_b' = F_b C_D C_M C_t C_V = (2400)(1.15)(1.0)(1.0)(0.936) = 2583 \text{ psi}$$

Determine Section Modulus Required by Bending

Assume weight of glued laminated timber = 40 lb/ft

Purlin loads = P (three at 1/4 points) = 5000 lb

$$M_{est.} = P(\ell/2) + w\ell^2/8 = (5000)(32/2)(12)+(40)(32)^2(12)/8 = 1{,}021{,}440 \text{ in-lb}$$

$$S_{required} = M/F_b' = 1{,}021{,}440/2583 = 395.45 \text{ in}^3 < 762.6 \text{ in}^3$$

Try a 5 x 22 member, $S_{xx} = 403.33$ in^3, $I_{xx} = 4437$ in^4

$$R_B = \sqrt{\frac{\ell_e d}{b^2}} = \sqrt{\frac{(12.32)(12)(22)}{(5)^2}} = 11.41$$

$$F_{bE} = \frac{K_{bE}E'}{R_b^2} = \frac{(0.609)(1{,}500{,}000)}{(11.41)^2} = 7022 \text{ psi}$$

$$C_L = \frac{1+7022/2760}{1.9} - \sqrt{\left[\frac{1+7022/2760}{1.9}\right]^2 - \frac{7022/2760}{0.95}} = 0.970$$

$C_V = (1.0)(21/32)^{1/20}(12/22)^{1/20}(5.125/5)^{1/20} = 0.951$

$C_V < C_L$, therefore C_V controls

Allowable Bending Design Value, F_b' (Table 2.3.1)

$$F_b' = F_b C_D C_M C_t C_V = (2400)(1.15)(1.0)(1.0)(0.951) = 2625 \text{ psi}$$

With a beam weight of 30 lb/ft for a 5x22 beam

$$M = (5000)(32/2)(12)+(30)(32)^2(12)/8 = 1{,}006{,}080 \text{ in-lb}$$

$$S_{required} = M/F_b' = 1{,}006{,}080/2625 = 383.27 \text{ in}^3 < 403.33 \text{ in}^3 \quad \textbf{ok}$$

A 5 x 20-5/8 member, $S_{xx} = 354.5$ in^3, is too small.

Use 5 x 22 beam

Shear (3.4)

The loads from the purlins at the supports are within a distance d of the face of the supports and can be neglected for shear (3.4.3.1 (a)).

$$V_{purlins} = 3P/2 = (3)(5000)/2 = 7500 \text{ lb}$$

Assuming a beam weight of 30 lb/ft and neglecting loads within a distance d of the support

$$V_{beam} = w(\ell/2 - (d + 1/2\ support)) = (30)(32/2 - (22 + 6/2)/12) = 418 \text{ lb}$$

$$V_{total} = V_{beam} + V_{purlins} = 418 + 7500 = 7918 \text{ lb}$$

Allowable Shear Design Value Parallel to Grain, F_v' (Table 2.3.1)

$$F_v' = F_v C_D C_M C_t = (200)(1.15)(1.0)(1.0) = 230 \text{ psi}$$

Actual Shear Stress Parallel to Grain, f_v (3.4.2)

$$f_v = \frac{3V}{2bd} = \frac{(3)(7918)}{(2)(5)(22)} = 108 \text{ psi} < F_v' = 230 \text{ psi} \quad \textbf{ok}$$

Bearing Perpendicular to Grain (3.10.2)

The purlin on the wall side of the beam transmits all of the load to the end of the beam. The purlin load at the support is included in determining load in bearing perpendicular to grain at the support (6 in. supports):

$$R_{purlins} = P + 3P/2 = 5000 + (3)(5000)/2 = 12{,}500 \text{ lb}$$

Assuming the weight of the beam as 30 lb/ft over the full length of the beam (end-to-end)

$$R_{beam} = w(\ell + 2(1/2\ support))/2 = 30(32+2(6/2)/12)/2 = 488 \text{ lb}$$

$$R_{total} = R_{purlins} + R_{beam} = 12{,}500 + 488 = 12{,}988 \text{ lb}$$

$$F_{c\perp}' = F_{c\perp\,tension} C_M C_t C_b = (650)(1.0)(1.0)(1.0) = 650 \text{ psi}$$

$$f_{c\perp} = 12{,}988/(5)(6) = 433 \text{ psi} < F_{c\perp}' = 650 \text{ psi} \quad \textbf{ok}$$

The purlins are held by hangers that hold 2 purlins, one on each side of the beam. The area required under the hanger on top of the beam is

$$A = P/F_{c\perp\,compression} = 5000/560 = 8.93 \text{ in}^2$$

A 3 in. wide hanger is more than adequate. Note: the design value, $F_{c\perp}$, for the compression edge may be increased by the use of the bearing area factor (C_b) in 2.3.10 when the length of bearing along the grain is less than 6 in. and not nearer than 3 in. to the member end. For a 3 in. wide strap on the compression edge, $F_{c\perp}' = (1.13)(560) = 633$ psi.

At this stage of the calculations, the span of the beam can be reviewed. The 32 ft span used in the trial calculations was based on the distance from center to center of supports as is customary. The length of the span to use in design is the distance from face to face of supports plus 1/2 the required bearing length at the ends (see 3.2.1). In this example, the distance between the inside faces is 32 ft - 6 in. = 31.5 ft. The required length of bearing on the wall end of the beam is 12,988/(5)(650) = 4.00 in. At the

(cont.)

Example C5.4-1 (cont.)

interior end, half of the purlin load is assumed to be transferred to the beam end. Required length in bearing = (2500+7500+488)/(5)(650) = 3.23 in. These required bearing lengths give a span length of 31.5 + (4.00/2)/12 + (3.23/2)/12 = 31.8 ft. This reduces the moment less than two percent, which is not enough to permit the use of the next smaller size beam. In some cases, however, the change in length may permit a change in size of the member.

Deflection (5.4.3)

The Specification does not give specific deflection limitations for roofs. In some applications, deflection may be critical and the designer may wish to limit deflection. Usually the average E in Tables 5A, 5B or 5C is used. However, the modulus of elasticity to the 5th or some other percentile, may be needed for some calculations. The customary engineering equations are used to determine bending deflection, but the designer may wish to include shear deflection as well. Ordinarily, the latter is small and is not considered.

Dead load deflection is usually calculated to determine the desired camber of the beam. The camber usually recommended is 1.5 x dead load deflection.

Deflection for three 5000 lb concentrated loads at the 1/4 points plus the 30 lb/ft beam weight is

$$\Delta_{total} = \frac{19P\ell^3}{384EI} + \frac{5w\ell^4}{384EI}$$

$$= \frac{(19)(5000)((32)(12))^3}{(384)(1{,}700{,}000)(4437)} + \frac{(5)(30/12)((32)(12))^4}{(384)(1{,}700{,}000)(4437)}$$

$$= 1.857 + 0.094 = 1.951 \text{ in.}$$

$1.951/(32)(12) = 1/x \quad x = 197$

Total Deflection = $\ell/197$ of the span which is reasonable

$\Delta_{dead\ load} = (1000/5000)(1.857) + 0.094 = 0.465$ in.

Camber = 1.5 $\Delta_{dead\ load} = (1.5)(0.465) = 0.698$

Use Camber = 3/4 in.

Southern Pine 24F-V1 5x22 glued laminated member satisfies NDS design criteria