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STANDARD PRACTICE FOR THE DERIVATION OF DESIGN PROPERTIES OF STRUCTURAL GLUED LAMINATED TIMBER IN THE UNITED STATES

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Standard Practice for the Derivation of Design Properties of Structural Glued Laminated Timber in the United States

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Abstract

Structural glued laminated timber (Glulam) has been used in North America for more than 70 years. The design properties for glulam when manufactured with a recognized manufacturing standard, such as the *American National Standard for Structural Glued Laminated Timber*, ANSI AI90.1, are typically derived in accordance with ASTM D 3737, *Standard Practice for Establishing Allowable Properties for Structural Glued Laminated Timber*.

ASTM D 3737 itself is an analytical model based on the "I_K/I_G" model established in 1954 through extensive research conducted by the US Forest Products Laboratory in Madison, Wisconsin. In addition to the bending strength, other design properties of glulam, such as modulus of elasticity, shear, compression parallel to grain, and compression perpendicular to grain, can be calculated using ASTM D 3737 when the glulam layup (grade combination) is defined. As compared to European practice, ASTM D 3737 represents a different perspective in assigning glulam design values, which is well supported by years of practical experience in North America and thousands of confirming full-scale beam tests. One of the differences is the fact that ASTM D 3737 and ANSI A190.1 are based on using the strength reducing characteristics of the laminating grades as the basis for assigning design properties and then requiring the use of an equivalent end joint strength to support these properties.

In addition, the ASTM D07 Committee on Wood is currently balloting a new standard that will permit the establishment of design bending stress and stiffness based on full-scale flexural tests. This paper describes the standard practice for the derivation of design properties of glulam in the United States based on both analytical and empirical approaches. This information provides alternative methods to the existing European practice in assigning glulam design values. Understanding the differences between the European and US practice could help facilitate the development and harmonization of glulam standards that are being developed in countries such as China and Taiwan as well as for ISO standards currently under development.

1. Introduction

While structural glued laminated timber (glulam) has been used in Europe for over 100 years, it was first introduced into the United States (U.S.) in 1935 with the first structure being a research laboratory at the U.S. Forest Products Laboratory in Madison WI. This structure used Tudor arches as the primary structural framing elements and is still in service today, even enduring the effects of a serious fire.

Since this first application, glulam has grown to be an approximately 500 million board foot per year industry in the U.S. Approximately 60% of all glulam produced in the U.S. is used in residential framing as shown in Figure 1. Residential framing applications include glulam headers over door and window openings, garage door headers, floor beams, roof rafters and ridge beams. While some of these applications take advantage of the aesthetics associated with glulam by exposing them, the majority of these end uses are in concealed applications. Nonresidential uses include churches, schools, warehouses, recreational facilities, retail, office buildings, chemical storage plants and others and are often exposed in the finished structure. Therefore, while the use of glulam is often predicated on its inherent aesthetic features, in all cases, the key to the final selection of glulam is its inherent strength, durability, integrity and unquestioned quality.

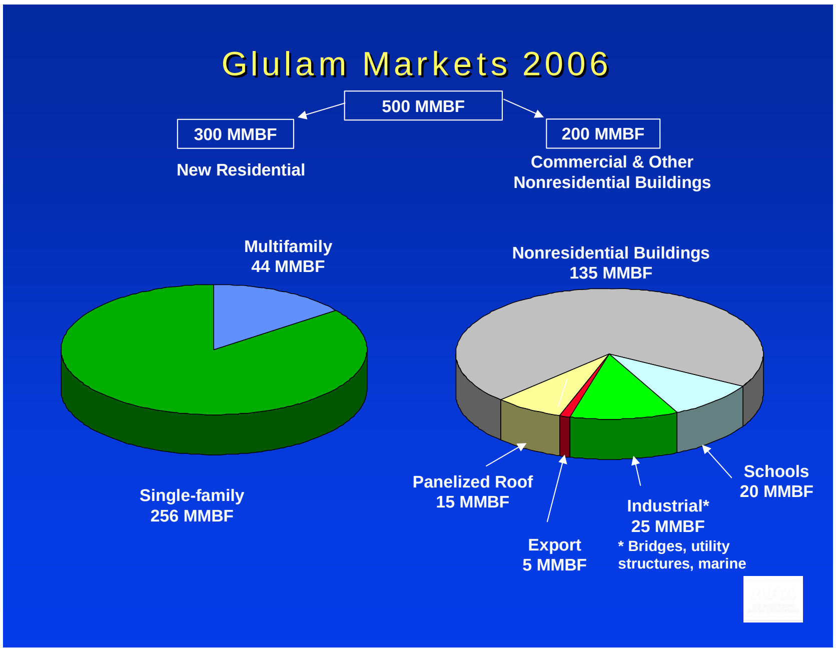

Figure 1

In 2000, the U.S. combined its three regional building codes into the International Building Code, IBC (primarily applicable to engineered construction such as non-residential) and the International Residential Code, IRC (primarily applicable to prescriptive residential construction). Both of these codes require that all glulam be trademarked as being in conformance with ANSI A190.1, “Structural Glued Laminated Timber” [1] and Section 4.3.6 of this standard requires that grade combinations for glulam be developed in accordance with ASTM D3737 “Standard Practice for Establishing Allowable Properties for Structural Glued Laminated Timber” [2] or shall be obtained by performance testing and analysis in accordance with recognized standards.

2. Early Glulam Research

Since glulam was a new product in the U.S., the US Forest Products Laboratory (FPL) in Madison, WI undertook a series of extensive tests on glulam arches beginning in 1934. This included tests of glulam to check for such factors as design formulas, working stresses and the effect on strength of curvature, end joints and knots and was reported in USDA Technical Bulletin 691, “The Glued Wooden Arch” [3]. With the great demand during

World War II for heavy timbers, the development of glued laminated timbers was greatly hastened and significant research was conducted in the areas of adhesives, lumber quality and the testing of full-size laminated beams and columns to supplement and confirm the work reported in Technical Bulletin 691. This work was published in USDA Technical Bulletin 1069, "Fabrication and Design of Glued laminated Wood Structural Members" [4] and formed the basis for the development of characteristic design stresses for glulam which is still used today.

The basic premise of Technical Bulletin 1069 is that the strength of glued laminated timber is dependent on the knot characteristics and their distribution in the glulam member. This led to the development of the "I_K/I_G" model that forms the basis for ASTM D3737 This standard has undergone numerous changes over the years including (a) incorporating provisions for using full-scale beams tests to determine flexural and horizontal shear properties, (b) adding special provisions for tension laminations and (c) introducing the volume effect factor with the current version of the standard being D3737-06.

It is important to note that in addition to being the basis for D3737, Technical Bulletin 1069 was also the predecessor of the manufacturing and fabrication requirements for glulam used today in the U.S. The first manufacturing standard for glulam was U.S. Department of Commerce Commercial Standard CS 253-63 published in 1963 and it was subsequently revised and published as Department of Commerce Standard, PS 56-73. At the same time it was also promulgated as ANSI Standard A190.1-1973, and this has been superseded by A190.1-1983, A190.1-1992 and the current version of A190.1-2002.

3. ASTM D3737

3.1 Introduction

Since ASTM D373 is relatively complicated, this paper will only address the determination of allowable bending stresses for a glulam member loaded on the X-X axis. The basic concept of D3737 is that clear wood strength properties and their expected variation for small clear, straight-grained specimens of green lumber based on ASTM D 2555 [5] can be used to develop stress index values for the various strength properties. For example, for a bending member loaded on the X-X axis, the bending stress index can be determined by calculating the fifth percentile of modulus of rupture in accordance with Test Methods D 2555, multiplying by an appropriate adjustment factor and multiplying by 0.743 to adjust to a 12-in. (30 cm) deep, uniformly loaded simple beam with a 21:1 span-to-depth ratio. As an alternative, results of testing and analysis of large glued laminated timber beams of Douglas Fir-Larch, Southern Pine and Hem-Fir are also used to establish stress indexes.

These stress indexes are then multiplied by stress modification factors developed based on the effects of strength reducing characteristics of knots, slope of grain and density. For example, the bending stress modification factor for knots, ($SMF_{bx\ knots}$) is given by the equation,

$$SMF_{bx\ knots} = (1 + 3\frac{I_K}{I_G})\ (1 - \frac{I_K}{I_G})^3\ (1 - \frac{I_K}{2I_G}) \quad (1)$$

3.2 I_K/I_G Analysis

The “I_K/I_G” analysis that forms the basis for D3737 is based on determining how strength reducing characteristics including knot sizes and slope of grain of the individual laminations and their distribution within the glulam member affect the overall strength of the finished glulam. The following definitions are used.

Ik is the sum of the moments of inertia of the cross sectional areas of all knots within 6 inches (150 mm) of a single cross section at the 99.5 percentile

Ig is the moment of inertia of the full of gross cross section

X-bar is defined as the average of the sum of all knot sizes within any 1-ft length along the piece of lumber

h is the difference between the 99.5 percentile knot size and X-bar

Thus, it is necessary to define the knot characteristics, X-bar and h, for all combinations of species and lumber grades to apply the “I_K/I_G” principles. Annex A6 of D3737 provides guidance on the determination of these knot dependent values. There are 8 types of knots that are measured and these are shown in Figure 2. Note that there is no knot type 8 by committee decision. All knots of 3/8” (6 mm) or greater are measured and the projected cross-sectional area for each knot type is determined.

Any linear regression routine that determines the parameters of the regression line and the value of the 99.5 percentile can be used to emulate the procedure of plotting the sum of knots cumulative frequency data on arithmetical probability paper and drawing a straight line through the data, which was the method used in USDA Bulletin 1069. The underlying assumption for using this procedure is that an analysis, which handles the knot data as normally distributed, is satisfactory.

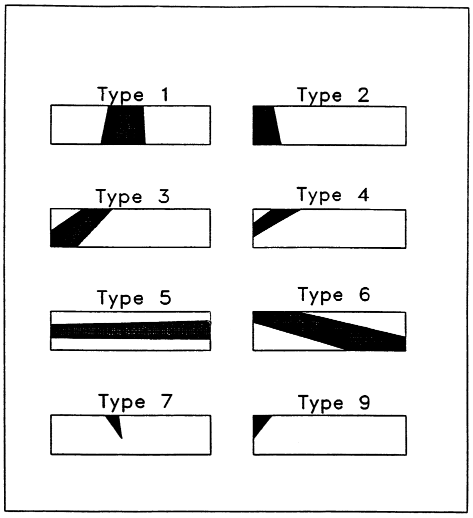

Figure 2

The following steps summarize the provisions of Annex A4 of D3737 to determine the allowable flexural design stress (F_{bx}) for horizontally laminated beams assuming the use of several zones based on different grades and or species of laminating lumber throughout depth of the member. This can be used for symmetric layups or for unsymmetric layups such as shown in Figure 3. Note that the grade combination in Figure 3 for a six-zone beam also shows that different species as well as different lumber grades can be intermixed.

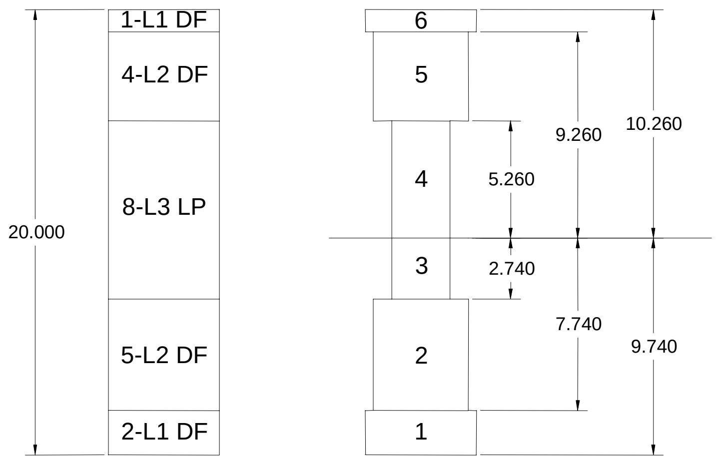

Figure 3

1. The location of the neutral axis of the transformed section is determined using Equation (2), and the distance from the neutral axis to the edges of each grade zone in the beam is determined using Equations (3) and (4).

$$\bar{y} = \frac{\sum_{j=1}^{n_1}\left[\frac{E_j}{2}\left(y_j^2 - y_{(j-1)}^2\right)\right]}{\sum_{j=1}^{n_1}\left[E_j\left(y_j - y_{(j-1)}\right)\right]} \qquad (2)$$

where: $\bar{y}$ = distance from bottom of beam to neutral axis
E_j = long span modulus of elasticity for *j*th zone
y_j = distance from bottom of beam to top of *j*th zone
$y_{(j-1)}$ = distance from bottom of beam to bottom of *j*th zone
n_1 = total number of zones in beam

$$N_j = \left(y_j - \bar{y}\right) \qquad (3)$$

$$N_{(j-1)} = \left(y_{(j-1)} - \bar{y}\right) \qquad (4)$$

where: N_j = distance from neutral axis to upper edge of *j*th zone
$N_{(j-1)}$ = distance from neutral axis to lower edge of *j*th zone

2. The transformed moment of inertia for each zone about the neutral axis is calculated using Equation (5), and the moment of inertia of the transformed section is calculated using Equation (6).

$$I_j = b\left(\frac{E_j}{E_T}\right)\frac{\left(N_j^3 - N_{(j-1)}^3\right)}{3} \qquad (5)$$

where: I_j = transformed moment of inertia of *j*th lam about neutral axis

E_T = modulus of elasticity of transformed section
b = un-transformed width of laminations

$$I_T = \sum_{j=1}^{n_1} I_j \tag{6}$$

where: I_T = transformed moment of inertia of the section

3. The moment of inertia of the un-transformed (gross) section is calculated using Equation (7).

$$I_g = \frac{bD^3}{12} \tag{7}$$

where: I_g = gross moment of inertia of the section
D = depth of the section

4. An I_K/I_G ratio is calculated for each zone using Equation (8).

$$\left(\frac{I_k}{I_g}\right)_j = \frac{\sum_{i=1}^{j}\left(x_i\left(\frac{E_i}{E_j}\right)(O_i)\right) + \sqrt{\sum_{i=1}^{j}\left(h_i^2\left(\frac{E_i}{E_j}\right)^2(P_i)\right)}}{2d_j^3} \tag{8}$$

where: x_j = the average knot size, expressed in decimal fraction of width, for the grade of lamination in the *j*th zone
h_j = the difference between the 99.5 percentile and average knot size, expressed in decimal fraction of the width, for the grade of lamination in the *j*th zone
d_j = the distance between the outermost edge of the *j*th zone and the neutral axis

5. The stress modification factor for knots, $SMF_{bx\ knots\ j}$, is calculated for each zone using Equation (9).

$$SMF_{bx\ knots\ j} = \left(1 + 3\left(\frac{I_k}{I_g}\right)_j\right)\left(1 - \left(\frac{I_k}{I_g}\right)_j\right)^3\left(1 - \left(\frac{I_k}{2I_g}\right)_j\right) \geq SR_{bx\ \min j} \tag{9}$$

6. The stress modification factor for slope of grain, $SMF_{bx\ SOG\ j}$, is determined for each zone based on tabulated data for slope of grain values from 1:4 to 1:20 given in Table 4 of D3737.

7. The stress modification factor for each zone is determined using Equation (10).

$$SMF_{bx\ j} = \min\left\{SMF_{bx\ knots\ j}, SMF_{bx\ SOG\ j}\right\} \tag{10}$$

8. The maximum stress permitted on each zone, $F_{max,j}$, is calculated using Equation (11).

$$F_{\max,j} = K\left(BSI_j\right)\left(SMF_{bx\ j}\right) \tag{11}$$

where: $F_{max,j}$ = maximum stress allowed at outer edge of *j*th zone
BSI_j = bending strength index of laminations in *j*th zone
$SMF_{bx\ j}$ = strength ratio for bending = Min($SR_{bx\ knots}$, $SR_{bx\ SoG}$)
K = 1.4 for flexural compression
= 1.0 for flexural tension

9. The apparent outer fiber stress on the beam corresponding to $F_{max,\,j}$ for each zone is calculated using Equation (12).

$$\sigma_{apparent,j} = F_{\max,j}\left(\frac{D/2}{d_j}\right)\left(\frac{E_T}{E_j}\right)\left(\frac{I_T}{I_g}\right) \qquad (12)$$

10. The allowable flexural design stress (F_{bx}) is determined using Equation (13).

$$F_{bx} = \min\left\{\sigma_{apparent,j}\right\}(TL) \qquad (13)$$

where: TL = tension lamination factor
= 1.0 if tension laminations meeting the requirements of section 4.3 of D3737 are used
= 0.85 if tension laminations meeting the requirements of section 4.3 of D3737 are not used and d ≤ 15 in. (0.38 m)
= 0.75 if tension laminations meeting the requirements of section 4.3 of D3737 are not used and d > 15 in. (0.38 m)

11. The required strength ratio of the tension lamination (SR_{TL}) is calculated using Equation 14, and the tension lamination grading requirements of section 4.3 of D3737 are determined, if a tension lamination factor of 1.0 is used in Equation (13).

$$SR_{TL} = \frac{F_{bx}\left(\frac{2d_{TL}}{D}\right)\left(\frac{E_{TL}}{E_T}\right)\left(\frac{I_g}{I_T}\right)}{BSI_{TL}} \qquad (14)$$

where: d_{TL} = the distance from neutral axis to the outer edge of the T.L.
E_{TL} = the long-span modulus of elasticity of the lumber in the outermost tension zone
BSI_{TL} = the bending stress index of the lumber in the outermost tension zone

Since this analysis is calculation intensive, APA has developed a computer software program designated as GAP (glulam allowable properties) and this is recognized in ICC Evaluation Service report ESR-1940 as an alternative to using the hand calculation procedures of D3737. By knowing the knot characteristics of X-bar and h, any combination of grades and species can be input into the computer model and the resulting design properties for that grade combination are generated. It is important to note that this calculation methodology, although dating back to the 1950's, has been verified by thousands of full-size beam tests conducted at APA, the USDA Forest Products Laboratory and various North American universities. While more sophisticated probabilistic models have been developed over the years at Texas A&M and Purdue Universities, they yield essentially the same results as D3737 and require much more complicated material property inputs and thus did not achieve widespread acceptance.

It is also important to note that countries exporting glulam into the U.S. must complete this analysis to develop their claimed design properties before the glulam can be accepted under the IBC or IRC codes.

3.3 Tension Laminations

As noted in steps 10 and 11 above, the term "tension lamination" has been introduced. The results of full-size beam tests reported in references [6] and [7] yielded an empirical relationship between the size of knots in the tension zone and bending strength that was adopted into D3737 in the early 1980's. This relationship dictates that special grading considerations be applied to the laminations used in the outer 10 % of the beam depth on the tension side. This tension side may exist on the top or bottom of the beam, or both, depending upon loading and support conditions. If horizontally laminated timbers are manufactured without applying these special tension lamination-grading considerations, the allowable bending stress shall be reduced by multiplying the calculated allowable stress by 0.85 if the beam depth is 15 in. (0.38 m) or less or by 0.75 if the beam depth exceeds 15 in. (0.38 m).

The special grading provisions for maximum permissible knot characteristics in tension laminations based on the SR_{TL} calculated in accordance with equation (14) depend on the location in the beam depth (i.e., the outer 5% of the beam depth and the next inner 5% of the depth), and the actual beam depth (i.e., 4 laminations to 12" (12.5 cm), 12" (12.5cm) to 15" (38cm) and greater than 15" (38 cm)).

3.4 Volume Factor

Traditionally, the design properties generated in accordance with D3737 for bending stress were further adjusted by a size factor, $C_F = (12/d)^{1/9}$, which is similar to the European requirements for establishing flexural design properties for a depth of 12 inches (30 cm) and adjusting them for other depths. However, research involving full-size beams with a large range in sizes conducted by the glulam industry in the late 1980's and reported in reference [8] led to the adoption of the volume effect factor, C_V, in D3737 in the early 1990's. This was also adopted by the U.S. codes and is referenced in the IBC and IRC codes as a required design adjustment factor for glulam.

This research demonstrated that the flexural strength of glulam beams is not only affected by the depth of the member but also by its width and length. Therefore, for horizontally laminated bending members, the bending stress determined in accordance with D3737 must be adjusted for sizes greater than the standard size beam (as defined below) by multiplying by the volume effect factor, C_V, defined as follows:

$$C_V = [\ 5.125/w\ ]^{1/x}\ [12/d\ ]^{1/x}\ [21/L\ ]^{1/x} \leq 1.0 \qquad (15)$$

where:

d = beam depth, in.
w = beam width, in.
L = length of beam between points of zero moment, ft.
x = exponent determined by procedures outlined in Annex A8 of D3737

The standard beam is assumed to be uniformly loaded and is defined as having a depth of 12 in. (30 cm), a width of 5-1/ 8 in. (13 cm) and a length of 21 ft (6.4 m). It is noted that for Western species in the U.S., the exponent "x" is 10 and for Southern pine the exponent is 20. For other species, including imported species, it is necessary for the certification agency and manufacturer to establish the exponent "x" to be able to publish flexural design properties in accordance with U.S. building codes.

4. ANSI A190.1

While D3737 focuses on the lumber properties as they influence design properties, it is acknowledged that an equally important consideration is the strength of the end joints, particularly in highly stressed tension zones of members. ANSI A190.1 requires that all end joints be qualified using a full-size tension test with a gauge length of 2 feet (60 cm). The requirement is that the 5% tolerance limit with 75% confidence shall exceed 1.67 times the Qualification Stress Level (QSL) using 2x6 lumber. For bending members the QSL is defined as the highest published tabular design value based on normal duration of loading and dry service conditions.

As an example, for a glulam bending member having a published bending stress of 2400 psi (16.5 MPa), the end joint qualification is 2400x1.67 = 4000 psi (27.6 MPa). For a member with a published design stress of 3000 psi (20.7 MPa), the requirement is 3000x1.67 = 5010 psi (34.5 MPa). Qualification tests are required for all combinations of species, adhesives and treatments used by any manufacturer. ANSI A190.1 also sets for the requirements for daily full-size tension tests to confirm the quality of the end joints.

The premise for the 1.67 factor is based on full-scale beam tests with the end joint strength being equivalent to the tension lamination quality. Thus, in a test of 100 beams, it is hypothesized that 50 would fail at an end joint and 50 would fail due to some lumber strength-reducing characteristic and this has been generally confirmed by the large magnitude of full-scale beam tests conducted in North America.

5. Performance Based Standard

As previously noted, a provision was added to ANSI A190.1-2002 to permit the development of characteristic values for grade combinations using performance testing as an alternate to the provisions of D3737. Similarly, Table 2 of D3737 provides bending stress index values based on full-size beam tests.

However, there is no published U.S. standard describing how to conduct full-scale glulam beam tests and how to analyze the resulting data. The values in Table 2 of D3737 are based on beams designed using these values and tested in accordance with ASTM Test Methods D 198 yielding bending strength values such that the lower fifth percentile will exceed the design bending stress by a factor of 2.1 with 75 % confidence. Analysis of test data assumed a lognormal distribution but there were no definitive sample preparation and sampling requirements.

To address this need, a Task Group of the ASTM Section Committee on Glulam, D07.02.02, has drafted a new standard, "Standard Practice for Establishing Characteristic Values for Flexural Properties of Structural Glued Laminated Timber by Full-Scale Testing". The scope of the standard is to develop procedures for full-scale testing of structural glued laminated timber to determine or verify characteristic values used to calculate flexural design properties. Guidelines are given for (1) testing individual structural glued laminated timber layups (with no modeling), (2) testing individual glulam combinations (with limited modeling), and for (3) validating models used to predict characteristic values. The sample size to be evaluated is based on which of these conditions are being evaluated.

This practice is limited to procedures for establishing characteristic flexural properties (MOR and MOE) although some of the principles for sampling and analysis presented may be applicable to other properties. The characteristic value is defined as a test statistic from which design values can be derived by the application of appropriate adjustment factors. For flexural strength properties of structural glued laminated timber, this characteristic value is typically a 5th percentile estimate with 75% confidence. For deformation-based properties, such as modulus of elasticity, this value is represented by the average value. This standard is currently being balloted by ASTM and is expected to be approved at the Fall 2007 meeting of D07.

6. Conclusions

With a large number of projects underway in ISO/TC165, Timber Structures, to develop ISO standards for glued laminated timber, it is important that countries involved in the process understand various national standards and how the provisions of those national standards need to be accommodated in the ISO process. This is also true when countries such as China and Taiwan move toward developing their own national standards for products such as glulam and must consider how other national standards have been developed. In virtually all cases some compromises are required by the various countries involved to be able to work towards harmonization of glulam standards through the ISO process while acknowledging national differences.

Acknowledgements: Special thanks go to Jeffrey Linville of the American Institute of Timber Construction who took the lead for the ASTM Glulam Section Committee on revising and simplifying Annex A4 of D3737 as presented in this paper. Also, for his efforts as Chairman of the Task Group of the Glulam Section Committee that developed the draft standard for performance-based testing of full-size beams referenced in this paper.

7. References

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