C/2 Design and Performance Aspects of United States and European Glulam

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1 Abstract

This paper overviews some design and performance aspects of United States and European glulam. First, the uses and design philosophy behind United States glulam are presented. Results from a Norwegian glulam study that influenced European design requirements are also presented.

2 United States Glulam

In the United States, glulam is used in a wide variety of applications, ranging from headers or support beams in residential house framing to major structural elements in the framing of domed stadiums that span more than 500 ft (150 m). Glulam is produced in many sizes and shapes, ranging from large, long-span straight beams to complex curved-arch configurations. With the introduction of wet-use or durable adhesives about 50 years ago, glulam became a viable construction matierial for diverse uses such as utility structure crossarms, ligthing standards, electric transmission line towers, and roadway and railroad bridge structures. In the United States, 600 000 m^3 (more than $2.5 * 10^8$ board feet) of lumber are used annually in the manufacture of glulam.

The engineering design of U.S. glulam follows national standards that prescribe performance-based criteria for its manufacture and 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 most common design application for glulam timber is as a bending member with the primary design loads applied perpendicular to the wide face of the laminations. To more effectively use the lumber resource in the United States and to enhance the competitive position of glulam in the marketplace, bending members are produced using engineered combinations. A single beam may incorporate three or more different structural grades of lumber, sometimes of different species. In these engineered combinations, the highest quality material is positioned in the member where the service loading will create the highest stress. Conversely, lower grade laminations are positioned in areas or zones where the stress will be lower. This use of multiple species and several different grades within a single beam is a distinctly different practice than for European glulam design, which limits beam design to a single grade (homogeneous lay-up) or two grades (combined lay-up).

The lumber grades used in the U.S. manufacture of glulam timber include special laminating grades, conventional visually stress-rated lumber grades, and E-rated lumber grades (grades defined by a modulus of elasticity (MOE) and knot size). In some design applications, it may be desirable to apply a bending load parallel to the wide face of the laminations. This is commonly referred to as a vertically laminated member. In addition, glulam may be used as tension members in truss chords or as compression members in columns. In these cases, the stresses are essentially uniform across the entire cross section of the member, and as a result, a single grade of lumber is typically specified for all laminations within the member.

2.1 Establishing Design Stresses for U.S. Glulam

Design stresses for glulam are published by either the American Institute of Timber Construction (AITC) or APA-The Engineered Wood Association. Manufacturers representing nearly all U.S. glulam production belong to one of these agencies. To justify published design stresses, the manufacturing standard American National Standards Institute (ANSI)/AITC Standard Al 90.1, Structural Glued Laminated Timber (ANSI/AITC 1992) must be followed. This standard sets minimum requirements for manufacturing, inspection, testing, and certification of glulam.

The AITC has established specific target design stresses for bending. The AITC also optimizes combinations of softwood lumber grades to meet target design levels. These levels are 11.0, 13.8, 15.2, 16.5, 17.9, and 20.7 MPa (1600,2000,2200,2400, 2600, and 3000 Ib/in^2) (AITC 1993). In most instances, specific 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 (ASTM) standard ASTM-D3737 (ASTM 1993) to develop the combinations of lumber in their manufacturing specifications (AITC 1993) that meet the required performance. ASTM-D3737 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 develop design stresses involves a concept of multiplying a stress index (analogous to a clear wood value) by a stress modification factor (analogous to a strength ratio) to determine the design stress of the glulam, F_b:

where BSI is a bending stress index and SMF_b is a stress modification factor for bending. Basically, the BSI is determined from the strength of clear wood and SMF_b

is an adjustment to account for the effects of knots and slope-of-grain. The overall methodology is shown in Fig. C/2-1.

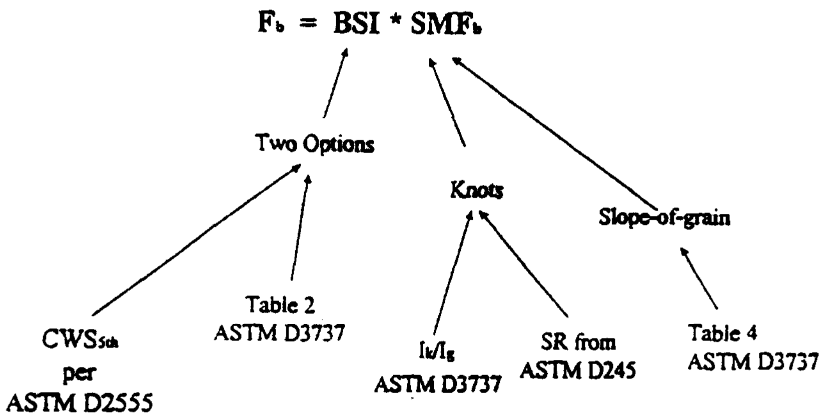


Fig. C/2-1 :Design stress calculation for U.S. glulam

F_b = design stress of glulam
BSI = bending stress index
SMF_b = stress modification factor for bending
CWS_{5th} = 5th percentile clear wood strength
I_k = moment of inertia of knots
I_g = moment of inertia of the beam
SR = strength ratio

Two options exist for determining the BSI. One option is to follow the same general procedure traditionally used for sawn lumber, which is based upon the strength of clear wood adjusted to account for knots and is given in ASTM-D2555 (ASTM 1988). This option results in the value CWS_{5th} which is a 5th percentile clear wood strength. This value is further multiplied by modification factors (size factor, moisture content, duration of load, safety factors, etc.) to arrive at a BSI. The second option is more commonly used, is based on an analysis of test beams, and involves a back-calculation of the test data to establish a BSI value. The notion of a glulam clear wood strength is hypothetical, however this methodology allows the use of glulam test results in these design value computations. Values of BSI for the second option are given in table 2 from ASTM D3737 for different species.

SMF_b is a stress modification factor for bending and accounts for the effect of either knots or slope-of-grain in the glulam. For the effect of knots, two options exist. The first is based on combination of statistical and empirical relationships presented by Freas and Selbo (1954). For horizontally laminated beams, statistical properties of the knots in the various lumber grades are used to calcutate 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 of the beam, I_g. ThisI_k/I_g, value is then empirically related to the SMF_b,. Because the I_k/I_g method does not model shallow beams very well, a second method to account for the effects of knots can be used. This method accounts for knots based upon the calculation of a strength ratio, SR, per ASTM D245 (ASTM 1992). The larger value generated from these two methods is used.

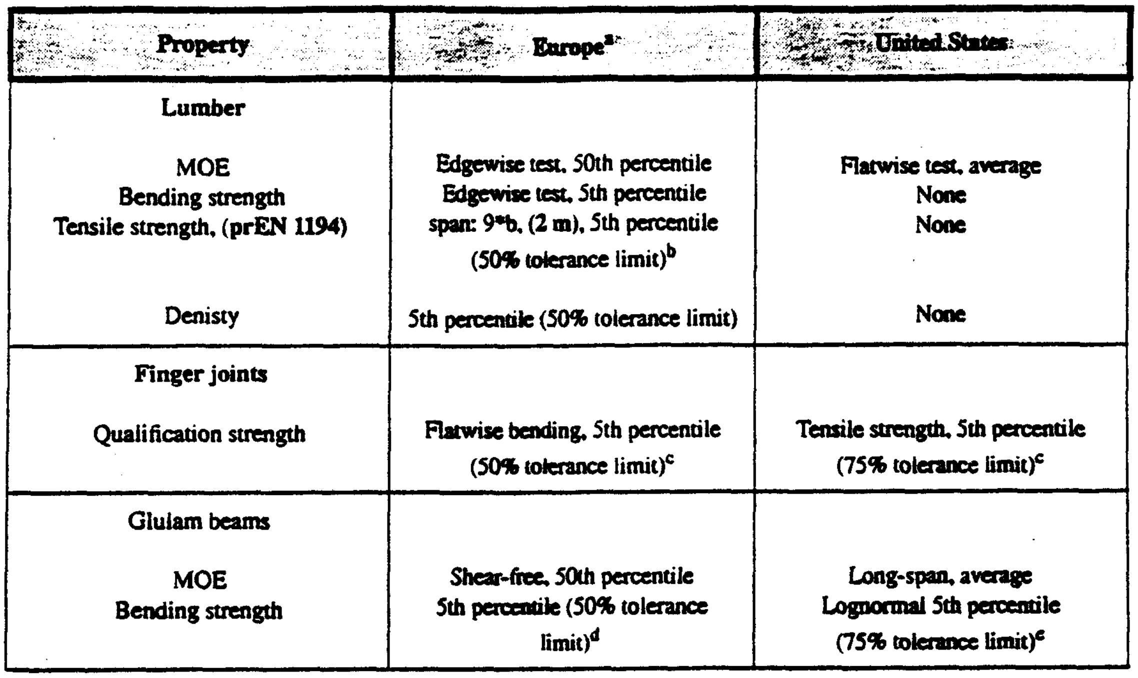
To account for slope-of-grain, table 4 from ASTM-D3737 is used. The critical SMF_b value is the smaller of the values generated from the knots and slope-of-grain.

2.2 Tension Laminations

An additional requirement of ASTM-D3737 is that certain minimum visual quality levels must be maintained for laminations on the outer 5 percent of the beams on the tension side. These tension laminations have specific grading restrictions to justify assigning higher design values. Grading restrictions specific to these members include limitations on knots, their associated grain deviation, slope-of-grain, density, specific gravity, and other characteristics. Thus, tension laminations are graded to provide a high visual grade. Common designation for tension laminations include 302-20,302-22, and 302-24. The ‘302’ is an abritrary designation and the ‘20’, ‘22’, or ‘24’ designate a target design bending stress, F_b, of 13.8 MPa (2000 lb./in^2), 15.2 MPa (2200 lb.in^2), or 16.5 -MPa (2400 lb/in^2), respectively.

2.3 End Joints and Gluing

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. Minimum strength levels for these glued joints and quality assurance procedures are prescribed in ANSI/AITC A190.1 (ANSI/AITC 1992). 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 joint. The most common joint is about 28 mm (1.1 in.) long with four fingers per inch. Required tensile strength of these finger joints is related to the design level of the beams. The 5th percentile of the finger-joint tensile strength must be equal to or exceed 1.67 times the design level of the beam in bending. Table C/2-1 indicates how some design parameters differ for U.S. and European glulam.



Property	Europe[a]	United States
Lumber		
MOE	Edgewise test, 50th percentile	Flatwise test, average
Bending strength	Edgewise test, 5th percentile	None
Tensile strength, (prEN 1194)	span: 9*b, (2 m), 5th percentile (50% tolerance limit)[b]	None
Denisty	5th percentile (50% tolerance limit)	None
Finger joints		
Qualification strength	Flatwise bending, 5th percentile (50% tolerance limit)[c]	Tensile strength, 5th percentile (75% tolerance limit)[c]
Glulam beams		
MOE	Shear-free, 50th percentile	Long-span, average
Bending strength	5th percentile (50% tolerance limit)[d]	Lognormal 5th percentile (75% tolerance limit)[e]

Tab. C/2-1 : A comparison of some design parameters and required tests for European and U.S. glulam standards

[a] All European statistical estimates are nonparametric.

[b] 1m=3.2808ft.

[c] Difference between the 50% tolerance limit and 75% tolerance depends on sample size.

[d] Find design strength adjusted to standard depth of 600 mm (23.6 in.).

[e] Final design strength adjusted to standard volume according to ANSI/AITC A190.1.

3 Norwegian Glulam

In 1990, Falk et al. (1992) performed a study to evaluate the engineering performance of glulam timber beams manufactured in Norway. The collection of information on specific material properties made possible an evaluation of these beams by applicable Comite European de Normalisation (CEN) standards as well as the U.S. design methods discussed earlier. This information also provided the necessary link for comparing the performance of U.S. glulam beams to that of their European counterparts. Testing was performed to determine the strength and stiffness of laminating lumber, finger joints, and full-size glulam beams. Results indicated that the beams constructed from the graded laminations exhibited properties that met or exceeded the requirements of CEN glulam combinations. A good estimate of beam strength and stiffness was optained using CEN glulam property prediction equations. The use of mechanical property data collected specifically for use in ASTM procedures indicated that predicted beam strengths also compared well with actual beam test results.

3.1 Prediction of Beam Properties

As an extension of the Norwegian glulam study, European and U.S. standards were used to predict beam performance on the basis of the material properties of the lumber and finger joints (Falk and Hernandez 1995). This allowed us to estimate the difference between glulam beams designed using European and U.S. standards.

3.2 Prediction with European Standards

Since the European method of glulam beam design is a performance-based approach (or strength class system), the predicted beam performance is based solely on the mechanical properties of the lumber and the finger joints. The CEN standard specifies a required characteristic bending strength for glulam beams, given the characteristic tensile strength of the laminating lumber used in the beams. The relationships found in prEN 1194 (Comite European de Normalisation 1996) were used to predict bending strength and stiffness of glulam. Table C/2-2 shows that the prEN 1194 equations predicted strength and stiffness quite close to the actual (tested) beam properties (Falk and Hernandez 1995).

3.3 Prediction with U.S. Standards

The beams tested in the Norwegian study were also evaluated by U.S. design methods (Falk and Hernandez 1995) to determine how well the U.S. methods can predict European beam performance. This analysis was conducted using the measured knot and MOE properties. In this comparison, the U.S. methods also predicted stiffness quite well; however, for the lower grade beams, the difference between actual and predicted strength was somewhat greater than with European methods. Because the U.S. design method is heavily dependent on knot properties, some assumptions for clear wood properties of lumber and maximum allowable knot sizes for a particular grade were assigned. As shown in Table C/2-2, the use of the SR option to determine SMF_b indicates a better estimate of bending strength than the I_k/I_g option

		TEST RESULTS	TEST RESULTS	PREDICTED RESULTS	PREDICTED RESULTS	PREDICTED RESULTS
Glulam comb.[a]	Property	EU reference[b]	U.S. reference[b]	EU equations	U.S. methods[c] (ASTM D3737) SMF_b I_k/I_g option	U.S. methods[c] (ASTM D3737) SMF_b SR option
LH35	MOE MOR	13,100 34.3	12,100 32.2	13,800 35.3	12,600 25.0	12,600 30.7
LC38	MOE MOR	14,600 39.2	13,500 35.3	14,100 35.8	13,600 31.7	13,600 35.3
LH40	MOE MOR	15,400 39.4	14,000 36.8	15,200 40.3	13,800 32.2	13,800 35.7

Tab. C/2-2 : Comparison of property predictions using European equations and ASTM D3737 (MPa)

[a] See Falk et al. (1992) for description of test beams.

[b] European MOE based on shear free zone. U.S. MOE based upon full span. U.S. MOR data adjusted to 300-mm depth, European MOR data to 600 mm.

[c] See Figure 1 for options to compute SMF_b.

3.4 Relationship between Lamination Strength and Beam Strength

In a study to investigate the relationship between the tensile strength of beam laminations and glulam bending strength, Falk and Colling (1995) presented the following figures for both North American and European glulam. Several observations can be made by comparing the European and North American data. First, by observing Figure C/2-2, it is seen that the relationship between $f_{t,lam,k}$ and $f_{b,gl,k}$ for European glulam is linear. The most current revision of prEN 1194 (Comite European de Normalisation 1996) includes a modified version of the equation in Figure C/2-2:

$$f_{b,gl,k} = 7 + 1.15 \cdot f_{t,lam,k} \qquad (C/2\text{-}2)$$

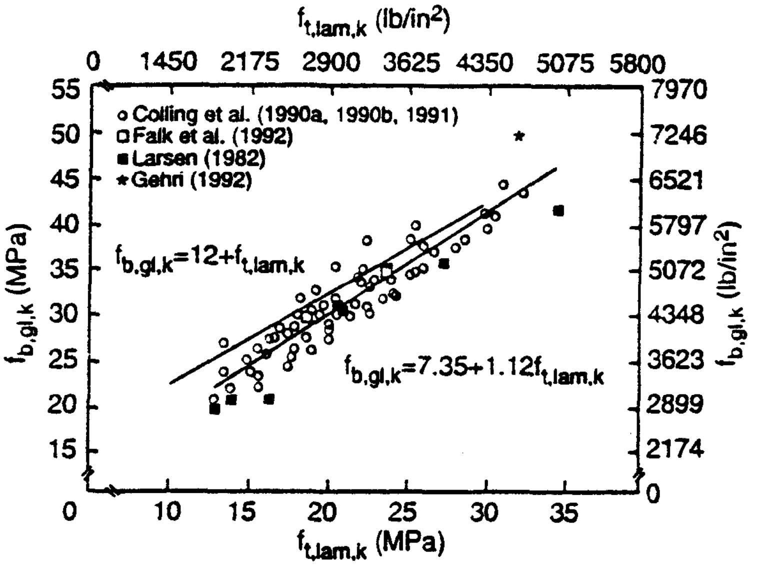


Fig. C/2-2 :European glulam data

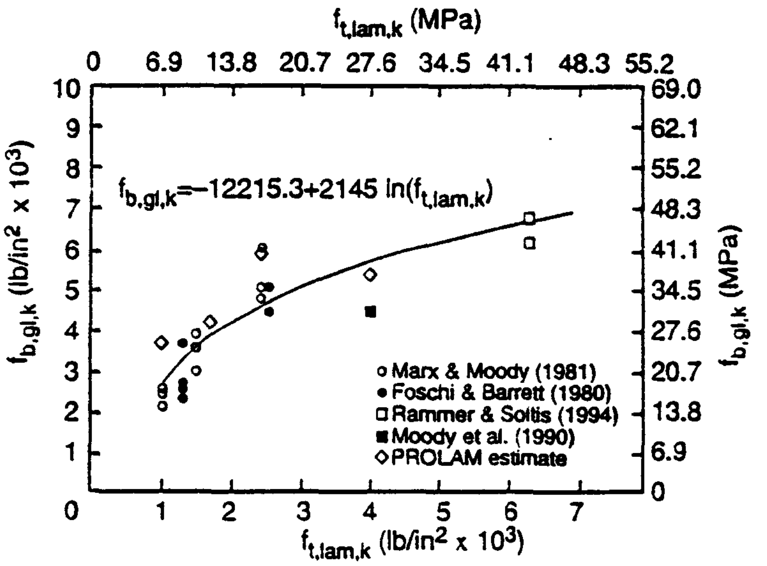


Fig. C/2-3 :North American glulam data

For the North American glulam, as lamination tensile strength increases, the rate of increase of glulam bending strength decreases as shown in Figure C/2-3. It is suspected that this nonlinear behavior is a result of the use of special tension laminations in the manufacture of North American glulam. This is borne out if a graphical comparison is made between the European and North American beam data (tests and simulations) that meet European glulam combination requirements. Simulations were performed with the U.S. glulam prediction model PROLAM. As shown in Figure C/2-4, regression lines fit to these two sets of data indicate that the trends are similar.

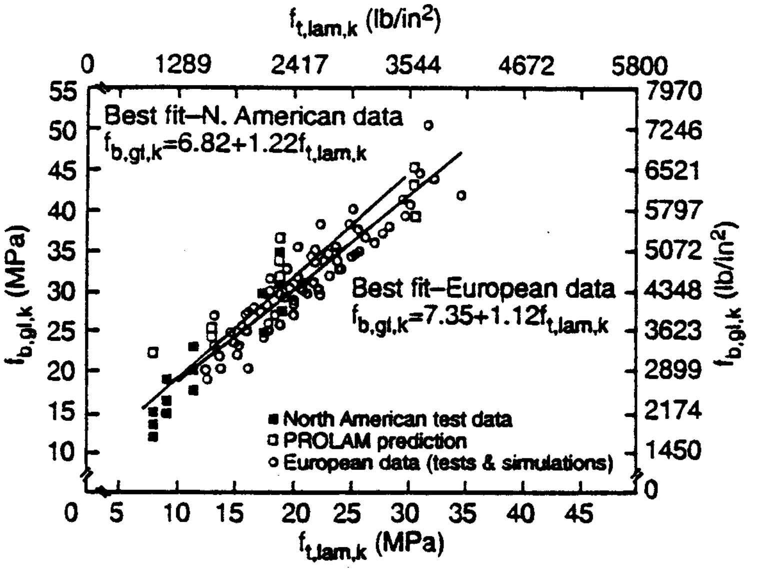


Fig. C/2-4 :North American and European glulam data

As concluded in Falk and Colling (1995), it is suspected that in North American beams constructed with special tension laminations, the gradient of stiffness is sharper than that of the more homogenous combinations of European beams. This results in lower beam bending strengths at higher lamination tension strength levels (Fig. C/2-3) and implies that European beams possess a more efficient structural balance between lamination tensile strength and beam bending strength. This is achieved, however, at the cost of using greater quantities of high-grade material for the tension zone.

4 References

- AITC. 1993. Standard specifications for structural glued laminated timber of softwood species. AITC 117-88 - Manufacturing. American Institute of Timber Construction, Vancouver, WA.
- ANSI/AITC. 1992. Structural glued laminated timber. ANSI/AITC A190.1. American National Standards Institute/American Institute of Timber Construction, Englewood, CO.
- ASTM. 1988. Standard test methods establishing clear wood strength values. ASTM D2555-88. American Society for Testing and Materials, Philadelphia, PA.
- ASTM. 1992, Standard practice for establishing structural grades and related allowable properties for visually graded lumber. ASTM D245-92. American Society for Testing and Materials, Philadelphia, PA.
- ASTM. 1993. Standard method for establishing stresses for structural glued-laminated timber (glulam). ASTM D3737-93. American Society for Testing and Materials, Philadelphia, PA.
- Colling, F. 1990a. Tragfähigkeit von Biegeträgern aus Brettschichtholz in Abhängigkeit von den festigkeitsrelevanten Einflussgrössen, Dissertation, Universität Karlsruhe, Germany.
- Coiling, F. 1990b. Bending strength of glulam beams - A statistical model. IUFRO S5.2, St. John, Canada.
- Colling, F., Ehlbeck, J., and Görlacher, R. 1991. Glued laminated timber: Contribution to the determination of the bending strength of glulam beams, CIB W18/ 24- 12- 1, Oxford, England.
- Comite European de Normalisation. 1996. Glued laminated umber - Strength classes and determination of characteristic properties. Draft Standard prEN 1194, Brussels, Belgium, September.
- Falk, R.H., and Colling, F. 1995. Laminating effect in glued-laminated timber beams. Journal of Structural Engineering, ASCE, 121(12): 1857- 1863.
- Falk, R.H., and Hernandez, R. 1995. The performance of glued-laminated timber beams of European manufacture. Forest Products Journal. 45(7-8): 27-34.
- Falk, R.H., Solli, KJ., and Aasheim, E. 1992. The performance of glued-laminated timber beams manufactured from machine stress graded Norwegian spruce. Report 77, Norwegian institute of Wood Technology, Oslo, Norway.
- Foschi, R.O., and Barrett, J.D. 1980. Glued-laminated beam strength: A model, J. Struct. Div., ASCE, 106(ST8): 1735- 1754.
- Freas, A.D., and Selbo, M.L. 1954. Fabrication an design of glued laminated wood structural members, Techn. Bull. 1069, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

- Gehri, E. 1992. Determination of characteristic bending values of glued laminated timber. CIB-W18, Ahus, Sweden.
- Larsen, H.J. 1982. Strength of glued laminated beams: Part 5. Report 8201, Institute of Building Technology and Structural Engineering, Aalborg University, Aalborg, Denmark.
- Marc, CM., and Moody, R.C. 1981. Bending strength of shallow glued laminated beams of a uniform grade. Res. Pap. FPL 380, USDA, Forest Service, Forest Products Laboratory, Madison, WI.
- Moody, RC., Falk, R-H., and Williamson, T. 1990. Strength of glulam beams - Volume effects. In Proceedings of the 1990 International Timber Engineering Conference, 23-25 Oct. 1990, Tokyo, Japan.
- Rammer, D.R and Soltis, L.A. 1994. Experimental shear strength of glued-laminated beams, Res.Pap. FPL 527, USDA Forest Service, Forest Products Laboratory, Madison, WI.