FOCUS ARTICLE

PERFORMANCE OF GLUED-LAMINATED TIMBER BEAMS OF EUROPEAN MANUFACTURE

ROBERT H. FALK
ROLAND HERNANDEZ

ABSTRACT

The engineering performance of glued-laminated (glulam) timber beams manufactured from European Whitewood is presented. Evaluation of these European beams by American design methods (ASTM) and developing European standards (CEN) was made possible by the collection of information on specific material properties. This information 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. 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 obtained 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.

A unified European Economic Community (EEC) will have an important impact on the commerce and trade of its 300 million people. In addition to the obvious economic implications of such a large free trade market, an important aspect of the unification process is the development of common building design and product performance standards. Currently under development are uniform performance standards for member countries under the auspices of the Comite European de Normalisation (CEN). To compete in this market, nations that produce wood products must ensure that the performance of EEC-destined products meet these unified standards. Because these requirements may differ from existing national standards, criteria are needed for evaluating products relative to the CEN standard.

The basic objective of this research was to characterize the performance of glulam timber beams manufactured in Norway from Norwegian spruce (European Whitewood) relative to the developing CEN standards. This study was also an opportunity to collect data for evaluating these European beams using American design methods, an important link in comparing the performance of U.S. glulam beams to their European counterparts. This linkage should help U.S. glulam manufacturers match the performance of U.S.-manufactured beams to necessasy European glulam performance requirements.

To meet this objective, tests were performed to determine the strength and stiffness of laminating lumber, finger-joints, and full-size glulam beams.

STANDARDS

The purpose of glulam performance standards is to establish minimum allowable properties of the constituent glulam components (lumber and finger-joints) that achieve a desired beam performance.

EUROPEAN GLULAM STANDARD

The necessary characteristic properties for laminating lumber and glulam beams used in Europe are currently provided in draft CEN standards. Standard prEN 338 (8) stipulates that lumber grades must meet a designated mean and characteristic bending stiffness, a characteristic bending strength, and a characteristic tensile strength (6). Utilizing these lumber grades, prEN 1194 (9) provides glulam combinations with targeted characteristic bending strengths and stiffnesses. In the European standard, only homogeneous (uniform-grade) and combined (two-grade) layups are allowed.

When this study was initiated in 1990, the laminating lumber and glulam draft standards were EN TC 124.203 (6) and EN TC 124.207 (7), respectively. The laminating lumber grade and glulam beam combination designations (and target design stresses) provided in these standards are somewhat different from the current draft CEN standards

The authors are Research Engineers, USDA Forest Serv., Forest Products Lab., One Gifford Pinchot Dr., Madison, WI 53705-2398. The Forest Products Laboratory is maintained in cooperation with the Univ. of Wisconsin. The authors would like to acknowledge the generous support of the Norsk Treteknisk Institutt (Norwegian Institute of Wood Technology), the Norges Teknisk-Naturvitenskapelige Forskningsråd (Royal Norwegian Council for Scientific and Industrial Research), and the Norske Limtreprodusenters Forening (Norwegian Glulam Producers Assoc.). This paper was received for publication in December 1994.

Forest Prod. J. 45(7/8):27-34.

TABLE 1. — Characteristic strength values for laminating lumber from EN TC 124.203 (6).

Property[a]	C13-7E	C15-8E	C15-11E	C18-9E	C21-10E	C21-13E	C24-11E	C30-12E	C30-15E	C37-14E	C48-20E	C60-22E
	Properties for various strength classes											
Strength (MPa (× 10^3 psi))												
Bending, $f_{m,k}$	13 (1.88)	15 (2.17)	15 (2.17)	18 (2.61)	21 (3.04)	21 (3.04)	24 (3.48)	30 (4.35)	30 (4.35)	37 (5.36)	48 (6.96)	60 (8.70)
Tension parallel, $f_{t,o,k}$	8 (1.16)	9 (1.30)	9 (1.30)	11 (1.59)	13 (1.88)	13 (1.88)	14 (2.03)	18 (2.61)	18 (2.61)	22 (3.19)	29 (4.20)	36 (5.22)
Stiffness (GPa (× 10^6 psi))												
Mean MOE parallel, $E_{o,mean}$	7 (1.01)	8 (1.16)	11 (1.59)	9 (1.30)	10 (1.45)	13 (1.88)	11 (1.59)	12 (1.74)	15 (2.17)	14 (2.02)	20 (2.90)	22 (3.19)
Minimum MOE parallel, $E_{o,min}$	4.9 (0.71)	5.5 (0.80)	7.4 (1.07)	6.5 (0.94)	7.0 (1.01)	8.7 (1.26)	7.4 (1.07)	8.5 (1.23)	10.3 (1.49)	10 (1.45)	14 (2.03)	15 (2.17)
Density (kg/m^3 (pcf))												
Density, ρ_k	290 (18.1)	300 (18.7)	450 (28.1)	320 (19.9)	350 (21.8)	480 (29.9)	380 (23.7)	410 (25.6)	520 (32.4)	450 (28.1)	600 (37.4)	700 (43.6)

[a] Parallel refers to parallel to the grain.

TABLE 3. — Target properties of glulam combinations from EN TC 124.207 (7).

Property	LH25	LH28	LH30	LH35	LH40	LC24	LC26	LC28	LC33	LC38
	Homogeneous layups					Combined layups				
Strength (MPa (× 10^3 psi))										
Bending, $f_{m,k,g}$	25 (3.62)	28 (4.06)	30 (4.35)	35 (5.07)	40 (5.80)	24 (3.48)	26 (3.77)	28 (4.06)	33 (4.78)	38 (5.51)
Tension parallel, $f_{t,o,k,g}$	20 (2.90)	23 (3.33)	25 (3.62)	28 (4.06)	32 (4.64)	17 (2.46)	19 (2.75)	21 (3.04)	24 (3.48)	26 (3.77)
Compression parallel, $f_{c,o,k,g}$	25 (3.62)	26 (3.77)	27 (3.91)	29 (4.20)	33 (4.78)	22 (3.19)	23 (33.3)	25 (3.62)	27 (3.91)	30 (4.35)
Stiffness (GPa (× 10^6 psi))[a]										
Bending, $E_{mean,m,g}$	10 (1.45)	11 (1.60)	11.5 (1.67)	12.5 (1.81)	13 (1.88)	9.5 (1.38)	10.5 (1.52)	11 (1.60)	12 (1.74)	13 (1.88)
Density (kg/m^3 (pcf))	320 (19.9)	350 (21.8)	380 (23.7)	410 (25.6)	450 (28.1)	250 (15.8)	300 (18.7)	320 (19.9)	350 (21.8)	380 (23.7)

[a] Modulus of elasticity, parallel.

(prEN 338 and prEN 1194). The data in **Tables 1** to **3** show the laminating lumber grades and glulam combinations relevant in 1990; **Tables 4** to **6** show laminating lumber grades and glulam combinations relevant at the time of this writing (1994).

The data in **Table 1,** which were taken from EN TC 124.203 (structural timber—strength classes), show pertinent material property requirements of several grades of laminating lumber that were applicable in 1990. Note particularly grade designations C30-12E and C37-14E, which will be referred to throughout this paper. **Table 2** lists different glulam combinations that can be manufactured using the laminating grades described in **Table 1; Table 3** indicates the target properties for these glulam combinations. **Tables 2** and **3** were reproduced from EN TC 124.207 (glulam timber—strength classes). Note particularly glulam designations LH35, LH40, and LC38. The grade designations in both of these CEN standards refer to the required characteristic bending strength (lower 5th percentile) and the required mean bending stiffness; the same designations are used for both lumber and glulam. For example, a C30-12E designation requires a lower 5th percentile bending strength of 30 MPa (4,350 psi) and a mean bending stiffness of 12 GPa (2.03 × 10^6 psi).

TABLE 2. — Glulam combinations from EN TC 124.207 (7).

Layup	Required lamination strength class				
Homogeneous glulam	LH25	LH28	LH30	LH35	LH40
All laminations	C18-9E	C21-10E	C24-11E	C30-12E	C37-14E
Combined glulam[a]	LC24	LC26	LC28	LC33	LC38
Outer laminations	C18-9E	C21-10E	C24-11E	C30-12E	C37-14E
Inner laminations	C13-7E	C15-8E	C18-9E	C21-10E	C24-11E

[a] One-sixth of the cross section on tension and compression sides is of higher grade

Table 4 indicates the laminating lumber properties required by CEN standard prEN 338 (structural timber—strength classes), the current version of the standard at the time of this writing. Note that the range of laminating grades has been narrowed compared to that in EN TC 124.203 (structural timber—strength classes) **(Table 1).** In particular, this version of the CEN standard does not include the C37 grade designated in the earlier standard. **Table 5** shows the different glulam combinations that can be manufactured using the laminating grades from **Table 4.** Note that the strength classes, as provided in prEN 1194 (glulam timber-strength classes), are now designated by a code different from that used in the earlier standard **(Table 2). Table 6** indicates the target properties for these glulam combinations.

TABLE 4. — Characteristic strength values for laminating lumber from prEN 338 (8).

Property[a]	C14	C16	C18	C22	C24	C27	C30	C35	C40
	Properties for various strength classes								
Strength (MPa (× 10^3 psi))									
Bending, $f_{m,k}$	14 (2.03)	16 (2.32)	18 (2.61)	22 (3.19)	24 (3.48)	27 (3.19)	30 (4.35)	35 (5.07)	40 (5.80)
Tension parallel, $f_{t,o,k}$	8 (1.16)	10 (1.45)	11 (1.59)	13 (1.88)	14 (2.03)	16 (2.32)	18 (2.61)	21 (3.04)	24 (3.48)
Stiffness (GPa (× 10^6 psi))									
Mean MOE parallel, $E_{o,mean}$	7 (1.01)	8 (1.16)	9 (1.30)	10 (1.45)	11 (1.59)	12 (1.74)	12 (1.74)	13 (1.88)	14 (2.03)
5% MOE parallel, $E_{o,.05}$	4.7 (0.68)	5.4 (0.78)	6.0 (0.87)	6.7 (0.97)	7.4 (1.07)	8.0 (1.16)	8.0 (1.16)	8.7 (1.26)	9.4 (1.36)
Density (kg/m^3 (pcf))									
Density, ρ_k	290 (18.1)	310 (19.3)	320 (19.9)	340 (21.2)	350 (21.8)	370 (23.1)	380 (23.7)	400 (24.9)	420 (26.2)
Average density, ρmean	350 (21.8)	370 (23.1)	380 (23.9)	410 (25.6)	420 (26.2)	450 (28.1)	460 (28.7)	480 (29.9)	500 (31.2)

[a] Parallel refers to parallel to the grain.

TABLE 6. — Target properties of glulam combinations from prEN 1194 (9).

Property	GL20	GL24	GL28	GL32	GL36
Strength (MPa (× 10^3 psi))					
Bending, $f_{m,g,k}$	20 (2.90)	24 (3.48)	28 (4.06)	32 (4.64)	36 (5.22)
Tension parallel, $f_{t,o,g,k}$	15 (2.17)	18 (2.61)	21 (3.04)	24 (3.48)	27 (3.91)
Compression parallel, $f_{c,0,g,k}$	21 (3.04)	24 (3.48)	27 (3.91)	29 (4.20)	31 (4.49)
Shear, $f_{v,g,k}$	2.8 (0.406)	2.8 (0.406)	3.0 (0.430)	3.5 (0.507)	3.5 (0.507)
Stiffness (GPa (× 10^6 psi))					
MOE parallel, $E_{0,mean,g}$	10.0 (1.45)	11.0 (1.59)	12.0 (1.74)	13.5 (1.96)	14.5 (2.10)
MOE parallel, $E_{o,.05,g}$	8.0 (1.16)	8.8 (1.28)	9.6 (1.39)	10.8 (1.57)	11.6 (1.68)
Density (kg/m^3 (pcf)) ρk	360 (22.4)	380 (23.7)	410 (25.6)	440 (27.4)	480 (29.9)

U.S. GLULAM STANDARD

Glulam standards in the United States are also based on the properties of the laminating lumber for determining the allowable performance of the glulam beam. The American Institute of Timber Construction (AITC) establishes standard glulam combinations for softwood and hardwood species of lumber. The AITC 117—Manufacturing standard (1) offers several combinations of glulam using softwood species of lumber (the most common are Douglas-fir and southern pine).

Development of the glulam combinations in AITC 117—Manufacturing was based on an empirical technique that relates information on both the clear wood properties of the lumber and the knot size distributions of the lumber grade to the bending strength of full-sized glulam beams. This empirical approach is referred to as the I_k/I_g method and was developed by Freas and Selbo (11). This method currently forms the basis for determining bending stresses of American glulam: the American Society for Testing and Materials (ASTM) Standard D 3737 (4). The criteria needed to analyze and develop glulam combinations according to ASTM D 3737 include lumber stiffness properties, lumber knot size, minimum bending strength ratio, and bending stress index. In order to analyze the European manufactured glulam beams, lumber stiffness properties and knot size distributions were determined from test data. Minimum bending strength ratios and bending stress indexes were determined from values used for American E-rated laminating lumber grades.

TABLE 5. — Glulam combinations from prEN 1194 (9).

Layup	GL20	GL24	GL28	GL32	GL36
	Required lamination strength class				
Homogeneous glulam					
All laminations	C18	C22	C27	C35	C40
Combined					
Outer laminations[a]	C22	C24	C30	C35	C40
Inner laminations	C16	C18	C22	C27	C35

[a] Requirements apply to the extreme one-sixth of the depth on both sides.

FINGER-JOINT PERFORMANCE

The finger-joint, which bonds individual pieces of lumber, is an important component of a glulam beam. A major difference between European and U.S. glulam standards is the qualification of finger-joint properties. In contrast to U.S. standards, which are based on a fill-size tensile strength qualification level, current European standards are based on a minimum flatwise finger-joint bending strength, which requires that the joint strength exceed the targeted beam bending strength (adjusted to a depth of 600 mm (24 in.) by 30 percent.

In the United States, the American National Standards Institute (ANSI) establishes the required performance levels for glulam in the ANSI A190.1 standard (3). In this standard, the characteristic tensile strength (5th percentile) of the tension lamination finger-joints is specified to meet a strength level 1.67 times the design bending strength of the glulam beam combination. The design bending strength of the glulam beam is based on the characteristic bending strength (5th percentile) divided by two values: a value of 2.1 to account for both load duration and safety, and a value to account for volume effect (2). The relationship between finger-joint qualification and beam design bending strength can be represented by the following equation, which includes a 1.67 factor that adjusts the required finger-joint tension strength based upon a laminating effect:

$$f_{t,fj,.05} = 1.67(f_{b,g,.05}) / (2.1C_v) \quad [1]$$

where:

$f_{t,fj,.05}$ = 5th percentile of finger-joint tensile strength

$f_{b,g,.05}$ = 5th percentile of glulam beam bending strength

C_v = volume effect

This relationship applies to finger-joints in nominal 2- by 6- inch (standard 38 by 140 mm) lumber. Adjustment factors are applied for widths other than the nominal 6 inches. If the strength of the tension lamination finger-joints does not meet this criterion, then the design bending strength of the glulam beams (f_{bg}) is controlled by finger-joint tensile

MATERIAL SELECTION AND BEAM MANUFACTURE

This section describes the manufacturing procedures for the studied glulam timber beams and sampling techniques

TABLE 7. — Visual grade limitations for Norwegian glulam laminating lumber.

Visual criterion	Grade LT20[a]
Ring width	8
Slope of grain	1/7
Face knot	b/3
Edge knot	t/2

[a] b = width of lumber piece; t = thickness of lumber piece.

for obtaining lumber and finger-joint specimens for experimental testing. Details of this experimental test program are found in Falk et al. (10).

Glulam beams manufactured in Europe are primarily produced from two species classifications: European Whitewood ***(Picea abies)*** and European Redwood ***(Pinus sylvestris).*** Norway spruce, a whitewood species, was studied for this project; the wood was provided by the largest manufacturer of lumber in Norway (Norske Skog A.S.). The lumber was visually graded by the manufacturer to meet the limitations of a Norwegian glulam industry visual grade, LT20. (Refer to **Table 7** for visual grade limitations for LT20 lumber.)

The test lumber (5,602 pieces) had nominal dimensions of 45 by 90 mm (2 by 4 in.) and variable length (2.2 to 4.5 m (7.2 to 14.8 ft.)). Each lumber piece was machine stress graded; displacement data were collected at 150-mm (6-in.) intervals along each piece. Average flatwise lumber stiffness (modulus of elasticity), denoted MOE_{mac}, was determined for each piece. After ranking all the lumber by MOE_{mac}, lumber pieces were selected from throughout this ranking (stratified random sampling) for material property testing.

Material property tests included 1) bending stiffness (edgewise), denoted MOE_{edge}; 2) bending strength (edgewise), denoted $f_{b,l}$; 3) tension strength, denoted $f_{t,l}$; 4) density; and 5) moisture content (MC). Lumber specimens were tested according to International Standards Organization standard ISO 8375 (12). All MOE data were adjusted to 12 percent MC, and all bending strength data were adjusted to a standard depth of 200 mm (7.8 mm) according to EN TC 124.203 (6). Note that the current reference width is 150 mm (6 in.) (prEN 338 (8)). Regression equations were established between various mechanical properties from the machine stress grading and material property data. This information was used to determine which lumber strength classes listed in **Table 1** would represent the supplied laminating lumber.

It was initially assumed that laminating grades C37-14E, C30-12E, C24-11E, and C21-1OE **(Table 1)** would represent the supplied lumber. However, a statistical analysis of the data indicated that the majority of the lumber (98%) fell into grades C37-14E and C30-12E, in almost equal proportion. Therefore, these grades (and glulam combinations that could utilize these grades) were targeted for testing. **Table 1** shows the minimum allowable lumber properties for these grades; **Table 8** shows the results of the experimental tests performed to determine these properties. More details (statistical distributions and regression relationships) of the results of the material property tests are provided in Falk et al. (10).

To obtain information required by ASTM D 3737 (4), information on the knot size distribution of grades C37-14E and C30-12E as well as on flatwise MOE (denoted MOE_{flat}) properties was gathered. The method used for determining the knot size distribution parameters from knot data measurements are outlined in Freas and Selbo (11). Flatwise MOE was determined for each piece by applying center-point loading over a l-m (39.4-in.) span, with the maximum visual characteristic of each piece of lumber at center span.

Table 9 shows the results of the knot analysis and measured MOE_{flat} properties for grades C37-14E and C30-12E. The table also includes properties estimated using ASTM D 3737 procedures (bending stress index and minimum strength ratio) for these grades. The bending stress index is based on the

TABLE 8. — Material property requirements and test results for laminating lumber grades.[a]

Property[a]	C30-12E Percentile[b]	C30-12E Required	C30-12E Test result	C30-12E COV[c] (%)	C37-14E Required	C37-14E Test result	C37-14E COV (%)
$f_{b,l,.05}$ (MPa ($\times 10^3$ psi))	5th	30 (4.35)	29.7 (4.31)	20.0	37 (5.36)	36.9 (5.35)	20.9
MOE_{edge} (GPa ($\times 10^6$ psi))	50th	12.000 (1.74)	12.505 (1.81)	15.9	14.000 (2.03)	15.180 (2.20)	14.7
	5th	8.500 (1.23)	8.965 (1.30)		10.000 (1.45)	11.865 (1.72)	
$f_{t,l,.05}$ (MPa ($\times 10^3$ psi))	5th	18 (2.61)	17.7 (2.56)	21.8	22 (3.19)	22 (3.22)	22.0
Density (kg/m^3 (pcf))	5th	410 (25.6)	422 (26.3)	7.7	450 (28.0)	460 (28.7)	7.9

[a] Data adjusted to 200 mm (6 in.) width per EN TC 124.203 (6).
[b] Percentiles determined using distributional estimates (50% tolerance limit) per Falk et al. (10)
[c] COV = coefficient of variation.

TABLE 9. — Measured and estimated properties of laminating lumber for ASTM D 3737 analysis.

Strength class	Measured[a] MOE	Measured[a] Average knot	Measured[a] Maximum knot	Estimated Strength ratio (SR_{min})	Estimated Bending stress index
	(GPa)(× 10^6 psi))	--------- (%) ---------			(MPa)(× 10^3 psi))
C30-12E	13.2 (1.91)	13.5	49.2	0.50	25.7 (3.0)
C37-14E	14.5 (2.11)	9.4	45.9	0.50	24.2 (3.5)

[a] Average knot is the average of the sum of all knot sizes within a 0.3-m (1-ft.) length, taken at 5-cm (2-in.) intervals. Maximum knot is the 99.5 percentile knot size.

TABLE 10. — Results of tests on finger-joints.[a]

Property	Tested strength classes C37-14E	Tested strength classes C30-12E
Tensile strength[b]		
$f_{t,fj,50}$	37.7 (5.47)	33.8 (4.91)
$f_{t,fj,.05}$ (75% tolerance)	28.2 (4.09)	25.5 (3.70)
Bending strength[c]		
$f_{b,fj,50}$	62.7 (9.09)	56.9 (8.25)
$f_{b,fj,.05}$ (50% tolerance)	51.9 (7.52)	48.7 (7.06)

[a] Failures not associated with finger-joints were not included in the analysis. Values are expressed in megapascals; values in parentheses are pounds per square inch (× 10^3).
[b] Based on lognormal distribution and adjustment to 150-mm (6-in.) width.
[c] Based on distributional estimates from Falk et al. (10) for European analysis.

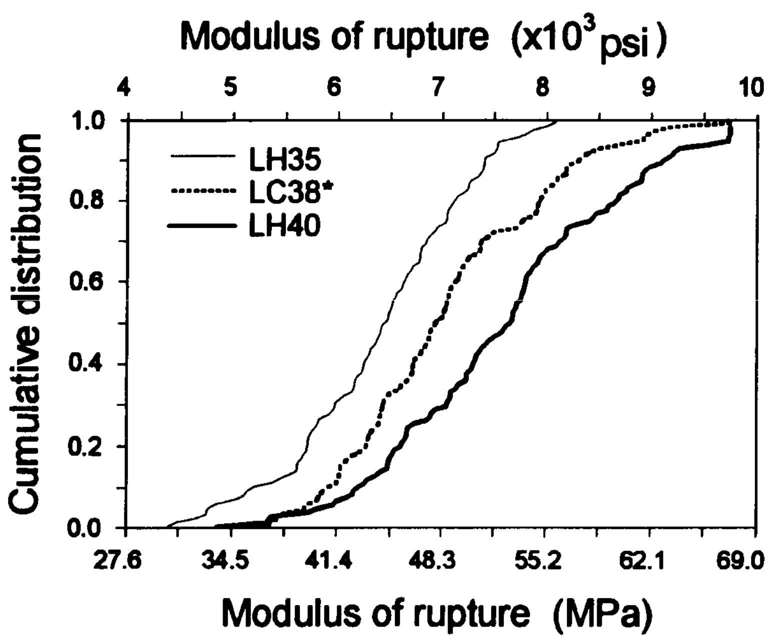

Figure 2. — Cumulative distribution of bending strength for tested glulam beams.

MOE_{flat} properties of grades C37-14E and C30-12E; the minimum strength ratio is based on the maximum edge-knot allowed by the original LT20 grade (50% edge knot).

FINGER-JOINT MANUFACTURE AND TESTING

Finger-joints were manufactured during the same production run as were full-sized glulam beams, which assured that the sample of tested finger-joints was representative of the joints used in the tested glulam beams. The finger-joints were vertically cut and had 15-mm- (0.60-in.-) deep fingers spaced at 3.5-mm (0.14-in.) intervals. Results of tension and bending tests are shown in **Table 10.**

GLULAM BEAM MANUFACTURE

The remainder of the laminations were sorted into the established C30-12E and C37-14E grades; three beam

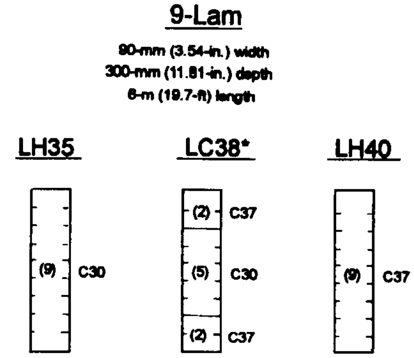

Figure 1. — Glulam beam layups. LH35 and LH40 are homogeneous layups; LC38* is a combined layup.

layups were targeted two homogeneous layups (LH35 and LH40) and one combined layup (LC38) **(Fig. 1; Tables 2** and **3).** The combined layup was necessarily constructed from C37-14E outer laminations and C30-12E inner laminations, not the C24-10E suggested in EN TC 124.207 (7). For this reason, the combined layup is referred to as LC38*. A total of 312 beams were manufactured from the various layups: LH35, 104 beams; LH40, 112 beams; and LC38*, 96 beams.

All beams were constructed of nine 33-mm- (1.3 -in.-) thick laminations and resulted in test beams 300 mm (12 in.) deep and 90 mm (3.5 in.) wide. Note that all beam combinations were symmetrical and no special tension laminations were used, as is standard practice in Europe.

The beams were manufactured by a commercial laminator (Raumnes Bruk A. S., Åmes, Norway) in 24-m (78-ft.) lengths. Laminations were finger-jointed, allowed to cure overnight, and then face-planed immediately before beams were glued and clamped. Phenol-resorcinol resin was used for bonding the finger-joints and for face-bonding the laminations. Temperature and humidity conditions were monitored and met Norwegian manufacturing standards.

TESTING PROCEDURES AND RESULTS

Beams were tested over a 5.4-m (17.5-ft.) span, with 1.8 m (5.9 ft.) between load heads. The MOE was measured in the shear-free zone between the load heads over a 1.5-m (4.9-ft.) span using an electronic displacement transducer in a manner similar to that specified in ISO 8375 (12). In addition, full-span MOE values were measured following procedures outlined in ASTM D 198 (5). These additional measurements were taken for the subsequent analysis using ASTM D 3737. MC readings were taken on each glulam beam, and the MOE values were adjusted to standard conditions (12% MC).

Distributions of bending strength ($f_{b,g}$) and long-span bending stiffness are shown in **Figures 2** and **3,** respectively. **Table 11** summarizes the glulam beam test results. Since the ISO 8375 (12) standard establishes MOE based upon shear-free deflection measurements, MOE values given by an ISO standard are expected to be higher than those determined by the American standard ASTM D 198 (5). In this study, we found that shear-free MOE (ISO) for glulam was on average 9 percent higher than long-span MOE (ASTM).

For the LH35 and LH40 layups, the 5th percentile estimate of beam bending strength (nonparametric, 50% tolerance limit) was found to be within 2 percent of the strength designations of EN TC 124.207 (7). For the LC38* layup, these requirements were exceeded. Note from **Figure 2** that there is no practical advantage in using the LH40 layup since the bending strength for this combination is about equal to that of the LC38* layup at the 5th percentile level, which uses approximately one third the number of high-grade laminations.

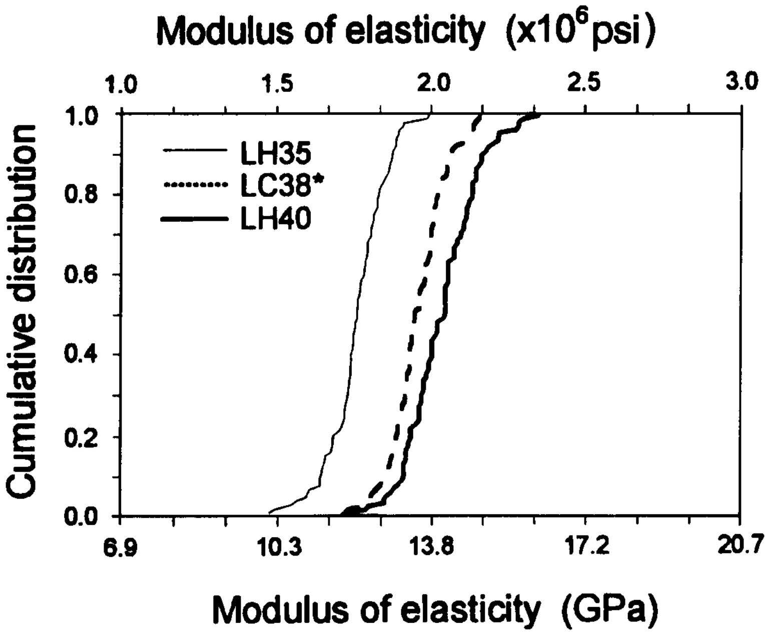

Figure 3. — Cumulative distribution of long-span bending stiffness for tested glulam beams.

Beams made with the LH40 layup were slightly stiffer than beams made with the LC38* layup because of the uniform use of the higher stiffness C37-14E grade. For the LH35 layup, 23 percent of the beams failed at the finger-joints, and 77 percent failed at defects in the laminations. In contrast, for the LH40 and LC38* layups, 34 and 45 percent of the beams, respectively, failed at the finger-joints, whereas the remainder failed at defects in the laminations. This result was expected because both the LH40 and LC38* layups contain the higher quality C37-14E lamination grade on the outer tension zone, and finger-joints are expected to initiate failure more of-ten in higher strength laminations.

PREDICTION OF BEAM PROPERTIES

European and U.S. standards were used to predict glulam beam performance on the basis of the material properties of the lumber and finger-joints. This allowed us to estimate the difference between glulam beams designed using European and American standards.

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 properties of the lumber and/or finger-joints. The CEN standard specifies a required characteristic bending strength for glulam beams, given the characteristic strength of the laminating lumber used in the beams. The following relationships are used to predict bending strength and stiffness of glulam beams made from laminations with an $f_{t,l,k}$ value less than 30 MPa (4,350 psi):

TABLE 11. — Property requirements and adjusted test results for glulam beam combinations.

	LH35		LC38*		LH40	
Property	Required	Test result	Required	Test result	Required	Test result
European reference[a]						
MOE (GPa (× 10^6 psi))						
shear free, 50th percentile	12.50 (1.81)	13.07 (1.89)	13.00 (1.84)	14.62 (2.19)	13.00 (1.84)	15.40 (2.23)
$f_{b,g,.05}$ (MPa (× 10^3 psi))	35.0 (5.07)	34.3 (4.97)	38.0 (5.51)	39.2 (5.68)	40.0 (5.80)	39.4 (5.71)
American reference[b]						
MOE (GPa (× 10^6 psi))						
full span, 50th percentile		12.11 (1.76)		13.45 (1.95)		14.03 (2.04)
$f_{b,g}$ (MPa (× 10^3 psi))		15.4 (2.23)		16.8 (2.43)		17.5 (2.54)

[a] Data not adjusted for depth. MOE was measured using ISO procedures—deflection relative to load points (shear-free).
[b] Data adjusted for volume per AITC (2). MOE was measured using ASTM procedures—deflection relative to supports (long-span).

TABLE 12. — European and U.S. predictions of glulam timber performance.

Property	LH35	LC38	LH40
European equations			
MOE (GPa (× 10^6 psi))			
50th percentile	13.84 (2.01)	14.14 (2.05)	15.24 (2.21)
$f_{b,g,.05}$ (MPa (× 10^3 psi))	35.3 (5.11)	35.8 (5.19)	40.3 (5.85)
U.S. methods			
MOE (GPa (× 10^6 psi))	12.56 (1.82)	13.62 (1.98)	13.78 (2.00)
$f_{b,g}$ (MPa (× 10^3 psi))			
I_k/I_g method	11.9 (1.72)	15.1 (2.19)	15.4 (2.24)
Strength ratio method	14.6 (2.12)	16.8 (2.43)	17.0 (2.46)

TABLE 13. — Comparison of referenced design parameters for European and U.S. glulam standards.

Property	European[a]	United States
Lumber		
MOE	Edgewise test, 50th percentile	Flatwise test, lognormal average
Bending Strength	Edgewise test, 5th percentile (50% tolerance limit)	None
Tensile strength	1-m span, 5th percentile (50% tolerance limit)[b]	None
Density	5th percentile (50% tolerance limit)	None
Finger-joints		
Qualification strength	Flatwise bending, 5th percentile (50% tolerance limit)[c]	Tensile strength, lognormal 5th percentile (75% tolerance limit)
Glulam beams		
MOE	Shear-free, 50th percentile	Long-span, lognormal average
Bending strength	5th percentile (50% tolerance limit)[d]	Lognormal 5th percentile (75% tolerance limit)[e]

[a] All European statistical estimates are nonparametric.
[b] 1 m = 0.3048 ft.
[c] Difference between the 50 percent tolerance limit and 75 percent tolerance depends on sample size.
[d] Final design strength adjusted to standard depth of 600 mm (23.6 in.)
[e] Final design strength adjusted to standard volume according to AITC (2).

5th percentile bending strength

$$f_{b,g,.05} = 12 + f_{t,l,.05} \quad [2]$$

Average glulam stiffness (shear-free), maximum of either

$$E_{0,g,50} = (1.25 - E_{0,l,50}/60{,}000)E_{0,l,50} \quad [3]$$

or

$$E_{0,g,50} = 1.05E_{0,g,50} \quad [4]$$

Therefore, to predict beam strength and stiffness, the characteristic properties of the experimentally tested lumber **(Tables 8** and **9)** were used in Equations **[2]** through **[4]** to obtain the predicted characteristic properties of the glulam beams.

Table 12 shows the results of this analysis and indicates that the predicted strength and stiffness are very comparable to the actual (tested) beam properties. In regard to stiffness (50th percentile of shear-free beam MOE), the percentage of difference between the actual and predicted performance was 2.8, 8.5, and 3.0 percent for the LH35, LC38*, and LH40 layups, respectively. For strength (nonparametric 5th percentile of beam modulus of rupture), the difference between the actual and predicted performance was 13.9, 13.1, and 17.6 percent for the LH35, LC38*, and LH40 layups, respectively.

In addition to the lumber/glulam relationship, criteria in prEN 1194 (9) for minimum strength properties for finger-joints are also given. The European standard for finger-joint quality control is based on a bending test, where the strength level of the finger-joints must meet the following relationship:

$$f_{b,fj,.05} \geq 1.30\ f_{b,g,.05} \quad [5]$$

If the characteristic finger-joint bending strength falls below the characteristic bending strength of the glulam beams, finger-joints would control the design level of the beams. In this study, the characteristic bending strength of the C37-grade finger-joints exceeded the characteristic bending strength of the LC38* and LH40 beams by 37 and 32 percent, respectively **(Table 10).** The characteristic bending strength of the C30-grade finger-joints exceeded the characteristic bending strength of the LH35 beams by 48 percent.

Prediction with American Standards

The beams tested in this study were also evaluated by U.S. design methods to determine how well these methods can predict European beam performance. This should help U.S. glulam manufacturers determine American glulam designs appropriate for the European market. The U.S. standard ASTM D 3737 is the basis for determining allowable bending stresses for glulam timber. This analysis was conducted using the measured knot and MOE properties given in **Table 9** for the lumber grades used for beam construction. Results of this analysis are given in **Table 11.** Since U.S. standards specify a lognormal distribution tit to beam data, this distribution was used for comparing beam strength.

The beam stiffness results (average long-span beam MOE) from **Table 11** show that the percentage of difference between the actual and predicted performance was 3.6, 1.3, and 1.8 percent for the LH35, LC38*, and LH40 layups, respectively.

For strength (75% tolerance limit of the lognormal 5th percentile of beam modulus of rupture), the difference between the actual performance and the performance predicted with the ASTM standard D 3737 procedures was 22.7, 10.1, and 12.0 percent for the LH35, LC38*, and LH40 layups, respectively. This prediction of strength is based on a minimum strength ratio (SR_{min}) that corresponds to a maximum allowable edge knot of 50 percent of the cross section (assumed SR_{min} equals 0.50; **Table 9)** and corresponds to the criteria for the LT20 visual grade. As indicated in Appendix 2 of Falk et al. (10), a significant percentage of the visually graded lumber was of higher quality than that of the LT20 grade. Thus, it is likely that the mechanically sorted C37 and C30 grades would be better represented by an SR_{min} greater than 0.50.

If a minimum strength ratio is selected that more closely corresponds to a higher stiffness material (as indicated by the MOE_{flat} results of **Table 9** and the strength ratio $/MOE_{flat}$ relationships typically used in U.S. design procedures), an SR_{min} value of 0.70 can be justified. Using this "SR_{min} override" on the D 3737 procedures, the difference between the actual and newly predicted bending strength performance was 5.2, 0, and 0.3 percent for the LH35, LC38*, and LH40 layups, respectively.

When comparing European- and U.S.-designed glulam beams, it should be noted that the design properties referenced by these two methods are significantly different. These different design parameters for lumber, finger-joints, and till-size glulam beams are summarized in **Table 13.**

CONCLUSIONS

In general, the results of this study show that high yields of two machine-stress-rated Norwegian spruce laminating grades are characterized by two strength classes: a high grade that meets a 37 MPa (5,360 psi) characteristic bending strength and 14,000 MPa (2.0×10^6 psi) modulus of elasticity, and a lower grade that meets a 30 MPa (4,350 psi) characteristic bending strength and 12,000 MPa (1.7×10^6 psi) modulus of elasticity. Glulam beams constructed from these grades exhibited strength and stiffness characteristics that met CEN standards.

The procedures for predicting the performance of glulam beams using the European prediction equations gave good approximations of actual beam strength and stiffness, where predictions were based on a straightforward application of the mechanical properties of the lumber. Predictions of glulam strength and stiffness using the U.S. standard also compared well, although they required some assumptions for clear wood properties of lumber and maximum allowable knot sizes for a particular grade.

The information gained in this study will help U.S. glulam manufacturers match their product to the appropriate stress-class categories accepted by European standards.

LITERATURE CITED

1. American Institute of Timber Construction. 1988. Standard specifications for structural glued laminated timber of softwood species. AITC 117-88-Manufacturing. AITC, Vancouver, Wash.
2. __________. 1991. Use of a volume effect factor in the design of glued laminated timber beams. Tech. Note 21. AITC, Englewood, Colo.
3. American National Standards Institute/American Institute of Timber Construction. 1992. Structural glued laminated timber. ANSI/AITC A190.1. ANSI/AITC, Englewood, Colo.
4. American Society for Testing and Materials. 1993. Standard method for establishing stresses for structural glued- laminated timber (glulam). ASTM D 3737-91. ASTM, Philadelphia, Pa.
5. __________. 1993. Standard method for evaluating allowable properties for grades of structural lumber. ASTM D 198-84. ASTM, Philadelphia, Pa.
6. Comite European de Normalisation. 1990. Structural timber—strength classes. Draft standard EN TC 124.203. Brussels, Belgium.
7. __________. 1990. Glued laminated timber—strength classes and determination of characteristic properties. Draft standard EN TC 124.207. Brussels, Belgium.
8. __________. 1991. Structural timber—strength classes. Draft Standard prEN 338. Sept. Brussels, Belgium.
9. __________. 1993. Glued laminated timber—strength classes and determination of characteristic properties. Draft Standard prEN 1194. Brussels, Belgium.
10. Falk, R.H, K.J. Solli, and E. Aasheim. 1992. The performance of glued-laminated timber beams manufactured from machine stress graded Norwegian spruce. Rept. No. 77, Norwegian Institute of Wood Technology, Oslo, Norway.
11. Freas, A.D. and M.L. Selbo. 1954. Fabrication and design of glued laminated wood structural members. Tech. Bull. No. 1069, USDA Forest Serv., Forest Prod. Lab., Madison, Wis.
12. International Standards Organization. 1985. Solid timber in structural sizes: Determination of some physical and mechanical properties. ISO 8375. ISO, Geneva, Switzerland.

on recycled paper