Laminating Effects in Glued-Laminated Timber Beams

By Robert H. Falk[1] and François Colling[2]

Abstract: Existing lamination and beam test results were analytically reviewed to quantify the laminating effect for European and North American glued-laminated (glulam) timber. The laminating effect is defined as the increase in strength of lumber laminations when bonded in a glulam beam compared with their strength when tested by standard test procedures. Fundamental concepts are presented to define the laminating effect, estimates are made of its magnitude, and relationships are presented to describe its character. Our review of experimental data indicated that the laminating effect ranged from 1.06 to 1.59 for European glulam and from 0.95 to 2.51 for North American glulam.

INTRODUCTION

Glued-laminated (glulam) beams are highly engineered timber products that are used in a variety of structural and architectural applications. Structural uses range from 150 mm (6 in.) deep members used in trusses and window and door headers to 2.5 m (100 in.) deep members used in long-span structures. To produce glulam, individual lumber lengths, ranging in width from 100 mm (4 in.) to 300 mm (12 in.), are finger-jointed together into long laminations that are then bonded together with waterproof adhesives. Typical thicknesses of the laminations are nominal 50.8 mm (2 in.) in the United States, Canada, the United Kingdom, and Scandinavia; and 36 mm (1.41 in.) in central European countries. Glulam has the following advantages over solid-sawn timber:

- Deeper, wider, and longer members can be produced
- Cambered, curved, and tapered configurations can be easily fabricated
- Lower-grade lumber can be used in lower-stressed zones of the member, resulting in more efficient use and, therefore, conservation of the timber resource
- Predrying the laminations leads to less member deformation and, therefore, less distress in the structure
- Naturally occurring, strength-reducing defects (e.g., knots) are randomized throughout the beam volume

An important characteristic of glulam manufacture is that the bonding of laminations can result in beams of higher strength than the strength of the single laminations from which they are constructed. This increase in strength is important because quality control measures used to determine necessary lamination quality are dependent on its magnitude.

There is confusion about this laminating effect, the physical explanations for its existence, and its magnitude. This paper discusses the laminating effect and quantifies its magnitude based on both European and North American lamination tensile strength and glulam beam bending strength data.

FUNDAMENTAL CONCEPTS

The most fundamental definition of the so-called laminating effect is a strength increase of lamination lumber as a result of being bonded into a glulam beam. A measure of this effect, the laminating factor λ, is typically computed by determining the ratio of the ultimate bending strength of a population of glulam beams (exhibiting wood failure) to the tensile strength of a population of lamination lumber

$$\lambda = f_{b,gl}/f_{t,\mathrm{lam}} \tag{1}$$

where $f_{b,gl}$ = mean bending strength of a population of glulam beams; and $f_{t,\mathrm{lam}}$ = mean tensile strength of a population of lamination lumber.

Similarly, a laminating factor can be calculated for the effect of finger joints by computing the ratio of the bending strength of a population of glulam beams (failing at finger joints) to the tensile strength of a population of finger-joint specimens

$$\lambda = f_{b,gl}/f_{t,fj} \tag{2}$$

where $f_{t,fj}$ = mean tensile strength of a population of finger joints.

Because characteristic strength values (typically, lower 5th percentiles) are used to establish design values for glulam, a laminating effect at this characteristic strength level can be determined. Determining characteristic strength values from a population of test data, this factor can be directly determined using a characteristic form of (1) as follows:

$$\lambda_k = f_{b,gl,k}/f_{t,\mathrm{lam},k} \tag{3}$$

where k refers to "characteristic." In general, a characteristic strength can be written as

$$f_k = f\cdot(1 - k_5\cdot v) \tag{4}$$

where f_k = characteristic strength; f = mean strength; v = coefficient of variation (COV); and k_5 = a statistical distribution constant to calculate the 5th percentile (in the case of a normal/Gaussian distribution at the 50% tolerance limit, $k_5 = 1.645$). Substituting (4) into (3) yields

$$\lambda_k = (f_{b,gl}/f_{t,\mathrm{lam}})\cdot k_{\mathrm{var}} \tag{5}$$

where

$$k_{\mathrm{var}} = (1 - k_5\cdot v_{b,gl})/(1 - k_5\cdot v_{t,\mathrm{lam}}) \tag{6}$$

with $v_{b,gl}$ = COV of glulam beam bending strength; and $v_{t,\mathrm{lam}}$ = COV of lamination lumber tensile strength. Combined with (1), (5) becomes

$$\lambda_k = \lambda\cdot k_{\mathrm{var}} \tag{7}$$

The factor k_{var} takes into account different test data COV for the glulam tested in bending and the lamination lumber tested in tension. For most glulam, values of $v_{b,gl}$ typically range from about 0.15 to 0.20. Lamination lumber tensile strength is usually more variable, with $v_{t,\mathrm{lam}} \approx 0.25$. This results in a k_{var} that ranges between approximately 1.15 and 1.30, implying that lamination effects at the 5th percentile level are 15–30% higher than at the mean strength level.

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Examination of lamination and beam test results suggests that the apparent strength increase due to the lamination effect is a summation of separate, though interrelated, physical effects, some of which are a result of the testing procedure and others the effect of the bonding process.

Effect of Tension Test Procedure

A difference exists in the tension performance of single lumber laminations as measured by standard test methods and their actual performance in a beam. Existing European and North American test methods [i.e., ISO 8375 (1985), ASTM D198 (*Standard* 1984)] for tension testing suggest a test configuration that provides no lateral restraint to the tension member. Although this test configuration is applicable for the simulation of free tension members, such as web members in trusses, it does not necessarily represent a lamination in a glulam beam.

According to these standard tests methods, uncentered defects (such as edge knots) or areas of unsymmetrical density can induce lateral bending stresses that, when combined with applied tensile stresses, reduce the measured tensile strength (Fig. 1). In a glulam beam, lateral bending stresses are negligible since these defects are offered nearly rigid lateral restraint because of the lamination bonding (Foschi and Barrett 1980). Thus, the tension lamination in a glulam beam has an apparent tensile strength higher than that indicated in a free tension test. The magnitude of this increase is a function of beam depth; the tension lamination in a shallow beam is subjected to both tension and bending stresses, while the tension lamination in a deep beam is subjected mainly to tension stresses.

In addition, the length of the test specimen between the grips of the tension machine affects test results. As the specimen length increases, the probability of an uncentered defect also increases.

Reinforcement of Defects

When bonded in a glulam beam, defects (e.g., knots) and other low-stiffness areas are reinforced (on at least one side) by adjacent laminations. This reinforcement provides alternative paths for stresses to flow around the defect through adjacent high-stiffness areas of neighboring laminations (Fig. 2). Thus, the laminating process reinforces defects existing in a lamination by redistributing stresses around the defect through the clear wood of adjacent laminations, thereby increasing the capacity of the cross section containing the defect.

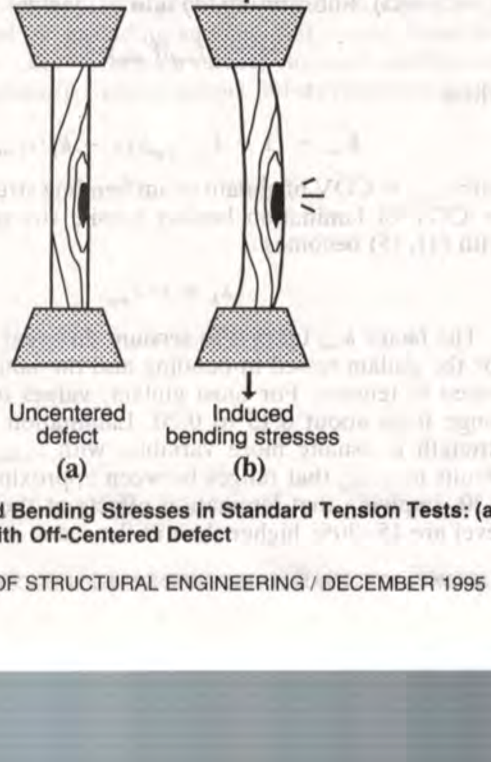

FIG. 1. Induced Bending Stresses in Standard Tension Tests: (a) No Defect; (b) with Off-Centered Defect

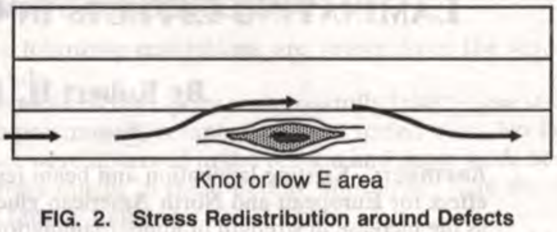

FIG. 2. Stress Redistribution around Defects

Although knots are typically lower in stiffness than the surrounding clear wood, finger-joint stiffness is strongly correlated to the average stiffness of the clear wood of the joined laminations (Burk and Bender 1989). Because of this correlation, it is speculated that little stress redistribution takes place around finger joints.

Dispersion of Low-Strength Lumber

Test data indicate that the bending strength distribution for glulam beams has a higher mean value and a lower COV than the tensile or bending strength distribution of the lamination lumber. This is due, in part, to the effect of testing procedure and the reinforcement of defects as explained earlier.

In addition, there is an effect of dispersion. If a population of lumber is tested in tension, the lower strength pieces will be represented in the calculation of the characteristic estimate of the population, $f_{t,\mathrm{lam},k}$. However, if the same population of tension specimens were fabricated into a glulam beam, the probability that the lowest strength pieces would end up in a high-stressed location that initiates failure is lessened. In other words, because low-strength lumber pieces are distributed throughout the beam volume, there is a decreased probability that the lowest strength lumber piece will initiate beam failure. Thus, this dispersion of low-strength lumber laminates in a glulam beam may provide an additional strengthening effect. However, the bending strength of glulam beams with greater dimensions is not affected only by the quality of the outer lamination. Failure may also be initiated in the second or third lamination (from the tension side). In this case, the higher number of potential failure points can reduce the dispersion effect.

Statistically, the dependency of beam failure on the probability of a low-strength lamination in a high-stressed zone includes a "size effect." If laminations with a given strength distribution are used to produce glulam beams of different sizes (lengths, depths), the lamination factors determined will differ for each beam size because the bending strength of the glulam depends on the dimensions of the beams.

QUANTIFICATION OF LAMINATING EFFECT

Based on the foregoing discussions, the laminating factor of (1) may be written as

$$\lambda = k_{\mathrm{test}} \cdot k_{\mathrm{reinf}} \cdot k_{\mathrm{disp}} \qquad (8)$$

with k_{test}, k_{reinf}, and k_{disp} corresponding to the test, reinforcement, and dispersion effects. Because these effects, test procedure, reinforcement, and dispersion are interrelated, they are difficult to quantify (Colling and Falk 1993). They vary and depend on several parameters, including lumber lamination quality (or grade) and beam layup. Even in the improbable case of identical lumber quality, different test series will lead to different results. Consider, for example, tests performed to determine the factor k_{test}. Assume that lateral displacements occurring in a free tension test are measured and k_{test} is calculated for each lamination. It is apparent that k_{test} will be statistically distributed in some way. This creates a problem in that the actual value of k_{test} corresponding to the lumber piece with a mean strength is not necessarily identical to the mean value of the k_{test} distribution.

This implies that the values for k_{test}, k_{reinf}, and k_{disp} in (8) can only be mean estimates derived on the basis of mean strength values. From (7), the lamination factor at the characteristic strength level may be estimated as

$$\lambda_k = k_{test} \cdot k_{reinf} \cdot k_{disp} \cdot k_{var} \quad (9)$$

For characteristic strength values, the following relationship is assumed valid:

$$\lambda_k = k_{test,5} \cdot k_{reinf,5} \cdot k_{disp,5} \quad (10)$$

The factors $k_{test,5}$, $k_{reinf,5}$, and $k_{disp,5}$ do not correspond to a 5th percentile of each factor, but to a mean estimate of the corresponding effects when the characteristic strengths (5th percentiles) are used as a basis for calculation.

In addition to the statistical difficulties discussed earlier, other influences affect the quantification of $k_{test,5}$, $k_{reinf,5}$, and $k_{disp,5}$. For example, k_{test} increases as the grade of lamination decreases because increasing the knot size presumably increases the magnitude of lateral displacement. The k_{reinf} values should also increase with a decreasing grade because redistribution of stresses increases as the number of low-stiffness zones increases. The factor k_{disp} varies with the lamination grade, the size and layup of the beam (homogeneous or combined grades), and with the relative population size of the lamination and beam tests.

EXPERIMENTAL AND SIMULATED DATA ANALYSIS

To quantify the magnitude of the laminating effect, beam and lamination test data as well as computer-simulated beam strength values were evaluated. We focused on the laminating effect computed from lamination lumber strength (not finger-joint strength) and beams exhibiting wood failures (not finger-joint failures). Both European and North American lumber lamination and beam strength data were evaluated. Although there is considerable experimental beam test data available for both European and North American glulam, few studies include matched test data on lamination tensile strengths. For the study reported here, the only beam data considered was that for which appropriate lamination tensile strength data were available.

To supplement beam test data, we used the Karlsruhe Model, a finite-element-based computer model developed in Germany, to simulate the strength of European glulam beams (Ehlbeck et al. 1985; Colling 1988, 1990a). This model uses lamination and finger-joint statistics [lumber density, modulus of elasticity (MOE) and strength] to predict the strength and stiffness of glulam beams of various layups. Input data for the laminations are based on tension and compression tests that do not allow lateral displacements of the specimens, that is, $k_{test} = 1.0$.

Likewise, a computer analysis model developed in the United States, PROLAM, was also used to supplement beam test data by simulating the strength of North American glulam beams (Hernandez et al. 1992). This model uses distributions of the mechanical properties of laminating stock (long-span MOE and short-span tensile strength) to determine the mechanical properties of glulam beams.

Adjustments to Experimental Data

In addition to adjusting experimental test data for moisture content and loading configuration, adjustments were made for member size. It has long been recognized that the bending strength of glulam beams is reduced as the size of the member increases (Moody et al. 1990). Similarly, as the length and width of a lamination lumber tension test specimen increases, the apparent tensile strength decreases. To account for these size effects, the different sized beams and laminating lumber evaluated in the study reported here were adjusted to a common size.

European Data Adjustments

The European experimental beam data were adjusted by multiplying the determined bending-strength values by the factor

$$k_{h,gl} = (h/600)^{0.2} \quad (11)$$

which adjusts the beam strength to a common depth h of 600 mm (24 in.) (Comite European de Normalisation 1993). The lumber tension strengths were adjusted to a common width of 150 mm (6 in.) using the following:

$$k_{h,lam} = (w/150)^{0.2} \quad (12)$$

where w = width of lamination lumber.

Because no formal length-adjusting equation is specified in the European standards, no adjustment for lamination length was made to the lumber tension strength data. For the specimen lengths evaluated [1.0–2.5 m (3.3–8.2 ft)], little effect of length is expected as long as the grade-determining defect is placed between the grips of the tension machine. An exception was made for lumber data used in some of the simulated beam data from the Karlsruhe model (Ehlbeck et al. 1985; Colling 1988, 1990a), where 4.5 m (14.8 ft) lamination data were used as input. The tensile-strength data were increased by 12% to adjust them to a length of 2 m (6.6 ft), based on the findings of Görlacher (1990).

North American Data Adjustments

For the North American data, the following volume equation was used to adjust beam strength data to a common size (AITC 1991). The following references a beam 130 mm (5 1/8 in.) wide (w), 300 mm (12 in.) deep (d), and 6.4 m (21 ft) long (l)

$$C_v = (5.125/w)^{0.1} \cdot (12/d)^{0.1} \cdot (21/l)^{0.1} \quad (13)$$

No adjustment was made to the North American lamination tension test data for width, because all test data were from specimens with a reference width of 150 mm (6 in.). Also, no adjustment was made for lumber length since all lamination data were from specimens of consistent length [2.1 m (7 ft)].

European Data

Table 1 summarizes test data and laminating factors that were computed from test data for European glulam. Bending tests were performed by Larsen (1982) on a total of 144 glulam beams [233 mm (9.2 in.) in depth] representing 33 different beam layups. By comparing mean tensile-strength values of the laminations with the mean bending strength values of the glulam beams, a lamination factor λ was calculated for each beam type. Values of λ increased with decreasing grade and ranged from 1.06 to 1.30.

Tests by Gehri (1992) estimated both λ and λ_k based on 35 tension tests of high-stiffness laminations and eight bending tests of 500 mm (19.7 in.) deep glulam beams. The results indicated $\lambda = 1.12$ and $\lambda_k = 1.56$.

Tests by Falk et al. (1992) provided estimates of λ and λ_k for glulam produced in Norway. For homogeneous beams constructed of tension laminations meeting the C30 grade, λ

TABLE 1. European Beam Data and Computed Laminating Factors

Source and lamination grade (1)	Beam Depth mm (2)	Beam Depth in. (3)	$f_{t,lam,05}$[a] MPa (4)	$f_{t,lam,05}$[a] sq in. (5)	$f_{t,lam,50}$[a] MPa (6)	$f_{t,lam,50}$[a] sq in. (7)	$f_{b,gl,05}$[b] MPa (8)	$f_{b,gl,05}$[b] sq in. (9)	$f_{b,gl,50}$[b] MPa (10)	$f_{b,gl,50}$[b] sq in. (11)	λ_k (12)	λ (13)
Larsen (1982)												
T400+	233	9.2	—	—	52.6	7,623	—	—	55.7	8,072	—	1.06
T400	233	9.2	—	—	36.1	5,232	—	—	41.1	5,957	—	1.14
T300+	233	9.2	—	—	41.4	6,000	—	—	47.9	6,942	—	1.16
T300−	233	9.2	—	—	24.7	3,580	—	—	27.7	4,014	—	1.12
Ucl+	233	9.2	—	—	31.7	4,594	—	—	40.2	5,826	—	1.27
Ucl	233	9.2	—	—	22.5	3,261	—	—	26.0	3,768	—	1.16
Ucl−	233	9.2	—	—	21.3	3,087	—	—	27.8	4,029	—	1.30
Gehri (1992)	500	19.7	32.0	4,638	50.0	7,246	50.1	7,261	55.9	8,101	1.56	1.12
Falk (1992)												
C30	300	11.8	18.7	2,710	30.4	4,406	29.8	4,319	38.4	5,565	1.59	1.26
C37	300	11.8	23.6	3,420	37.0	5,362	34.3	4,971	45.5	6,594	1.45	1.23
C37/C30 (Combined)	300	11.8	23.6	3,420	37.0	5,362	34.1	4,971	42.3	6,130	1.44	1.14

[a]Adjusted to 150 mm (6 in.) width per (12).
[b]Adjusted to 600 mm (24 in.) depth per (11).

= 1.26 and λ_k = 1.59. Use of higher grade C37 laminations in a homogeneous layup resulted in λ = 1.23 and λ_k = 1.45. The use of C37 grade as the outer lamination in a combined layup resulted in beams with λ = 1.14 and λ_k = 1.44. This investigation, which was based on several hundred lamination and beam bending tests, confirmed a decreasing lamination effect with increasing lamination quality, and a higher lamination factor at the 5th percentile level than at the mean strength level.

To illustrate the results of this analysis, the experimental beam data are combined and plotted (Fig. 3). These results are combined with data from Colling (1990) and Colling et al. (1991), which are a mixture of German test data and simulation results using the Karlsruhe model (Görlacher 1990; unpublished calculations, 1992). A strong linear relationship exists between the lamination tensile strength and the beam bending strength (Fig. 3). The results of the Karlsruhe model simulation follow the same trend as the experimentally tested beams. The data from Table 1 are plotted in Fig. 3 and can be described by the following regression equation (in megapascals):

$$f_{b,gl,k} = 7.35 + 1.12 \cdot f_{t,lam,k} \tag{14}$$

with a coefficient of correlation r = 0.945, or by using (1)

$$\lambda_k = 1.12 + 7.3/f_{t,lam,k} \tag{15}$$

This relationship indicates a λ_k range of 1.4–1.9 for lamination tensile strength (5th percentiles) ranging from 10 to 30 MPa (1,450–4,350 lb/sq in.), with the highest value of λ_k corresponding to the lowest strength value.

Considering the test results of Falk et al. (1992), Gehri (1992) proposed the following relationship to estimate the characteristic bending strength of a 600 mm (24 in.) deep glulam beam, based on the characteristic tensile strength of the laminations

$$f_{b,gl,k} = 12 + f_{t,lam,k} \tag{16}$$

A comparison with test and simulation results shows this relationship [(16)] predicts a greater lamination effect than that predicted by (14), especially for low-quality laminations. Using (1), (16) can be written as

$$\lambda_k = 1 + 12/f_{t,lam,k} \tag{17}$$

Eq. (15) is the basis for the current draft of the European standard prEN 1194 (Comite European de Normalisation 1993). Eqs. (14)–(17) are valid only for strength values in megapascals.

According to (15), a lamination with a characteristic tensile

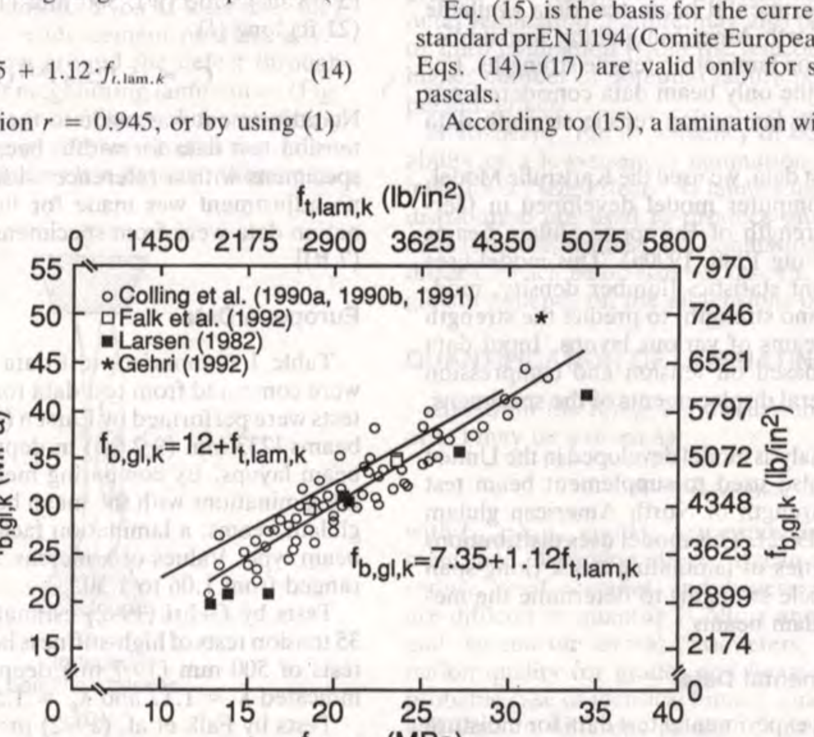

FIG. 3. European Glulam Data

TABLE 2. North American Beam Data and Computed Laminating Factors

Source and lamination grade	Beam Depth		$f_{t,\mathrm{lam},05}$		$f_{t,\mathrm{lam},50}$		$f_{b,gl,05}$[a]		$f_{b,gl,50}$[a]			
	mm	in.	MPa	sq in.	MPa	sq in.	MPa	sq in.	MPa	sq in.	λ_k^*	λ
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Foschi and Barrett (1980)												
B	305	12	—	—	35.7	5,177	—	—	51.2	7,419	—	1.43
B	457	18	—	—	35.7	5,177	—	—	39.7	5,748	—	1.11
D	152	6	—	—	19.0	2,758	—	—	30.9	4,484	—	1.63
D	305	12	—	—	19.0	2,758	—	—	28.9	4,195	—	1.52
D	305	12	—	—	19.0	2,758	—	—	26.7	3,875	—	1.41
D	610	24	—	—	19.0	2,758	—	—	29.1	4,214	—	1.53
Rammer and Soltis (1994)												
302-24 (SP: 24F-V5 layup)	279	11	43.7	6,330	—	—	45.5	6,602	—	—	1.04	—
302-24 (SP: 24F-V5 layup)	279	24	43.7	6,330	—	—	41.6	6,028	—	—	0.95	—
Marx and Moody (1981)												
L1	76	3	17.0	2,470	—	—	32.7	4,744	—	—	1.92	—
L1	152	6	17.0	2,470	—	—	41.7	6,040	—	—	2.44	—
L1	229	9	17.0	2,470	—	—	34.3	4,965	—	—	2.01	—
L3	76	3	7.3	1,050	—	—	16.6	2,410	—	—	2.29	—
L3	152	6	7.3	1,050	—	—	14.7	2,136	—	—	2.03	—
L3	229	9	7.3	1,050	—	—	17.3	2,514	—	—	2.39	—
No. 2	76	3	10.5	1,520	—	—	24.2	3,510	—	—	2.31	—
No. 2	152	6	10.5	1,520	—	—	26.4	3,822	—	—	2.51	—
No. 2	229	9	10.5	1,520	—	—	20.3	2,937	—	—	1.93	—
Moody et al. (1990)												
302-24 (DF: 24F-V3 layup)	610	24	27.7	4,020	—	—	35.3	5,115	—	—	1.27	—
302-24 (DF: 24F-V3 layup)	1,220	48	27.7	4,020	—	—	35.9	5,197	—	—	1.29	—

[a]Adjusted to 300 mm (12 in.) depth per (13).

strength of 18 MPa (2,600 lb/sq in.) would be strengthened by about 52% ($\lambda_k = 1.52$) after being bonded into a glulam beam. Eqs. (14)–(17) are valid only for beam strengths at a depth of 600 mm (24 in.).

North American Data

To establish a meaningful relationship between $f_{t,\mathrm{lam},k}$ and $f_{b,gl,k}$, a wide range of lamination tensile strengths should be considered. Unfortunately, data on North American glulam beam strengths constructed with lower-grade tension laminations are limited. Typically, special high-grade tension laminations are used in most North American glulam manufacture (Marx and Evans 1986). An exception is the study performed by Marx and Moody (1981) in which 90 beams of lower grade (Douglas fir L1, L3 and southern pine No. 2 grades) were tested. Using lamination tensile-strength data tested by Marx and Evans (1988), laminating factors for these beams were computed. Lamination factors were found to range from $\lambda_k = 1.92$ to 2.51 (Table 2).

The bending capacity of Douglas-fir glulam beams of different sizes and layups was studied by Foschi and Barrett (1980). Analysis of this test data indicated a clear tendency of decreasing λ with the increasing quality of the laminations. Laminating factors were found to range between 1.14 and 1.43 for higher-grade laminations (grade B) and between 1.41 and 1.63 for the lower lamination grade D (Table 2).

Rammer and Soltis (1994) investigated the bending and shear performance of 20 southern-pine glulam beams of two depths and lengths. These beams were manufactured with tension laminations of the 302-24 grade. Because their study did not include the collection of lamination tensile-strength data for this lamination grade, data from Marx and Evans (1986) were used. Lamination factors of $\lambda_k = 0.95$ and 1.04 were found for these data (Table 2).

Moody et al. (1990) reported the results of bending tests on 45 glulam beams with depths of 600 mm (24 in.) and 1,200 mm (48 in.). This represents the largest beams evaluated, and laminating factors were found to be nearly equal, with $\lambda_k =$ 1.27 and 1.29, respectively.

The computer model PROLAM was also used to estimate the strength of glulam beams. PROLAM requires a statistical distribution of lamination tensile strengths for each laminating grade. Currently, the necessary input data are not available for southern pine laminating lumber; thus, only Douglas-fir beams could be simulated using this model. The simulation data represents Douglas-fir beam layups using laminating grades L1, L2, L3, and 302-24 and meeting the requirements of AITC (1993) (Fig. 4).

The data from Table 2 as well as the PROLAM simulation results indicate a nonlinear relationship between $f_{b,gl,k}$ and $f_{t,\mathrm{lam},k}$ (Fig. 4). The regression equation describing this relationship is (in lb/sq in.)

$$f_{b,gl,k} = -12{,}215.3 + 2{,}145 \cdot \ln(f_{t,\mathrm{lam},k}) \tag{18}$$

with a coefficient of correlation $r = 0.746$; or by using (1),

$$\lambda_k = [-14{,}877.4 + 2{,}486 \cdot \ln(f_{t,\mathrm{lam},k})]/f_{t,\mathrm{lam},k} \tag{19}$$

This relationship indicates a λ_k range of 1.2–2.2 for lamination tensile strengths (5th percentiles) ranging from 1,450 to 5,800 lb/sq in. (10–40 MPa).

ANALYSIS

Several observations can be made by comparing the European and North American data. First, the laminating factors found from the North American data are generally greater than those from the European data. The North American data include several sets of beams with lower-grade laminations than those represented in the evaluated European data. The size factor used to adjust the European beam bending strength [(11)] uses a different exponent and references a different beam depth than the North American size, (13). Thus, there is a greater difference between $f_{t,\mathrm{lam},k}$ and $f_{b,gl,k}$ for the North American data than there is for the European data.

Figs. 3 and 4, and (14) and (18) show that the relationship between $f_{t,\mathrm{lam},k}$ and $f_{b,gl,k}$ for European glulam is linear. For the North American glulam, as lamination tensile strength increases, the rate of increase of glulam bending strength decreases. We suspect 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. This comparison can be illustrated by plotting the

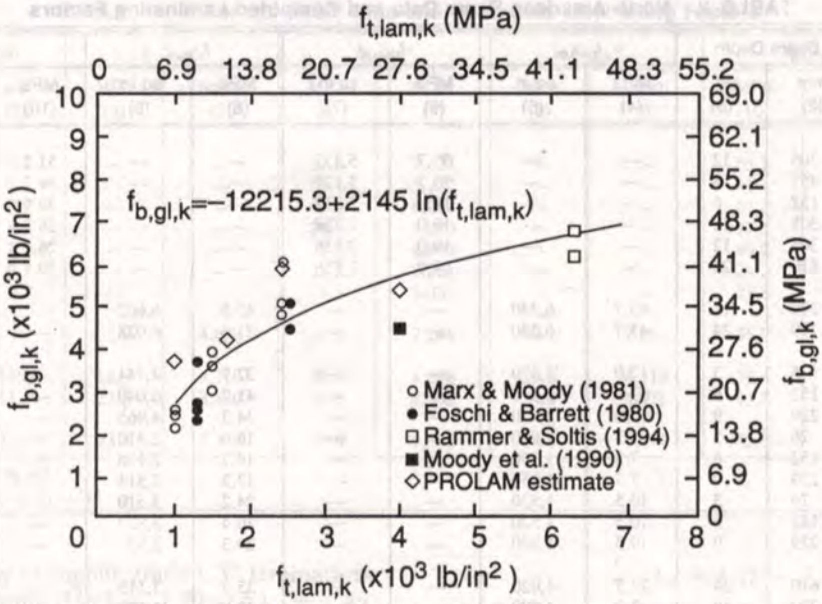

FIG. 4. North American Glulam Data

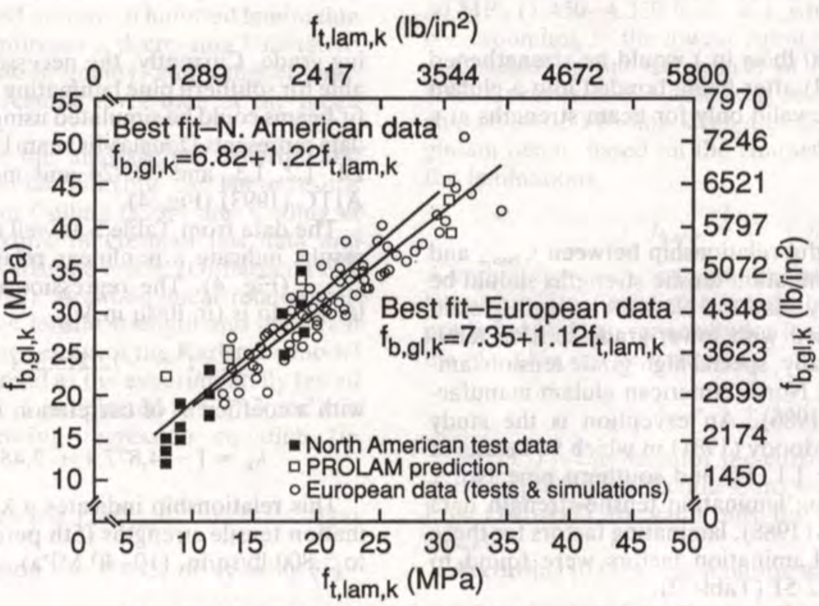

FIG. 5. North American and European Glulam Data

European beam data of Fig. 3 and selected North American beam data (tests and simulations) that meet European glulam layup requirements. [The raw North American data was first adjusted using (11) and (12).] (See Fig. 5.) To meet European requirements, beams must be manufactured out of a single homogeneous grade or must be laid up using two grades (the higher grade occupying one-sixth of the tension and compression sides of the beam). No special tension laminations are used in Europe.

Regression lines fit to these two sets of data indicate that the trends are similar (Fig. 5). The North American data in Fig. 5 does not include beams with special tension laminations, while the data in Fig. 4 does. This implies that the reduced laminating effect at the higher lamination strengths shown in Fig. 4 [and (18)] is due to the use of special tension laminations.

We suspect that in North American beams constructed with special tension laminations, the gradient of stiffness is sharper than that of the more homogenous layups of European beams. This results in lower beam bending strengths at higher lamination tension-strength levels (Fig. 4), 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 greater quantities of high-grade material.

CONCLUSIONS

The increase in strength of lumber laminations when bonded in a glulam beam, or the laminating effect, can be explained by three physical factors: an effect of testing procedure, a reinforcement of defects, and an effect of dispersion.

An analysis of lamination tensile strengths and beam bending strengths for both European and North American data indicate that lamination effects are more pronounced at the characteristic strength level than they are at the mean strength level. This may be explained by the higher coefficient of variation of the lamination tensile strength compared with that of the glulam bending-strength data. In addition, the lamination effect typically decreases with the increasing quality and strength of laminations. This is due to a lower reinforcement effect (caused by smaller knots) and the reduced influence of testing procedure (caused by more homogeneous material properties in a higher grade).

APPENDIX. REFERENCES

American Institute of Timber Construction (AITC). (1991). "Use of a volume effect factor in the design of glued laminated timber beams." *Tech. Note No. 21*, Englewood, Colo.

American Institute of Timber Construction (AITC). (1993). "Glued laminated timber design values/specifications." *AITC 117-93*, Englewood, Colo.

Burk, A. G., and Bender, D. A. (1989). "Simulating finger-joint performance based on localized constituent lumber properties." *Forest Products J.*, 39(3), 45–50.

Colling, F. (1988). "Estimation of the effect of different grading criterions on the bending strength of glulam beams using the 'Karlsruhe calculation model.'" *Proc., Int. Union of Forest Res. Org., Group S5.2*, Tech. Univ. of Denmark, Lyngby, Denmark.

Colling, F. (1990a). "Tragfähigkeit von Biegeträgern aus Brettschichtholz in Abhängigkeit von den festigkeitsrelevanten Einflußgrößen," PhD dissertation, Univ. of Karlsruhe, Germany.

Colling, F. (1990b). "Bending strength of glulam beams—a statistical model." *Proc., Int. Union of Forest Res. Org., Group S5.2*, Tech. Univ. of Denmark, Lyngby, Denmark.

Colling, F., and Falk, R. H. (1993). "Investigation of laminating effects in glued-laminated timber." *Proc., Meeting 24, Int. Council for Build. Res. Studies and Documentation Working Commission W-18*, Dept. of Timber Struct., Univ. of Karlsruhe, Karlsruhe, Germany.

Colling, F., Ehlbeck, J., and Görlacher, R. (1991). "Glued laminated timber: contribution to the determination of the bending strength of glulam beams." *Proc., Meeting 24, Int. Council for Build. Res. Studies and Documentation Working Commission W-18*, Dept. of Timber Struct. Univ. of Karlsruhe, Karlsruhe, Germany.

Comite European de Normalisation. (1993). "Timber structures—glued laminated timber—strength classes and determination of characteristic values." *Standard No. prEN 1194*, Central Secretariat, Brussels, Belgium.

Ehlbeck, J., Colling, F., and Görlacher, R. (1985). "Einfluß keilgezinkter Lamellen auf die Biegefestigkeit von Brettschichtholzträgern." *Holz als Roh- und Werkstoff*, Vol. 43, 333–337.

Falk, R. H., Solli, K. H., and Aasheim, E. (1992). "The performance of glued laminated beams manufactured from machine stress graded Norwegian Spruce." *Rep. No. 77*, Norwegian Inst. of Wood Technol., Oslo, Norway.

Foschi, R. O., and Barrett, J. D. (1980). "Glued-laminated beam strength: a model." *J. Struct. Div.*, ASCE, 106(8), 1735–1754.

Gehri, E. (1992). "Determination of characteristic bending values of glued laminated timber." *Proc., Meeting 25, Int. Council for Build. Res. Studies and Documentation Working Commission W-18*, Dept. of Timber Struc., Univ. of Karlsruhe, Karlsruhe, Germany.

Görlacher, R. (1990). "Klassifizierung von Brettschichtholzlamellen durch Messung von Longitudinalschwingungen," PhD dissertation, Dept. of Timber Struct., Univ. of Karlsruhe, Germany.

Hernandez, R., Bender, D. A., Richburg, B. A., and Kline, K. S. (1992). "Probabilistic modeling of glued-laminated timber beams." *Wood Fiber Sci.*, 24(3), 294–306.

International Standards Organization (ISO). (1985). "Solid timber in structural sizes: determination of some physical and mechanical properties." *ISO 8375*, Geneva, Switzerland.

Larsen, H. J. (1982). "Strength of glued laminated beams." *Rep. No. 8201; Part 5*, Inst. of Build. Technol. and Struct. Engrg., Aalborg Univ., Aalborg, Denmark.

Marx, C. M., and Evans, J. W. (1986). "Tensile strength of AITC 302-24 grade tension laminations." *Forest Products J.*, 36(1), 13–19.

Marx, C. M., and Evans, J. W. (1988). "Tensile strength of laminating grades of lumber." *Forest Products J.*, 38(7/8), 6–14.

Marx, C. M., and Moody, R. C. (1981). "Bending strength of shallow glued laminated beams of a uniform grade." *Res. Paper FPL 380*, U.S. Dept. of Agr., Forest Service, Forest Products Lab., Madison, Wis.

Moody, R. C., Falk, R. H., and Williamson, T. (1990). "Strength of glulam beams—volume effects." *Proc., 1990 Int. Timber Engrg. Conf., Vol. 1*, 176–182.

Rammer, D. R., and Soltis, L. A. (1994). "Experimental shear strength of glued-laminated beams." *Res. Paper FPL 527*, U.S. Dept. of Agr., Forest Service, Forest Products Lab., Madison, Wis.

Standard test methods of static tests of timbers in structural sizes; ASTM D198. (1984). ASTM, Philadelphia, Pa.