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GLUED-LAMINATED TIMBER: LAMINATING EFFECTS

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SUMMARY

In this paper, existing lamination and beam test results are analytically reviewed to quantify the laminating effect for European and North American glued-laminated (glulam) timber. Estimates are made of the magnitude of the laminating effect, and relationships are presented to describe its character based on an evaluation of beam and lamination test data.

INTRODUCTION

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

The objective of this paper is to discuss the laminating effect and quantify its magnitude based on both European and North American lamination tensile strength and glulam beam bending strength data.

FUNDAMENTAL CONCEPTS

As described in Falk and Colling (1993), the laminating factor is typically computed by determining the ratio of the ultimate bending strength of a population of glulam beams to the tensile strength of a population of lamination lumber, and is given the symbol λ:

$$\lambda = f_{b,gl}/f_{t,lam} \qquad (1)$$

where $f_{b,gl}$ is the mean bending strength of a population of glulam beams, and $f_{t,lam}$ is the 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, as follows:

$$\lambda = f_{b,gl}/f_{t,fj} \qquad (2)$$

where $f_{t,fj}$ is the 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, there is a need to determine a laminating effect at this characteristic strength level. Determining characteristic strength values from a population of test data can be directly determined using a characteristic form of Equation(1):

$$\lambda_k = f_{b,gl,k}/f_{t,lam,k} \qquad (3)$$

where $f_{b,gl,k}$ is the characteristic bending strength of a population of glulam beams, and $f_{t,lam,k}$ is the characteristic tensile strength of a population of lamination lumber. The subscript k refers to characteristic.

Lamination and beam test results suggest that the apparent strength increase due to the lamination effect is a summation of separate, although interrelated physical effects; some of which are effects of testing procedure and others which are due to the lamination bonding process. These include (1) an effect of tension test procedure, (2) defect reinforcement, and (3) an effect of dispersion and are represented by k_{test}, k_{reinf}, and k_{disp}, respectively. These factors are described in detail in Falk and Colling (1993).

EXPERIMENTAL AND SIMULATED DATA ANALYSIS

Beam and lamination test data as well as results of computer simulated beam strengths were evaluated to quantify the magnitude of the laminating effect. This analysis 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 considered.

Although considerable experimental beam test data are available for both European and North American glulam, relatively few studies include information on lamination tensile strength. For this paper, only beam data were considered for which appropriate lamination tensile strength data could be found.

A finite-element-based computer model developed in Germany for the analysis of glulam beams, referred to as the "Karlsruhe Model," was used in our study to supplement the European beam test data by simulating the strength of European manufactured glulam beams (Ehlbeck et al. 1985, Colling 1988, 1990b). This model utilized statistical input on the properties of the laminations and finger joints of glulam beams (lumber density, modulus of elasticity (MOE), and strength) to predict the strength and stiffness of beams of various layups.

Likewise, a computer analysis model developed in the United States, referred to as PROLAM (PRObabilistic modeling of LAMinations), was used to simulate the strength of North American glulam beams (Hernandez et al. 1992). This model used distributions of the mechanical properties of laminating stock (long-span MOE and short-span tensile strength) to determine the mechanical. properties of the glulam beams.

Adjustments to Experimental Data

In addition to adjusting all experimental test data for moisture content and loading configuration, adjustments were made for member size. The European experimental beam data were adjusted by multiplying the determined bending strength values by the following factor:

$$k_{h,gl} = (h/600)^{0.2} \qquad (4)$$

which adjusts beam strength to a depth (*h*) of 600 mm (24 in.) (Comite European de Normalisation 1993). 'The lumber tensile strength was adjusted to a common width using the following (Comite European de Normalisation 1991):

$$k_{h,lam} = (w/150)^{0.2} \qquad (5)$$

For the North American data, the following volume equation was used to adjust beam strength data to a common size (AITC 1991).

$$C_V = (5.125/w)^{0.1} \ (12/d)^{0.1} (21/l)^{0.1} \qquad (6)$$

Equation (6) references a beam 5-l/8 in. (130 mm) in width (*w*), 12 in. (300 mm) deep (*d*), and 21 ft. 16.4 m) in length (1).

European Data

Table 1 is a summary of test data and laminating factors 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 were found to increase 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 8 bending tests of 500-mm- (19.7-in.-) deep glulam beams. The results indicated λ = 1.12 and λ_k = 1.56.

Table l-European beam data and computed laminating factors

Source and lamination grade	Beam depth (mm (in.))	$f_{t,lam,05}$[a] (MPa (lb/in^2))	$f_{t,lam,50}$[a] (MPa (lb/in^2))	$f_{b,gl,05}$[b] (MPa (lb/in^2))	$f_{b,gl,50}$[b] (MPa (lb/in^2))	λ_k	λ
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
C37/30 (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 width per Equation (5).

[b] Adjusted to 600-mm depth per Equation (4).

Recent testing by Falk et al. (1992) provided estimates of λ and λ_k for Norwegian-produced glulam. For homogeneous beams constructed of C30 tension laminations, $\lambda = 1.26$ and $\lambda_k = 1.59$. Use of higher grade C37 laminations in a homogeneous layup resulted in $\lambda = 1.23$ and $\lambda_k = 1.45$. The C37 grade used as the outer laminations in a combined layup results in beams with $\lambda = 1.14$ and $\lambda_k = 1.44$. This investigation, which was based upon several hundred lamination and beam bending tests, confirmed a decreasing lamination effect with increasing lamination quality and a greater lamination factor at the 5th percentile level than at the mean strength level.

To illustrate the results of our analysis graphically, the experimental beam data are shown in Figure 1. Note that these results were combined with data from Colling (1990a, 1990b) and Colling et al. (1991), which were a mixture of German test data and simulation results using the Karlsruhe model (Görlacher 1990, 1992). Figure 1 indicates a strong linear relationship between the lamination tensile strength and the beam bending strength. Note also that the results of the Karlsruhe model simulation followed the same trend as did the experimentally tested beams. Data from Table 1 are plotted in Figure 1 and can be described by the following regression equation (in MPa):

$$f_{b,gl,k} = 7.35 + 1.12 \cdot f_{t,lam,k} \qquad (7)$$

with a coefficient of correlation r = 0.945, or by using Equation (3)

$$\lambda_k = 1.12 + 7.3/f_{t,lam,k} \qquad (8)$$

This relationship indicates a range of λ_k of 1.4 to 1.9 for lamination tensile strength (5th percentile) ranging from 10 to 30 MPa (1,450 to 4,350 lb/in^2), with the highest value of λ_k corresponding to the lowest strength value.

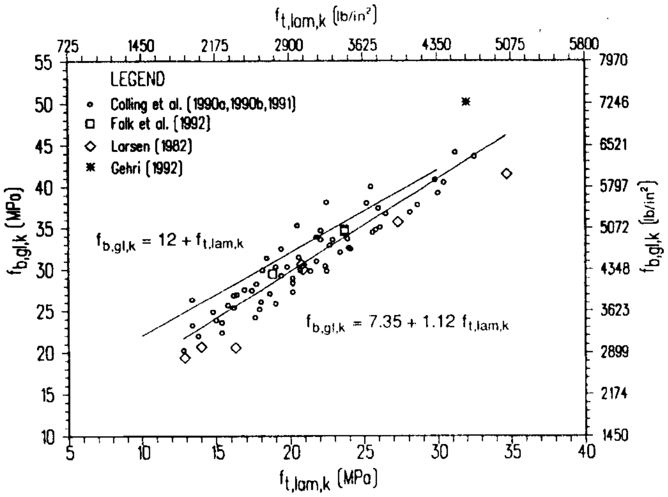

Figure l-European glulam data.

Considering the test results of Falk et al. (1992), Gehri (1992) proposed the following relationship for estimating the characteristic bending strength of 600-mm- (24-in.-) deep glulam beams on the basis of the characteristic tensile strength of the laminations:

$$f_{b,gl,k} = 12 + f_{t,lam,k} \qquad (9)$$

This relationship is also shown in Figure 1, and a comparison with test and simulation results shows that this relationship predicts a greater lamination effect than that predicted by Equation (8)) especially for low-quality laminations. Using Equation (3), the following can be written:

$$\lambda_k = 1 + 12/f_{t,lam,k} \qquad (10)$$

Equation (10) has been adopted into the current draft of the European standard prEN 1194 (Comite European de Normalisation 1993). Note that Equations (7)-(10) are valid only for strength values in MPa.

According to Equation (l0), a lamination with a characteristic tensile strength of 18 MPa (2,600 lb/in^2) would be strengthened by about 67 percent (λ_k = 1.67) after being bonded into a glulam beam. Note that Equations (7) to (10) are valid only for beam strength values at a depth of 600 mm (24 in.).

North American Data

To establish a meaningful relationship between $f_{t,lam,k}$ and $f_{b,gl,k}$, a wide range of lamination tensile strength values needs to be considered. Unfortunately, only limited strength data exist on North American glulam beams constructed with lower grade tension laminations. Typically, special high-grade tension laminations are used in most North American glulam manufacture (Marx and Evans 1986, 1988). An exception is the study performed by Marx and Moody (1981) where 90 beams of lower grade (Douglas Fir L1, L3 and Southern Pine No. 2 grades) were tested. These data are shown in Table 2.

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

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 302-24 tension laminations. Because this study did not include the collection of lamination tensile strength data for this lamination grade, lamination data from Marx and Evans (1986) were used. Table 2 indicates that lamination factors of λ_k = 0.95 and 1.04 were found for these data.

Moody et al. (1990) provided the results of bending tests on 45 glulam beams of 24 in. (600 mm) and 48 in. (1,200 mm) depth. These data represent the largest beams evaluated, although laminating factors were found to be nearly equal for the two sizes, λ_k = 1.27 and 1.29.

The computer model PROLAM was also used to estimate the strength of glulam beams. Because PROLAM requires a statistical distribution of lamination tensile strength for each laminating grade, and currently the necessary input data are not available for Southern Pine laminating lumber, only Douglas-fir beams could be simulated using this model. The simulation data are shown in Figure 2 and represent Douglas-fir beam layups using laminating grades L1, L2, L3, and 302-24, meeting the requirements of AITC (1993).

Table 2-North American beam data and computed laminating factors

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

[a] Adjusteed to 12-in. depth per Equation (6).

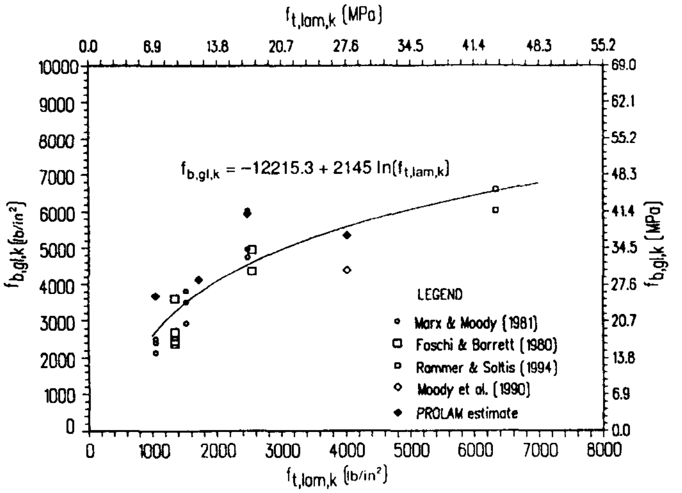

Figure 2-North American glulam data.

Data from Table 2 as well as the PROLAM simulation results are shown in Figure 2 and indicate a nonlinear relationship between $f_{b,gl,k}$ and $f_{t,lam,k}$. The regression equation describing this relationship is (in lb/in^2):

$$f_{b,gl,k} = -12215.3 + 2145 \cdot \ln(f_{t,lam,k}) \tag{11}$$

with a coefficient of correlation r = 0.746, or by using Equation (3)

$$\lambda_k = [-14877.4 + 2486 \cdot \ln(f_{t,lam,k})]/f_{t,lam,k} \tag{12}$$

This relationship indicates a range of λ_k of 1.2 to 2.2 for lamination tensile strength (5th percentile), ranging from 1,450 to 5,800 lb/in^2 (10 to 40 MPa).

DISCUSSION

Several observations can be made by comparing the European and North American data just described. First, the laminating factors found in the North American data are generally greater than those found in the European data. This is partly because the North American data included quite low-grade laminations (Marx and Moody 1981), which exhibited greater laminating factors than did the evaluated European data.

Also, the size factor used to adjust the European beam bending strength (Eq. (4)) used a different exponent and referenced a different beam depth than did the North American size Equation (6). This difference in size factors resulted in a greater difference between $f_{t,lam,k}$ and $f_{b,gl,k}$ for the North American data than for the European data.

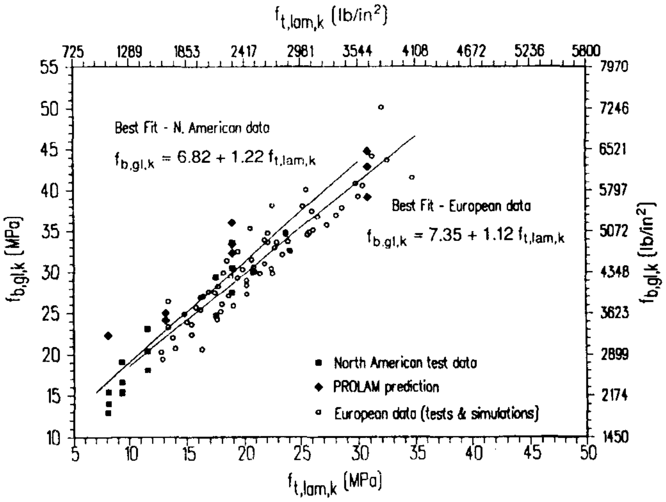

Figure 3-Comparison of North American and European glulam data.

By observing Figure 3, we see that the relationship between $f_{t,lam,k}$ and $f_{b,gl,k}$ for European glulam was very linear throughout the range of lamination tensile strength. For the North American glulam, as lamination tensile strength increased, the rate of increase of glulam bending strength decreased. We suspect that this observed behavior is a result of the use of high strength tension laminations in North American glulam. This is borne out if a graphical comparison is made between the European and North American beam data.

Figure 3 shows this comparison by plotting the European beam data (tests and simulations of Fig. 1), overlaid with North American beam data (tests and simulations) that meet European requirements, that is, beams of a single homogeneous grade or of a combined layup using two grades (the greater of which occupies one-sixth of the tension and compression sides of the beam!. The overlaid North American beam data were adjusted according to Equation (4). Regression lines fit to these two sets of data are shown in Figure 3 and indicate that the trends of the two sets of data are similar. The North American data in Figure 3 does not include beams with special tension laminations, while the data of Figure 2 does. This implies that the lower laminating effect at greater lamination strength values shown in Figure 2 and Equation (12) are due to the use of special tension laminations.

We suspect that the North American beams constructed with special tension laminations had a sharper gradient of stiffness than did the more homogenous layups of European beams, resulting in lower beam bending strength at greater lamination tension strength levels. Although this implies that European beams possess a more structurally efficient balance between lamination tensile strength and beam bending strength, it appears to be at the cost of greater quantities of high-grade material used in beam construction.

CONCLUSIONS

An analysis of lamination tensile strength and beam bending strength for both European and North American data indicates that lamination effects are more pronounced at the characteristic strength level than at the mean strength level. This may be explained by the greater coefficient of variation of the lamination tensile strength compared with glulam bending strength data. This analysis also indicates that lamination effects typically decrease with increasing quality and strength of the laminations. This can be explained by a lower reinforcement effect (caused by smaller knots) and less influence of testing procedure (caused by more homogeneous material properties in a higher grade).

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