INVESTIGATION OF LAMINATING EFFECTS IN GLUED-LAMINATED TIMBER

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Abstract

In this study, existing lamination and beam test results were analytically reviewed in an attempt to quantify the laminating effect for glued-laminated (glulam) timber. Laminating effect is defined as the increase in strength of lumber laminations when bonded in a glulam beam compared to their strength when tested by standard test procedures. In this study, fundamental concepts are presented to describe the laminating effect, estimates are made of the various physical factors that make up the effect, and a relationship is presented to quantify the magnitude of the effect.

Introduction

An important characteristic of glued-laminated (glulam) beams is that the bonding of laminations can result in beams with strengths higher than that of the individual lumber pieces from which the beams are constructed. This increase in strength is called the laminating effect and is of significant importance because quality control measures used to determine necessary lamination quality are dependent on the magnitude of this strength increase.

The objectives of this paper are to review the laminating effect and the physical characteristics which can be used to define it as well as to quantify the effect through an analysis of test data and analytical simulation.

Fundamental Concepts

The most fundamental definition of the laminating effect is a strength increase of a lamination 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 bending strength of a population of glulam beams to the tensile strength of a population of laminations:

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

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where $k_{b,glulam}$ is the mean bending strength of a population of glulam beams, and $f_{t,lam}$ is the mean tensile strength of a population of laminations.

Characteristic strength values (typically lower 5th percentiles) are used to establish design values for glulam; thus, there is a need to determine a laminating effect at this characteristic strength level. When determining characteristic strength values from a population of test data, the laminating factor λ_k can be directly determined using the following equation:

$$\lambda_k = f_{b,glulam,k}/f_{t,lam,k} \tag{2}$$

where k refers to characteristic.

Lamination and beam test results have indicated that the apparent strength increase caused by the lamination effect is a summation of separate, though interrelated, physical effects. Some of these effects are a result of the testing procedure and others the effect of the bonding process. These effects will be discussed next.

Effect of Tension Test Procedure, k_{test}

The tension performance of single laminations as measured by standard test methods differs from the actual performance of the laminations in a beam. Existing test methods for tension testing (i.e., ISO 8375 (ISO 1985), ASTM D198 (ASTM 1992)) suggest a test configuration that provides no lateral restraint to the tension member (unhindered). Although this test configuration is quite 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.

When a lamination is tested according to the standard methods, uncentered defects (such as edge knots) or areas of unsymmetrical density in a lamination can induce lateral bending stresses that combine with the applied tensile stresses, reducing the measured tensile strength of the lamination. If the laminations are bonded together in a glulam beam, no lateral bending stresses develop, because these defects are rigidly and laterally restrained. Thus, the tension lamination in a glulam beam has an apparent tensile strength higher than that indicated in a free tension test.

Reinforcement of Defects, k_{reinf}

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 higher stiffness areas of neighboring laminations. Thus, the laminating process reinforces defects in a lamination, redistributing stresses around the defect through the clear wood of adjacent laminations and effectively increasing the capacity of the cross section containing the defect.

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

Dispersion of Low-Strength Lumber, k_{disp}

Experimental test data indicate that the bending strength distribution for glulam beams has a higher mean value and a lower coefficient of variation (COV) than does the tensile strength distribution of the lamination lumber. This characteristic is partly explained by the effect of testing procedure and the reinforcement of defects explained previously. Additionally, there is an effect of dispersion of low-strength lumber that affects the beam. For example, if a population of laminations are tested in tension, the lower strength pieces will be represented in the calculation of the characteristic estimate of the population ($f_{t,lam,k}$). 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 location in the beam that initiates failure is lessened. An additional strengthening effect may be expected because of this dispersion of laminations.

On the other hand, the bending strength of glulam beams with larger dimensions is not only affected by the quality of the outer lamination but 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 lead to a negative dispersion effect.

From a statistical point of view, the dependency of beam failure on the probability of a low-strength lamination occurring in a high-stressed zone includes a so-called size effect. That is, if laminations with a given strength distribution are used to produce several glulam beams with different sizes (lengths and depths), the lamination factors determined according to Equations (1) and (2) will differ for each beam size, because the bending strength of the glulam depends on the dimensions of the beams. Also, lamination tensile strength is affected by the tested lamination lengths and depths.

Quantification of Laminating Effect

On the basis of the previous discussions, the lamination factor of Equation (1) may be written as

$$\lambda = k_{test} \cdot k_{reinf} \cdot k_{disp} \tag{3}$$

where k_{test} k_{reinf}, and k_{disp} correspond, respectively, to the effects discussed in the previous sections. These factors vary and depend on various parameters, such as the quality (or grade) of laminations and the beam layup. Even in the improbable case of identical lamination quality, different test series lead to different results. Consider, for example, tests performed to determine k_{test}. Assume that lateral displacements occurring in a free tension test are measured and k_{test} is calculated (estimated) for each lamination. The factor k_{test} will be statistically distributed. This creates a problem in that the actual value of k_{test} corresponding to the lamination with a mean strength is not necessarily identical to the mean value of the k_{test} distribution. This problem suggests that the values for k_{test}, k_{reinf}, and k_{disp} in Equation (3) can only be mean estimates derived on the basis of mean strength values. On the basis of characteristic strength values, the following relationship is valid:

$$\lambda_k = k_{test,5} \cdot k_{reinf,5} \cdot k_{disp,5} \qquad \textbf{(4)}$$

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 previously, other influences affect the quantification of $k_{test,5}$, $k_{rcinf,5}$, and $k_{disp,5}$. For example, k_{test} increases as the grade of lamination decreases, because increasing knot size presumably increases the magnitude of lateral displacement. The same is true for k_{rcinf}, which should also increase with decreasing grade, because there is likely an increased redistribution of stresses as the number of low-stiffness zones increases. The factor k_{disp} varies with the grade of lamination, with 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

In spite of the described interrelations, attempts were made in Europe to quantify the factors described previously (Ehlbeck and Colling 1986; Colling et al. 1991). These works led to a rough estimation of the lamination factor λ_k and represented the basis for glulam beam design criteria used in the European Community (Comite European de Normalisation 1993). Because the intention of this paper is to give better insight into the laminating effect, previous studies involving both the analysis and testing of beams and laminations have been evaluated in an attempt to quantify some of the laminating factors described previously. This reevaluation involved both European and North American research data. This distinction is made because different faotors are used in Europe than in North America to adjust test data. A more complete description of the data analyzed is given in Colling and Falk (1993).

For example, the influence of specimen size (length and depth of laminations and glulam beams) is an important consideration in adjusting data. In Europe, current practice is to adjust lamination strength values and beam strength values by multiplying the determined strength values by the following factors, respectively:

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

and,

$$k_{h,gl} = (h/600)^{0.2} \tag{6}$$

where $k_{h,lam}$ adjusts lamination depth (or width) to a reference 150 mm (6 in.) and $k_{h,gl}$ adjusts beam depth to a reference 600 mm (24 in.).

Equations (5) and (6) were used to adjust all data analyzed in this study to the reference sizes. No adjustment for lamination length was made (except as noted), because little length effect was expected for lamination lengths ranging from 1.0 to 2.5 m (3.3 to 8.2 ft), as long as the grade defect was placed between the grips of the tension machine,

Estimates of test data characteristic values were used where given in the studies evaluated. In the case of data where no characteristic estimates were given, estimates were made based upon statistical assessments of data variability.

Testing Procedure

Estimation of k_{test}

Foschi and Barrett (1980) developed a finite-element-based glulam strength prediction model in which the lateral restraint of laminations was taken into account. Our analysis indicated that the lateral displacement was statistically distributed, depending on the number, size, and location of knots. Calculating the values of k_{test} for the four lamination grades tested by Foschi and Barrett indicated a range of 1.04 to 1.14, with k_{test} = 1.04 for the highest lamination quality (grade A) and k_{test} = 1.14 for the lowest grade lamination (grade D). These values were calculated at a mean strength level. The effect of the testing procedure was assumed to be higher at the characteristic strength level.

By measuring lateral deflections occurring in free tension tests (with hinged end conditions), Larsen (1982) attempted to quantify the factor for testing procedure (k_{test}). The free length of test specimen was 2.1 m (7.1 ft) and deflections were measured over a length of 600 mm (24 in.). The measured deflections were quite small (usually < 0.5 mm (< 0.02 in.)) and were highly variable. As a result of small and variable deflections, k_{test} ranged from 1.1 to 2.0, with a trend of increasing k_{test} with decreasing grade.

Estimation of k_{test} and $k_{test,5}$

Based on the determined density and MOE-properties of the two lamination grades used by Falk et al. (1992), Görlacher (1992) calculated hindered tension strengths of laminations with the help of regression equations given in Ehlbeck et al. (1985) and Colling (1988, 1990a). These calculations indicate a value of k_{test} = 1.2 and $k_{test,5}$ = 1.3.

Defect Reinforcement and Low-Strength Lumber Dispersion

A finite-element-based computer model was developed in Germany for the analysis of glulam beams (Ehlbeck et al. 1985, Colling 1988, 1990a). This model, referred to as the "Karlsruhe Model", utilizes statistical input on the properties of the laminations and finger joints of glulam beams (lumber density, MOE, and strength) to predict the strength and stiffness of 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, $k_{test} = 1.0$.

Because the simulation results of Coiling (1990a) excluded the effect of testing procedure, a value for $k_{test,5}$ was needed for our calculations to transform the hindered tensile strength values of the laminations into unrestrained, or free, tensile strength values. Based on the calculations of Görlacher (1992), a value $k_{test,5} = 1.3$ was used.

Estimation of $k_{reinf,5} \cdot k_{disp,5}$ by Simulation

Using the Karlsruhe Model, Colling (1990a) calculated the bending strength of 300-mm- (12-in.-) deep glulam beams. Various grades of laminations were accounted for through different knot area ratios (KAR), density, and MOE (54 combinations in total). In a complementary study, Colling et al. (1991) calculated the corresponding tensile strengths of the laminations (4.5 m (14.8 ft) long) for each glulam combination by using the Karlsruhe Model regression equations for the laterally restrained, or hindered, tensile strength.

For our analysis, the simulated tensile strength values were increased by 12% to adjust them to a length of 2 m (6.6 ft). This increase was based upon the simulation modeling performed by Görlacher (1990). Therefore, our results correspond to the hindered tensile strength of the laminations, i.e., the product of $k_{test} \cdot f_{t,lam}$, where $f_{t,lam}$ corresponds to the free tensile strength of the lamination determined from standard test methods. Thus, with the effect of testing procedure being eliminated, the lamination factors determined on the basis of these calculations were reduced to the effects of reinforcement k_{reinf} and dispersion k_{disp}.

The simulations performed in our study indicate a close relationship between the characteristic glulam bending strength and characteristic lamination tensile strength.

Estimation of $k_{reinf} \cdot k_{disp}$ and $k_{reinf,5} \cdot k_{disp,5}$ by Simulation and Tests

Verification of the Karlsruhe Model on the basis of bending tests with glulam beams having a depth of 600 mm (24 in.) was performed by Colling (1990a). Six test series were performed with seven tests each (see also Colling (1990b) and Ehlbeck and Colling (1990)). The glulam bending strength values (both simulations and tests) include glulam beams with finger-joint failures. Because the Karlsruhe Model uses hindered lamination tension strength input, k_{test} could not be quantified in our calculations.

Our analysis showed a clear tendency of decreasing lamination factor with increasing lamination quality. The product of $k_{reinf} \cdot k_{disp}$ varied between 0.90 and 1.22, and $k_{reinf,5} \cdot k_{disp,5}$ varied between 1.09 and 1.51. Again, the lamination effects were found to be more pronounced at the 5th percentile level than at the mean strength level.

Estimation of k_{reinf}

A stress distribution analysis of 600-mm (24-in.) glulam beams (20 laminations) performed by Colling (1990a) measured the effect of reinforcement k_{reinf}. In Colling (1990a), the MOE of laminations was varied as well as the MOE of the single finite element cells representing defects. If the MOE of a single cell in the outer or second tension lamination of the beam is varied while the MOE of the rest of the beam is held constant, k_{reinf} can be measured. The results of Colling (1990a) indicated that the stiffness zones were strengthened significantly by the laminations to which they were bonded. The magnitude of this reinforcement effect depended on the difference between the MOE of the cell and the MOE of the surrounding wood and varied between about 1.15 and 1.50 depending on the visual grade (knot size) of the lamination. If the low-stiffness zone occurred in the second lamination, reinforcement from laminations above and below were shown to add even more reinforcement.

Laminating Effect

Estimation of λ

Foschi and Barrett (1980) studied the bearing capacity of glulam beams (Douglas-fir) of different sizes and beam layups. Analysis of this test data indicated a clear tendency of decreasing λ with increasing quality of the laminations. Our results indicated laminating factors of approximately 1.1 for the higher grade laminations (grade B) and approximately 1.25 for lamination grade D.

Larsen (1982) performed bending tests on a total of 144 glulam beams (233 mm (9.2 in.) in depth) with 33 different beam layups represented. 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. As with the values of k_{test}, the values of λ were found to increase with decreasing grade and ranged from 1.06 to 1.37.

Estimation of λ and λ_k

Recent testing by Falk et al. (1992) offered insight into the relationship between strength characteristics of the laminations and the resulting bending strength of glulam beams and provided estimates of λ and λ_k. For beams constructed of C37-14E tension laminations, $\lambda = 1.25$ and $\lambda_k = 1.45$. For beams constructed of C30-12E tension laminations, $\lambda = 1.30$ and $\lambda_k = 1.55$. This investigation, which was based upon 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.

Tests by Gehri (1992) estimated 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 $\lambda = 1.12$ and $\lambda_k = 1.56$.

Considering the test results of Falk et al. (1992), Gehri (1992) proposed the following relationships 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:

$$f_{b,glulam,k} = 12 + f_{t,lam,k} \tag{7}$$

or using Equation (2):

$$\lambda_k = 1 + 12 / f_{t,lam,k} \tag{8}$$

Equation (7) has been adopted into the current draft of the European standard EN TC.124.207 (Comite European de Normalisation 1993). Equations (7) and (8) are valid only for strength values in MPa.

According to Equation (8), a lamination with a characteristic tensile strength of 18 MPa (2600 lb/in^2) would be strengthened by about 67% ($\lambda_k = 1.67$) after being bonded into a glulam beam. Equation (8) is valid only for 600-mm (24-in.) glulam beams.

Results

Specific values of the factors of Equations (3) and (4) have been estimated based upon the described analysis of the experimental and simulated data.

Effect of Testing Procedure

Based on our analysis, the following ranges of values of k_{test} (at mean strength level) and $k_{test,5}$ (at the characteristic strength level) may be expected:

$k_{test} = 1.1$ to 1.3

$k_{test,5} = 1.2$ to 1.4

These factors are strongly dependent on lamination quality, especially on the size and location of knots.

Effect of Defect Reinforcement

The strengthening effect of zones with low stiffness are estimated to be in the following range of values for k_{reinf} and $k_{reinf,5}$:

k_{reinf} = 1.0 to 1.25

$k_{reinf,5}$ = 1.15 to 1.50

These factors are strongly dependent on knot sizes.

Effect of Low-Strength Lumber Dispersion

As explained previously, the dispersion effect includes size effects, i.e., the influence of both lamination and glulam length and depth. Based primarily on the Karlsruhe Model and the results of simulations, the following range of dispersion effect is expected:

k_{disp} = 0.9 to 1.0

$k_{disp,5}$ = 0.9 to 1.0

A value below 1.0 may be explained by the mutual influence of neighboring laminations in larger glulam beams. Furthermore, if the length of the lamination test specimen is less (approximately 2 m (6.6 ft)) than the average length of the laminations in the beams (approximately 4 m (13.2 ft)), the reference tensile strength of the laminations is apparently too high, thus resulting in a negative dispersion effect.

Laminating Effect

To graphically illustrate the laminating effect, the results of our analysis are combined and plotted in Figure 1. All the presented results are test results, with the exception of the data from Colling et al. (1991), which are a mixture of test data and simulation results using the Karlsruhe Model. Figure 1 indicates that a strong linear relationship exists between the lamination tensile strength and the beam bending strength. Lamination effects tend to be greater when tensile strengths (or grade) is lower. The results shown in Figure 1 may be described by the following regression equation (in Mpa):

$$f_{b,glulam,k} = 6.9 + 1.141 \cdot f_{t,lam,k} \qquad (9)$$

with a coefficient of correlation r = 0.945. Or by using Equation (2), the results shown in Figure 1 may be described by:

$$\lambda_k = 1.141 + 6.9 / f_{t,lam,k} \qquad (10)$$

The relationship proposed by Gehri (1992) is also plotted in Figure 1. A comparison with test and simulation results showed that this relationship overestimates lamination effects, especially in the case of low-quality laminations.

The systematic reevaluation of the described data made it possible to roughly estimate the different effects of laminating discussed in this paper. The total lamination factor λ_k may be described by the following relationship (in MPa):

$$\lambda_k = 1.15 + 7 / f_{t,lam,k} \qquad (11)$$

This relationship indicates a range of λ_k of 1.4 to 1.9 for lamination tensile strengths (5th percentiles) ranging from 10 to 30 Mpa (1450 to 4350 lb/in^2), with the highest value of λ_k corresponding to the lowest strength value.

Concluding Remarks

Although the analysis of research data showed a great deal of variability in measures of laminating factors, the following qualitative tendencies were apparent:

- Lamination effects were more pronounced at the characteristic strength level than at the mean strength level. This may be explained by the higher coefficient of variation of the lamination tensile strength compared with glulam bending strength data.

- Lamination effects decreased with increasing quality and strength of the laminations. This may 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).

- Factors that contribute to the lamination effect were interrelated, making it difficult to accurately quantify them separately.

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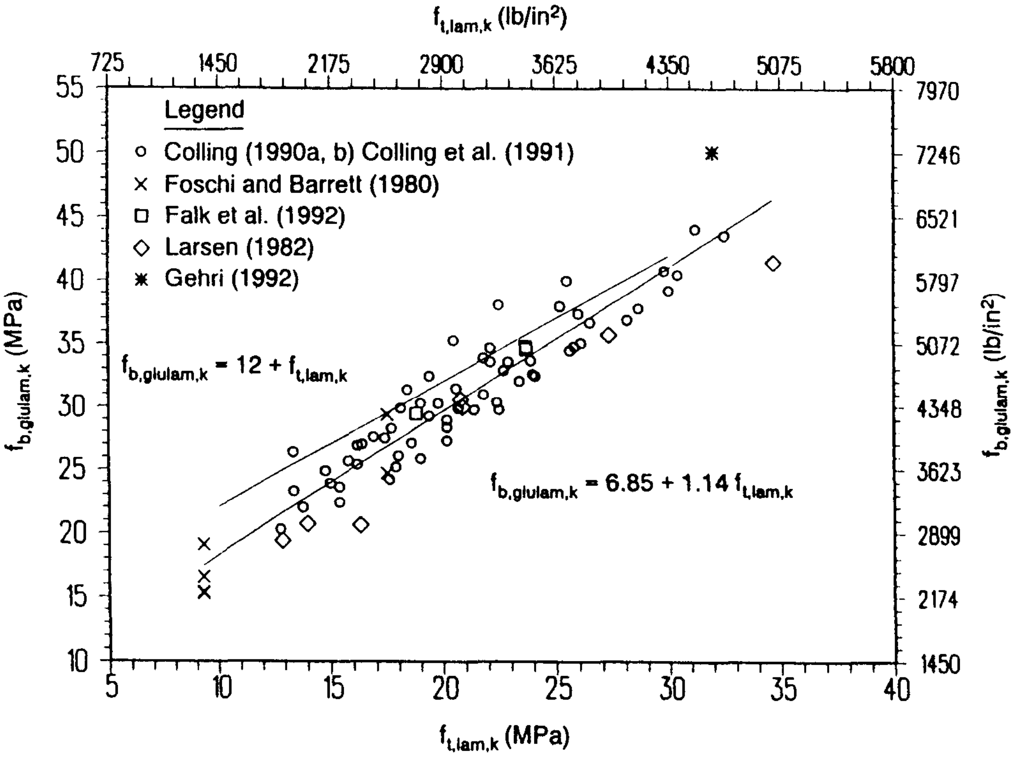

Figure 1
Lamination effect based on test data and simulations.