BUTT JOINT REINFORCEMENT IN PARALLEL-LAMINATED VENEER (PLV) LUMBER[1]

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ABSTRACT

Parallel-laminated veneer (PLV) is a high-strength structural material consisting of thin parallel-laminated wood veneers. The use of graphite-cloth reinforcement, placed on either side of a butt joint in 1½- by 3½- by 32-inch Douglas-fir PLV tensile members, was assessed. The finite-element method of analysis was used to predict the behavior in different unreinforced and reinforced butt-jointed PLV tensile members. Relationships between the reinforcing parameters—length, modulus of elasticity, and thickness—and the stresses in the wood and reinforcement components were developed by regression analysis techniques. The reinforcing mechanism reduced the peak stresses at the butt joint and hence increased the ultimate strength of the member. Design of PLV material whose strength is limited by shear stresses that develop at the butt joint is facilitated by use of the proposed relationships.

Experimental testing confirmed the predictions of the finite-element analysis. Failure initiated at the unreinforced joint in the specimens. Average tensile strength increased and variability decreased

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in reinforced specimens. Application of a small amount of reinforcement at the butt joint has been shown to enhance PLV performance.

Keywords: Parallel-laminated veneer (PLV), laminated veneer lumber (LVL), joints, butt joints, stress analysis, design, reinforcement.

INTRODUCTION

A composite lumber material made by laminating thin wood veneers has properties more reliable, uniform, and predictable than those of similar-dimension solid wood. This is because in veneering, gross defects are reduced. Laminating also tends to randomly distribute these defects. The strength-reducing impact of individual defects is thus lessened.

Laminated beams of relatively uniform high strength can be made by placing stiffer veneers in the outermost portion of the beam and less stiff veneers near the center of the beam, i.e., the neutral axis (Koch and Bohannan 1965; Koch 1974). Placement of laminae with respect to modulus of elasticity (MOE) not only increases the average modulus of rupture (MOR) of beams, but also decreases the variability in strength and stiffness among beams.

From 1950 to 1975, much research was performed applying various reinforcing mechanisms to wood flexural members in order to increase their strength and stiffness. Load-carrying capacity increased in direct proportion to increases in stiffness. Strength and stiffness of the reinforced beams was also more reliable, uniform, and predictable.

A relatively new wood product called parallel-laminated veneer (PLV) lumber provides an excellent opportunity to apply reinforcing and laminating technologies. Reinforced PLV is a high-strength, high-stiffness composite consisting of PLV containing interlaminar reinforcements. With the judicious use of reinforcement, relatively higher strength PLV can be made from low-grade logs containing knots and other defects as well as from logs of low-density, rapid-growing species.

The technical and economic feasibility of reinforced PLV was determined by Rowlands et al. (1985) and Laufenberg et al. (1984). This paper presents the results of a study concerned with the application of reinforcement in butt joints. Butt joints in PLV can seriously degrade the mechanical performance. As a result, interlaminar reinforcement of PLV offers the potential of lessening the strength-reducing effects of butt joints.

Butt joints occur where the square ends of adjoining veneers abut in a single lamina in PLV. As there is no continuity in wood fibers' connections, such joints transmit no tensile load. Stress concentrations in both shear and tension can occur in a localized area around the joint (Forest Products Laboratory (FPL) 1974). Failures in tensile test specimens of Bohlen (1974) were initiated primarily at the butt joint. In PLV with high-quality veneer, wood failure initiated at the outer butt joint, progressed along the glueline to the next butt joint, and so on, to complete failure. Joint strength can be increased using high-quality partial-load-transmitting scarf or finger joints.

Aside from a concern for increased strength, economy of production is an important consideration in the development of new composites. Butt-jointing laminae eliminates the expensive step of fabricating scarf or finger joints (Koch and Woodson 1968).

To preserve the performance benefits of PLV, reinforcing mats providing con-

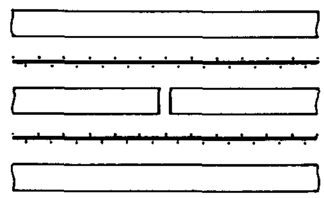

FIG. 1. Hypothetical cross section showing the butt joint, with its local discontinuity and the reinforcing mats on either side providing local continuity.

tinuity at butt joints can be placed between laminations (Fig. 1). The reinforcing mat provides a high-stiffness element in the low-stiffness region of the butt joint. As the composite is loaded, the high-stiffness reinforcing material shares the tension load. The butt-jointed area, which now incorporates a stiff reinforcing mat, is restricted in its deformation (Spaun 1979). Mechanisms that would normally initiate local failure, i.e., local discontinuities at the butt joints, no longer limit the tensile strength of the member.

The objective of the research reported here was to develop the technology for sizing and placement of high-strength reinforcements of butt-jointed veneers in LVL. Finite-element methods, as used to analyze the reinforced butt joints, provided the input on which we based the design parameters. Experimental results of a single joint design allowed a comparison to analytically predicted strain levels.

BUTT JOINT THEORETICAL ANALYSIS AND DESIGN

A laminated, reinforced, butt-jointed composite has varying properties across its cross section and a complex geometry that requires a sophisticated analysis. The finite-element method has many useful advantages applicable to the analysis of composite structures. The SAP IV, a structural analysis computer program, was used (Bathe et al. 1974).

Unreinforced butt joint

The composite modeled in this analysis (Fig. 2) consisted of one butt joint placed in a 1½- by 3½- by 9¾-inch Douglas-fir tensile member. The joint was located at the center of the length of the veneer in the lamina below the top. A fine square mesh of two-dimensional plane-stress elements (0.09375 by 0.09375 inch) was used to analyze the stresses and strains in the area surrounding the joint (Fig. 2). The member was supported by rollers and pins at one end and a tensile load was applied at the other end. The gluelines were regarded as straight-line inclusions producing no stress concentrations and having a negligible influence on the state of stress in anisotropic mediums (Savin 1961). Therefore they were neglected in the analysis.

Wood is assumed to be an orthotropic material, with unique and independent mechanical properties in each of its three axes. The direction of the parallel-to-grain (1) mechanical properties coincided with the longitudinal (9¾ inches) direction of the model; the radial direction of wood (2) coincided with the width (1½ inches); and the tangential direction (3) coincided with the thickness (3½ inches). The properties of clear, straight-grained, 10% moisture content Douglas-fir were used (American Society of Civil Engineers (ASCE) 1975):

$$
\begin{aligned}
E_{11} &= 2{,}280 \text{ ksi}\\
E_{22} &= 155 \text{ ksi}\\
E_{33} &= 114 \text{ ksi}\\
\nu_{12} &= 0.022\\
\nu_{13} &= 0.02\\
\nu_{23} &= 0.39\\
G_b &= G_{12} = 146 \text{ ksi}
\end{aligned}
$$

where E is elastic stiffness, ν is the Poisson's ratio, and G is the shear modulus. The subscripts 1, 2, and 3 represent the longitudinal, radial, and tangential directions. Subscript b represents a bulk property of the material.

For purposes of qualitative comparison, a tensile load of 6 kips was used. This results in an average uniaxial stress, f_1', of 1.14 ksi in the longitudinal direction in the Douglas-fir member. A butt joint in the 1–2 plane will cause a redistribution of stress from the unjointed state to an f_1, f_2, and f_{12} state where (Savin 1961):

$$
\begin{aligned}
f_1 &= f_1' + f_1^*\\
f_2 &= f_2' + f_2^*\\
f_{12} &= f_{12}' + f_{12}^*
\end{aligned}
$$

where:

$$
\begin{aligned}
f_1' &= 1.14 \text{ ksi (by definition)}\\
f_2' &= 0\\
f_{12}' &= 0.
\end{aligned}
$$

f_1^*, f_2^*, f_{12}^* are the additional stress components due to the presence of the joint. Subscripts are directional notations of the principal material directions.

Allowable unit stresses for structural glued-laminated Douglas-fir timber members stressed principally in axial tension (dry condition of use) are (American Institute of Timber Construction (AITC) 1974):

Tension parallel to grain, F_t = 1.800 to 2.000 ksi
Compression perpendicular to grain, F_c = 0.385 to 0.450 ksi
Horizontal shear, F_v = 0.145 to 0.165 ksi.

The analysis shows large longitudinal tensile stresses occurring in the laminae above and below the butt joint (Fig. 3a, unreinforced). The finite element directly above the line of butt-joint elements shows an f_1 of 2.87 ksi, which is 2½ times larger than f_1'. Large shear and perpendicular-to-grain compressive stresses occur in the laminae abutting the joint, with the axes of principal stress no longer coinciding with the material axes. Moving farther away from the joint, the additional stresses (f^*) attenuate rapidly.

The site of the gap between the ends of abutting veneers was varied from 0.0425 inch to 0.0938 inch to 0.1875 inch. As expected, the smallest gap resulted in the largest peak stresses. The peak shear stress varied from −0.25 ksi to −0.24 ksi to −0.23 ksi, and the peak tensile stress varied from 2.98 ksi to 2.87 ksi to 2.70 ksi. But these differences are not significant. The 0.0938-inch joint was assumed representative of an actual butt joint.

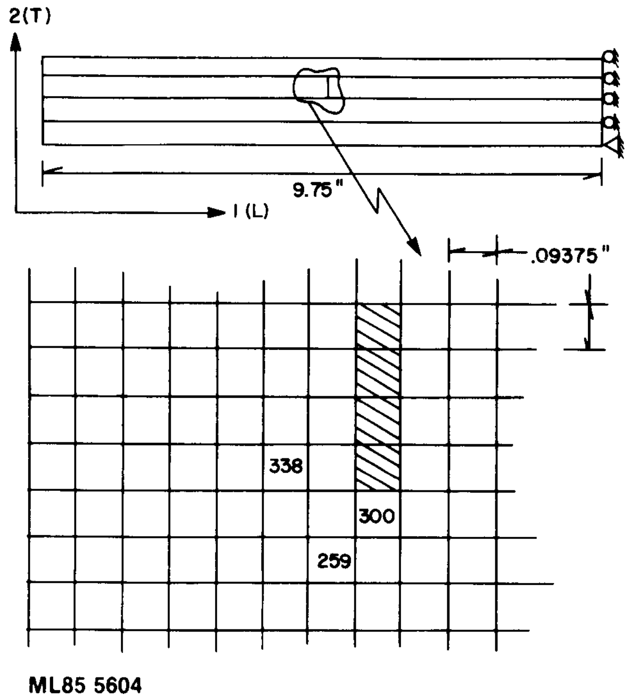

FIG. 2. Finite-element model of one butt joint within a laminated-wood tensile member.

It should be noted that the high stresses at the element centroids (in this case at the inside edge of the butt joint) are not the true maximum values, because of the averaging effect inherent in the finite-element approximation. A theory of elasticity analysis predicts infinite stresses at a sharp corner. This too is obviously incorrect, in that it predicts failure under any applied load. The true maximum stresses at the corners are bounded and influenced by the actual corner geometry down to the microscopic level and possibly by localized yielding of the adhesive and wood substrate.

Reinforced butt joint

As noted, high-elastic-modulus reinforcing material can be used to reinforce the butt-joint areas. As with wood, one has to assume material property values of the reinforcing material and make preliminary calculations. The reinforcing material modeled was a unidirectional cloth of graphite-fiber resorcinol-formaldehyde composite lamina with a longitudinal stiffness (E_r) of 17,100 ksi and an allowable tensile stress (F_{tr}) of 62.54 ksi. This composite was the same Douglas-fir laminate used in the test specimens for the experimental phase of this study described later.

The reinforcing laminae used in the analyses were 0.09375 inch thick, the same as the finite-element mesh. The graphite-adhesive laminae with $E_r = 17,100$ ksi, lengths of 4½ inches and the full-member width, were centered directly above and below the joint for the analysis.

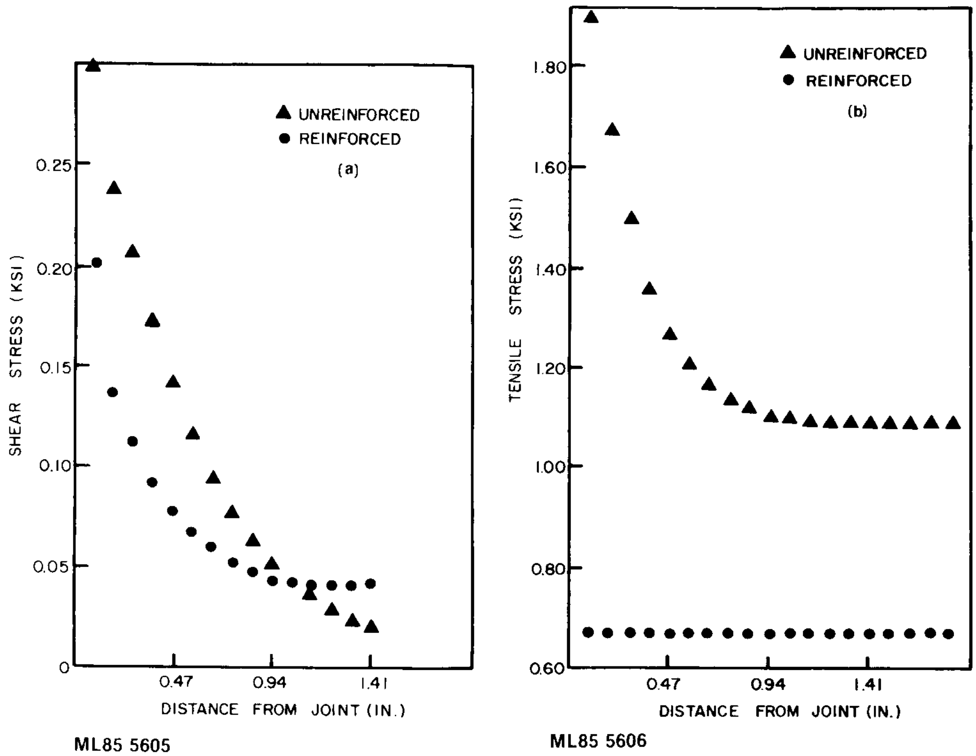

FIG. 3. Shear (a) and tensile (b) stresses along the length of the finite-element model.

Again, a 6-kip tensile load was used in the model. The longitudinal peak stress in the wood laminae, f_1, was reduced from 2.87 ksi to 0.67 ksi (Fig. 3b, reinforced); the peak shear stress in the wood laminae, f_{12}, was reduced from −0.242 to −0.133 ksi; and the local peak perpendicular-to-grain compressive stress, f_2, was reduced from −0.194 to −0.127 ksi. The utilized capacity of the reinforcement, quantified by the ratio of the observed peak reinforcement stress to the corresponding allowable tensile stress, f_{1r}/F_{tr}, was 9.27%. For both f_1 and f_{12}, the reinforcing reduced those wood stresses to values within their allowable limits. The finite-element analysis predicts significant benefits from reinforcing the butt joint in the PLV tensile member.

Butt joint parameter study

Variations in peak joint-stress levels due to different reinforcing parameters were studied. It was assumed that three properties of the reinforcement, MOE, length, and thickness (assuming reinforcement width equal to member width), determined its stress-reducing ability. Each parameter was independently modeled using various combinations of the other two factors. Seventy-two different combinations of the parameters (4 by 6 by 3) were considered. The range of parameters was based on the initial composite theory calculations and the properties of probable reinforcing materials. Four reinforcement-laminae longitudinal stiffnesses were used,

$E_1 = 17{,}100$ ksi
$E_2 = 12{,}825$ ksi
$E_3 = 8{,}550$ ksi
$E_4 = 4{,}275$ ksi

with six lamina lengths,

$L_1 = 0.84$ inch
$L_2 = 1.59$ inches
$L_3 = 2.34$ inches
$L_4 = 3.09$ inches
$L_5 = 3.75$ inches
$L_6 = 4.50$ inches

and three lamina thicknesses,

$T_1 = 0.09375$ inch
$T_2 = 0.06250$ inch
$T_3 = 0.03125$ inch.

Analysis of variance and regression analyses were applied to reduce the data into usable information about the reinforcing.

Analysis of variance

The analysis of variance (ANOVA) techniques, applied to the results of these repetitive finite-element studies, allow for investigation of the assigned parameters even when there is residual variation from unassigned variables present (Johnson and Leone 1977). Statistical analyses were performed on the observed stress values in the two finite elements giving peak tension and shear stresses in the wood and on the capacity ratio of observed stress to allowable stress of the reinforcement material, f_{lr}/F_{tr}.

The one-way ANOVA classification guides subsequent investigations to formulate design equations and optimum combinations. The effects of the different parameters on the peak tensile stress predicted are:

1. At a 95% confidence level, varying the length of the reinforcing alone does not significantly affect the peak tensile stress.
2. At a 95% confidence level, the thickness of the reinforcement affects the tensile stress at the joint. Reduced thicknesses (smaller cross sections of reinforcement) provide less reinforcing benefit.
3. As the longitudinal stiffness of the reinforcing (E_r) increases, the tensile stress in the stress-concentration region decreases.

The effects of parameter variations on reducing the peak shear stress are:

1. Lengthening the reinforcing significantly reduces peak shear stress.
2. Varying the thickness of reinforcing, and hence its cross-sectional area, does not significantly affect the shear stresses at the butt-joint stress concentration.
3. The MOE factor is also significant in reducing shear stresses. Quantitatively, it appears to have the same degree of significance as the length parameter.

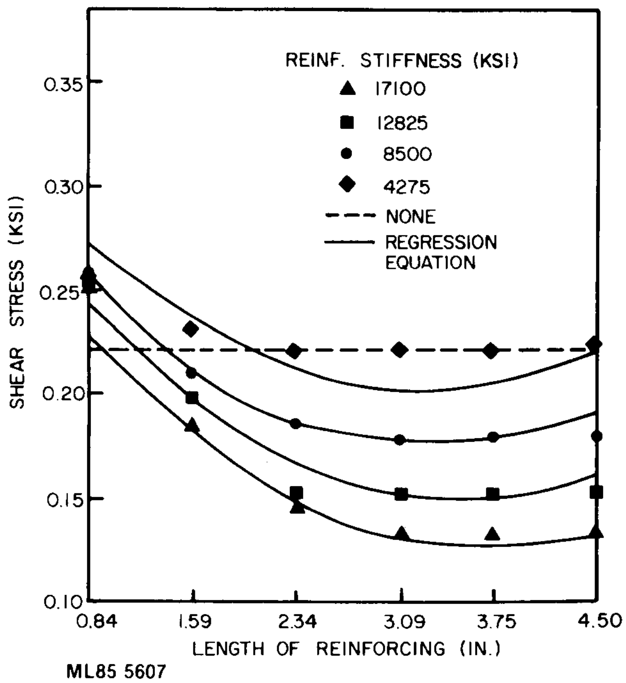

FIG. 4. Peak shear stress as a function of reinforcement length for four different reinforcement stiffnesses.

The effects of different parameters on the ratio of observed tensile stress to allowable tensile stress in the reinforcement, f_{1r}/F_{tr}, are:

1. Variation in the length of reinforcing does not significantly affect the peak stress ratio.
2. Decreasing the thickness of reinforcing significantly increases the f_{1r}/F_{tr} ratio.
3. As E_r decreases, stresses increase.

In addition to the effects of independent parameters, interactions between parameters must be considered. Again, considering shear and tensile stresses in separate analyses, three two-way cross-classification parameter studies were performed. In each case, the insignificant factors determined from the one-way classification were used to provide for repetitive observations (cells) of the other significant two-factor combinations. At a 95% confidence level, there is a significant effect of interaction between the length and stiffness factors on the reductions of shear stress due to reinforcing. There was no observed interaction of stiffness and thickness on the reductions of tensile stresses in the wood. A significant interaction between stiffness and thickness exists for the reinforcement's ability to distribute stresses.

Regression analyses

Regression analyses were performed to determine relationships between the significant factors and the predicted peak stresses. Orthogonal designs were used

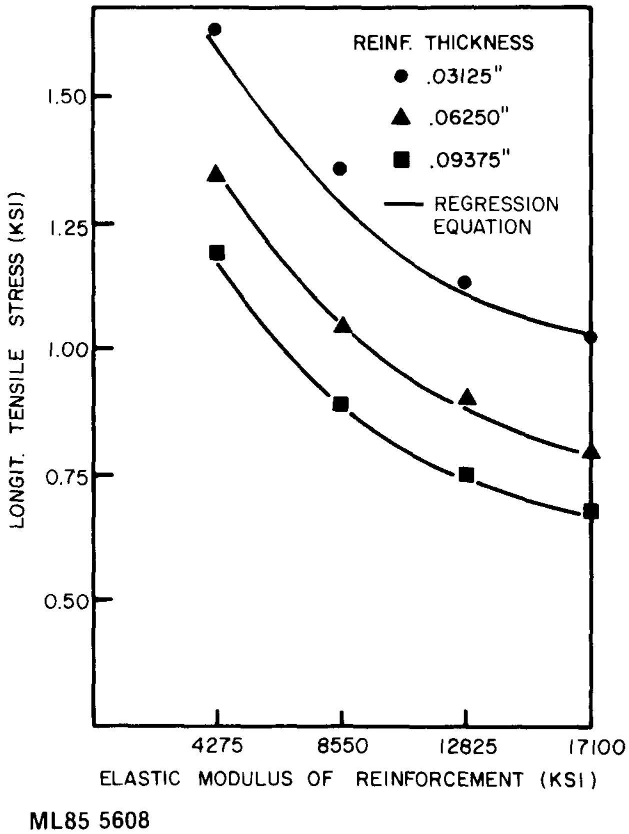

FIG. 5. Peak tensile stress as a fraction of reinforcement thickness.

which require relating the factors to a convenient coordinate system. The resulting equations were fitted only to the data points shown (Figs. 4–6).

The equation that relates peak shear stress to the stiffness and length of the reinforcement is:

$$f_{12} = -(171.25 - 20.675y - 23.25x + 6.898x^2 - 2.928yx)\frac{f_1'}{1,143}$$

where:

f_{12} is the peak shear stress, psi
y is an orthogonal term for $E_r = (E_r/4,275) - 3$
x is an orthogonal term for length = (length/0.75) − 3.125
f_1' is tensile stress on the gross cross section, psi.

At each stiffness level, a best-fit curve of the finite-element data points tends to flatten out after a specific reinforcement length is reached (Fig. 4).

The equation that relates the peak tensile stress to the stiffness and thickness parameters is:

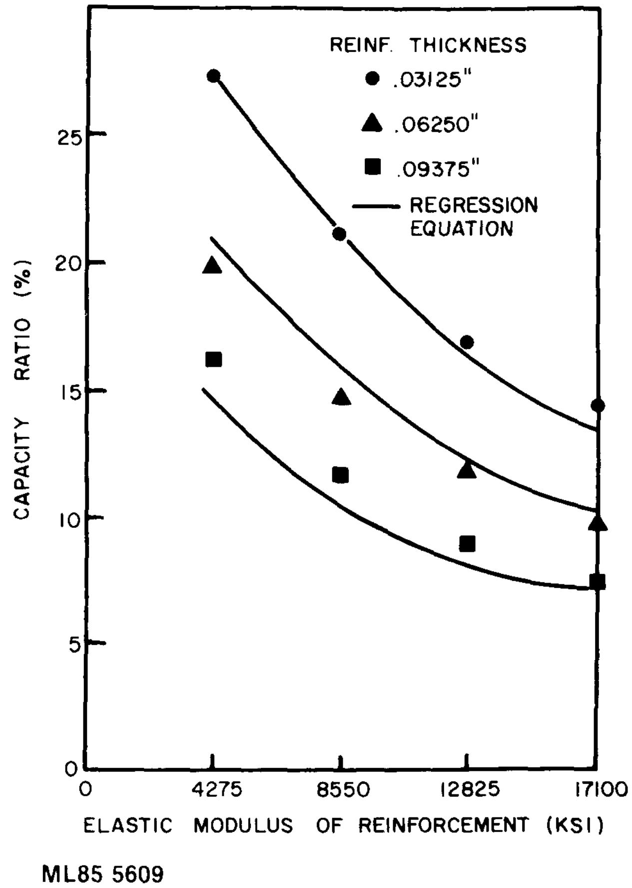

FIG. 6. Utilized capacity ratio (f_{lr}/F_{tr}) of reinforcing laminae having four elastic moduli and three thicknesses.

$$f_l = (1{,}100.06 - 473.548z - 204.625x + 293.36z^2 - 79.929z^3)\frac{f_l'}{1{,}143}$$

where:

f_l is the peak tensile stress, psi
z is an orthogonal term for $E_r = (E_r/8{,}550) - 1$
x is an orthogonal term for thickness = (thick/0.03125) − 2
f_l' is the tensile stress on the gross cross section, psi.

As the reinforcement stiffness increases, the rate of tensile stress reduction decreases (Fig. 5).

The utilized capacity of the reinforcing laminae, as predicted by the f_{lr}/F_{tr} ratio, is expressed as:

$$f_{lr}/F_{tr} = (15.989 - 8.776z - 5.336x + 3.344z^2 + 2.311xz)\frac{f_l'}{1{,}143}$$

where:

f_{1r}/F_{tr} is the capacity ratio, percent
z is an orthogonal term of $E_r = (E_r/8{,}550) - 1$
x is an orthogonal term for thickness = (thick/0.03135)
f_1' is the tensile stress on the gross cross section, psi.

For the studied range of parameters, the ratio never exceeded 30% (Fig. 6).

Design of reinforced butt joints

The finite-element analysis of the reinforced PLV indicates that shear stresses near the joint exceed their allowable working stress limits before the tensile stress exceeds its allowable working stress. Penny (1977), in his work on the fracture mechanics of butt joints, noted this, observing that embedded butt joints fail primarily in shear. In most of the parameter combinations, the ratio of observed shear to allowable working shear of the wood exceeded 100%. Correspondingly, the ratio of observed tensile to allowable working tensile stress in the wood only approached 75% at the worst parameter combination. The reinforcing's capacity ratio never exceeded 30%. Failure appears determined chiefly by shear stresses near the butt joints.

The design of an optimum combination of reinforcement parameters would first involve satisfaction of the shear criteria. A relation between E_r and length is obtained by minimizing the shear equation with respect to length. Assuming a minimum allowable shear stress and back substituting into the minimized equation, the length parameter can be found. The E_r is then obtained from this shear regression equation, knowing the length and the minimum allowable shear stress. The thickness parameter is then chosen by solving the wood tension-stress regression equation with the previously determined E_r and an observed tensile stress equal to the stress in the unweakened plane, f_1'. Finally, the stress in the reinforcement is checked. Applying the determined E_r and thickness parameters to the third regression equation will indicate the capacity of the reinforcing mechanism.

Based on the regression equations, a suitable reinforcement for the parameters used consists of a pair of unidirectional graphite-adhesive laminae: 0.03125 inch thick, 3.64 inches long, with a longitudinal stiffness of 13,560 ksi. These laminae would be centered above and below the butt joint. The peak stresses predicted by the regression equations for this reinforcement combination are:

$$f_{12} = 0.148 \text{ ksi}$$
$$f_1 = 1.11 \text{ ksi}$$
$$f_{1r}/F_{tr} = 15\%.$$

The addition of the reinforcing material brings the shear stress in the wood to the allowable stress, and the tension stress in the wood adjacent to the butt joint down to 60% of the allowable stress.

The regression equations were developed using a specific species of wood and are applicable only for the design of Douglas-fir PLV members. Adjustments, which are based on the modulus ratio of the MOE of the reinforcement, E_r, to the MOE of the wood, E_w, can be applied to the equations. At each reinforcement MOE level, as the modulus ratio changes for the different wood species, the sharing of stresses between the wood and the reinforcement changes. Generally, at each reinforcement MOE level, an increase of E_r/E_w obtained by decreasing the MOE of the wood results in an increase of the f_{1r}/F_{tr} ratio and a decrease of the observed tensile stress and shear stress on the wood. The generalization of the regression equations permits the design with any wood species for which the MOE is known.

Using the finite-element method of analysis, the trends in the changing peak stresses due to the changing modulus ratio were observed. Each E_r level exhibited a different trend of increasing tensile stress in the reinforcing and decreasing wood stresses as the modulus ratio increased. The shear stress trends were not significantly different between each E_r level. As the modulus ratio increased, the peak shear stress decreased in the same manner at each reinforcement level. The shear equation is mostly dependent on the length parameter, as the stiffness parameter appears only in the linear and the small interaction terms. The generalized equations are:

$$f_{12g} = [-f_{12} + 2.21 \times 10 - 5(E_w - 2{,}280)]$$
$$f_{1g} = f_1 + [67 - 9(2{,}280 - E_r) + 0.000268](E_w - 2{,}280)$$
$$(f_{1r}/F_{tr})g + f_{1r}/F_{tr} = [-24 - 7(2{,}280 - E_r) - 0.00472](E_w - 2{,}280).$$

EXPERIMENTAL TESTING

Small-scale laboratory testing of specimens was performed to verify the theoretical application of the concept.

Materials

Six Douglas-fir specimen blanks with one butt joint and various reinforcement levels were fabricated. Only one butt joint, which consisted of a 0.2- by 0.375-inch rectangular hole in the lamina next to the top, was placed in each blank. Two blanks contained no reinforcement; two blanks contained one layer of reinforcement, 0.015 inch thick by 8½ inches long, centered top and bottom of the butt joint; the remaining two blanks contained two layers of reinforcement, total thickness of 0.025 inch with lengths of 8½ and 6½ inches, centered on the top and bottom of the butt joint. A unidirectional graphite cloth was selected as the reinforcement. The graphite cloth had a longitudinal stiffness of 37,000 ksi and a tensile strength of 250 ksi. The adhesive was a resorcinol formaldehyde. The tensile tests suggested by Rowlands et al. (1985) were used. The stiffness, ultimate tensile stress, and ultimate strain of the composite were determined to be 9,700 ksi, 64,000 ksi, and 0.008 inch/inch, respectively. Glueline thickness was 0.005 inch. The average MOE of the wood was 2,300 ksi.

Tension specimens were prepared from the six blanks. Each of the 1½- by 2½- by 36-inch blanks was cut into five 1½- by ½- by 36-inch specimens. The ends of the specimens were built up by gluing ½- by ½- by 10-inch strips of Douglas-fir onto each side of the ends. The strips were tapered to gradually decrease from 2½ to 1½ inches at the gage section (Fig. 7). Aluminum plates, 2½ by 4½ inches, were bonded to the faces of these built-up ends. These steps were taken to prevent premature failure in the grips of the testing machine.

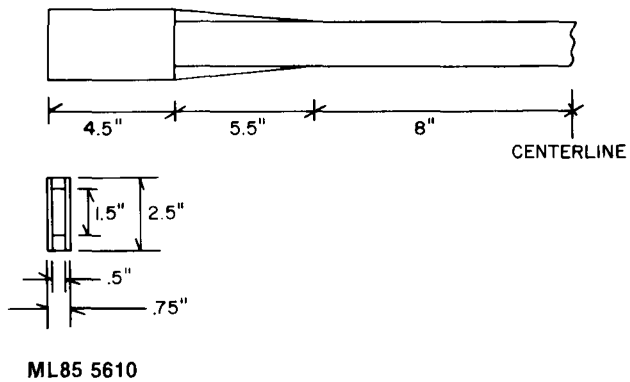

FIG. 7. Test specimen dimensions. (This represents one-half the entire specimen.)

Methods

Testing was done to observe ultimate strengths and failure modes for the different composite types.

Each specimen was loaded in tension at 0.0375 inch/min. Strain was measured with polyester-backed, foil strain gages bonded with epoxy gage adhesive. The gages were 0.08 inch long and 0.044 inch wide. Special precautions were taken so the gages measured only the dimensional changes of the specimen due to tensile stresses and not those changes due to temperature (Hete'nyi 1950). When gluing strain gages to wood perpendicular to the grain, as was done at one location, the problem of localized stiffening of the wood by the gage and the adhesive can occur. Sliker (1971) indicated that strain gage readings in this direction are 25 to 50% less than actual strains, while gage readings in the parallel-to-grain direction are generally within 2% of the actual strains.

Each specimen had at least one gage located within the second laminae, directly beside the butt joint, to measure longitudinal strain. One specimen from each of the three reinforced combinations had gages placed along its length (Fig. 8). The locations were selected to coincide with the centroids of elements adjacent to the butt joint and reinforcement in the finite-element model.

Results

One-way parametric analyses of variance were done (Table 1). At a 95% confidence level, a statistical difference does exist between the unreinforced and two-

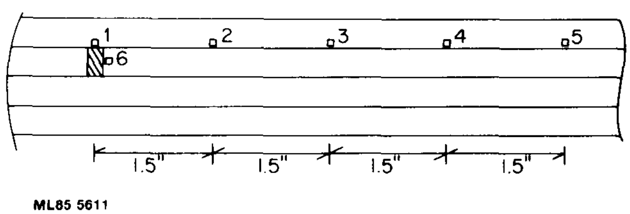

FIG. 8. Gage locations.

TABLE 1. *Experimental testing ultimate stresses.*

	No reinforcement	One layer	Two layers
		Psi	
	4,900	4,467	4,907
	5,100	4,747	5,327
	5,173	4,800	5,807
	6,713	6,680	6,680
	5,273	5,160	6,060
	5,360	5,480	6,067
	5,600	5,720	6,167
	5,873	5,767	6,453
	6,420	6,420	6,667
	6,713	6,680	6,680
			6,833
Mean	5,600	5,560	6,230
Standard deviation	584	707	455

layer reinforced specimen groups. There is no statistical difference between the unreinforced and the one-layer groups.

In all but two specimens, failure initiated at the butt joint. The exceptions were a premature failure of the tapered area and at a knot. The unreinforced and one-layer specimens failed suddenly, with the fracture turning 90° from the plane of the butt joint and following the slope of the grain or the glueline of the adjacent laminae.

The mode of failure in the two-layered specimens progressed in two stages. First, the wood failed suddenly at stress levels of the same magnitude as those of the unreinforced and one-layer groups. Second, the load was transferred from the wood to the reinforcement laminates, and the members continued to be stressed until total failure, which was sudden. This type of failure was observed by Spaun in 1979 while testing tensile specimens of Douglas-fir cores with veneer and fiberglass laminated to the outer faces.

Comparison of finite-element predictions to test results

A finite-element analysis of the ½- by 1½- by 32-inch Douglas-fir test specimens was performed for the three reinforcement combinations. To allow comparison of theoretical and empirical results, a 0.857-kip tensile load was applied. This was equivalent to the 6-kip load applied in the theoretical model. The peak longitudinal tensile stresses show that the theoretical strength of the specimen should increase by 37 and 47% compared to the unreinforced specimen for one and two layers of reinforcement, respectively. From a shear-stress standpoint, the increases in apparent strength should be only 3.8 and 6.4%, respectively. Since shear was observed as the controlling stress at failure, the predicted 6.4% increase in apparent strength correlates well with the 10% strength increase observed for the small-scale specimen testing.

The predicted strain behavior corresponds well to the observed (Table 2) except at gage location 6 (Fig. 8). This gage measured perpendicular-to-the-grain strains.

TABLE 2. *Strain for tensile stress increments of 33 psi: finite-element predictions versus specimen test results.*

Reinforcement	Gage location (Fig. 8)	Finite-element predictions	Actual
		10^{-6} inch/inch	
None	1	262	239
	2	146	96
	6	−262	−153
One layer	1	215	194
	2	137	100
	3	135	104
	4	149	110
Two layers	1	183	180
	2	129	59

The adhesive and the gage act to locally reinforce the wood, resulting in smaller strain increments (Sliker 1971). This would explain the significant difference between predicted and measured strains that occurred at location 6.

CONCLUSIONS

A two-dimensional finite-element analysis was shown to be a promising tool for the analysis and design of butt-joint reinforcement in PLV. It compares well with the experimental test results.

Based on the localized stresses predicted from the finite-element analysis, butt-jointed, PLV tensile members do benefit from the application of reinforcement. The peak stresses in the wood can be reduced to below the allowable stress limitations of the species. Therefore, the ultimate strength of the tensile member is increased.

The effectiveness of the reinforcing mechanism in distributing stresses at the butt joint depends principally on three reinforcement parameters: thickness, length, and longitudinal MOE. Reductions in peak tensile stresses in the wood are chiefly influenced by the MOE and thickness of the reinforcing laminae. Correspondingly, the capacity of the reinforcement, as measured by the ratio of the predicted tensile stress to the allowable tensile stress in the reinforcement, depends on the same two parameters. Reductions in shear stresses in the wood near the butt joint are determined by the reinforcement's length and MOE. The peak stresses in any wood species, as well as the strength needed of the reinforcement, can be predicted with the statistical relations developed involving the three parameters. Efficient design of the reinforcing mechanism can be made using the regression equations with attention to the allowable stress limitations of the components. In the example design, the predicted strength of a reinforced tensile member is approximately 30% greater than that of an unreinforced member.

Shear stresses near the butt joint control the strength of the PLV member and therefore its design. Failure occurred as a shear fracture at the butt-jointed area.

As the MOE of the reinforcement increases, changes in the modular ratio, E_r/E_w, have a smaller effect on the benefits gained from using reinforcement. This indicates that there is an upper limit on the reinforcement MOE parameter based on both the tensile-stress-reducing efficiency and cost limitations inherent in providing a higher reinforcement MOE.

Although the number and range of test specimens were limited, the benefits of localized reinforcing of butt joints were seen. As little as 1.7% of the cross-sectional area of reinforcing provided an increase in ultimate strength and in uniformity. The strength increased by 10% and the standard deviation of the specimens in a group decreased by 22.4% over the unreinforced group.

Further experimental work should be done with specimens reinforced to levels indicated by the analytical study. This would serve to test the validity and accuracy of the performance predictions resulting from the finite-element modeling.

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