STRESS ANALYSIS AND PREDICTION IN 3-LAYER LAMINATED VENEER LUMBER: RESPONSE TO CRACK AND GRAIN ANGLE

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ABSTRACT

A mathematical model has been developed that can predict the elastic properties in tension of 3-layer laminated veneer lumber with clear, straight-grained outer layers and an inner layer with sloping grain and a crack parallel to that grain. This analysis provides a theoretical means of determining the tension behavior of the material containing a crack at any angle to the direction of the stress and takes into account the orientation and basic properties of the individual orthotropic layers.

Keywords: Tensile strength, laminated veneer lumber, crack, sloping grain.

INTRODUCTION

The design of structural composites requires the determination of the final geometry and dimensions of the components, and the selection of material, in such a way that the composite will perform its function properly under the expected environmental conditions. This is usually accomplished by applying a failure criterion that in general is the comparison of a critical load factor representing the intensity of the applied load with the geometry and a characteristic strength parameter of the material. In order to select and apply the most appropriate failure criterion, one needs to know the probable mode of failure. This paper describes the development of a finite-element analysis capable of predicting the uniaxial tension behavior of laminated veneer lumber (LVL) made from three layers of veneer when the middle layer may contain sloping grain and a crack.

BACKGROUND

Grain angle effect

Slope of grain has a significant effect on the mechanical properties of wood because the strength and stiffness of wood are much less perpendicular to the grain than along the grain. For example, the average tensile strength of clear Douglas-fir is 17,600 psi parallel to the grain but only 390 psi perpendicular to the grain (USDA 1987).

The following empirical formula due to Hankinson is commonly used to estimate the strength of wood stressed at an angle θ to the grain when the strength is known parallel and perpendicular to the grain.

$$\sigma_\theta = \frac{\sigma_0 \cdot \sigma_{90}}{\sigma_0 \sin^n\theta + \sigma_{90}\cos^n\theta} \qquad (1)$$

where σ_θ, σ_0 and σ_{90} are the values of the property in directions at $\theta°$, 0° and 90° to the applied

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stress. The value of n is usually taken as equal to 2.

The shear strength of the material and any differences between the properties in the radial and tangential directions are ignored. Goodman and Bodig (1974) demonstrated the usefulness of this formula.

Effect of cracks

Schniewind and Lyon (1973) investigated the tensile strength perpendicular to the grain in dimension lumber of Douglas-fir and determined the extent to which it was affected by the presence of defects in the form of checks, knots, resin streaks, pitch pockets, and pitch. They found that checks were the major defect reducing strength.

Cracks produce a complex stress distribution near the crack tip. A material property related to the energy needed to cause a crack to propagate is called the "critical stress intensity factor" (CSIF). Porter (1964) found that varying the specimen thickness between ⅛ and 1 in. (3.2 and 25.4 mm) did not affect the CSIFs of white pine cleavage specimens machined to fail in the TL (tangential-longitudinal) and RL (radial-longitudinal) systems—the first index represents the direction of the stress and the second index the direction of propagation of the crack. Schniewind and Lyon (1973) observed that the CSIFs decreased as the size of specimen increased. Barrett (1976) investigated the effect of crack size and specimen width on the tensile strength perpendicular to the grain, and his results showed a decrease in CSIF with increasing specimen width. Schniewind and Pozniak (1971) found that for the TR system (stress parallel to the growth rings and radial direction of crack propagation), length to width ratios from 0.67 to 2.0 had no discernible effect on the CSIFs. They also examined the effect of strain gauge length and crack orientation. In testing tensile specimens in the TR system, a short gauge length is desirable to avoid effects resulting from ring curvature, but tests with gauge lengths ranging from 1 to 3 in. showed no noticeable effect of gauge length. This would indicate that the local stress field surrounding the crack tip was indeed highly localized and was not affected by the imposed changes in boundary conditions. Schniewind and Pozniak also showed that the critical CSIF was lower for the TL than for the TR system.

MATHEMATICAL MODEL FOR LVL

It is convenient to view LVL as a "stack" of laminae in which the laminae may have different flaws, properties, and orientations of the principal axes. An entire stack can be modeled as a single plate because the material properties of the stack are completely reflected in the matrices of the elastic moduli for the elements into which each layer may be subdivided. This permits one to define the effective elastic properties of the stack as a whole and to compute integrated values of the in-plane stress components across the laminate thickness.

This paper describes the modeling by a finite-element method (FEM) of the effect of a crack in the core of a 3-layer specimen of LVL subjected to axial tension and made from yellow poplar veneers. The outer layers of the specimen were assumed to be straight-grained and free from defects while the core grain was at various angles to the length of the specimen. For some specimens, the core contained a central crack that was always parallel to the grain of the core as illustrated in Fig. 1.

Generation of finite element mesh

Al-Dabbagh (1980) used an FEM with a "false element" to simulate a crack in his study of stress analysis of anisotropic solids. Henshell and Shaw (1975) showed that it is possible to obtain quite accurate solutions to the problem of determining the stress intensity at the tip of a crack. Dabholkar (1980) used an FEM to investigate strains near a knot and obtained good agreement between the strains given by the FEM and experiment. Cramer and Goodman (1983) used Dabholkar's FEM model with success.

The present study used an FEM based on a two-dimensional, 4-node quadrilateral with a

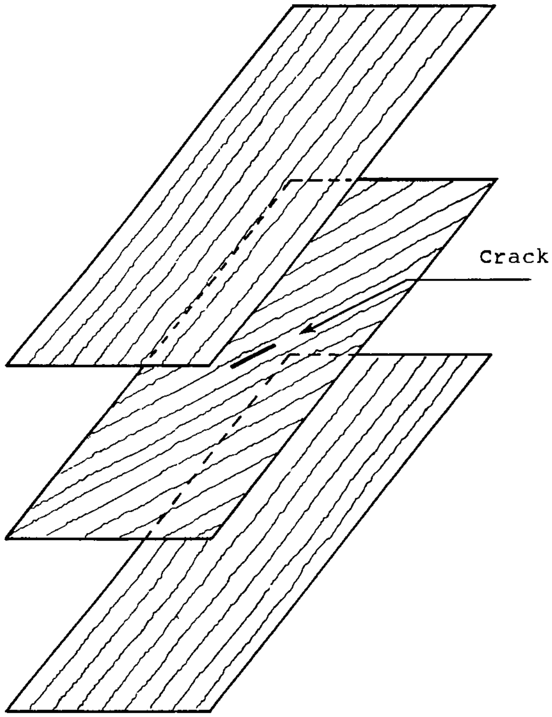

FIG. 1. Exploded view of a typical three-layer specimen showing core with sloping grain and a crack.

total of 8 degrees of freedom, so that it was a constant strain, plane, isoparametric, linear element. The stress distributions near the advancing crack tip were required, so small elements were used near the crack. The crack itself was modeled by a "false" element with near-zero stiffness.

The modeling of an angled crack involved the use of two quadratic equations to generate an angled mesh parallel to the crack. Narrow elements in the mesh were necessary at critical locations around the crack to provide adequate simulation of the strain distribution. Figure 2 is a representation of the mesh used to simulate the pattern of an angled crack in the LT plane of the specimen. It should be noted that the mesh does not have the curved lines expected from quadratic equations. The quadratic equations gave mesh lines that intersected at varying angles and led to oddly shaped elements around the crack. For simplicity, the computed curved elements were modified and re-

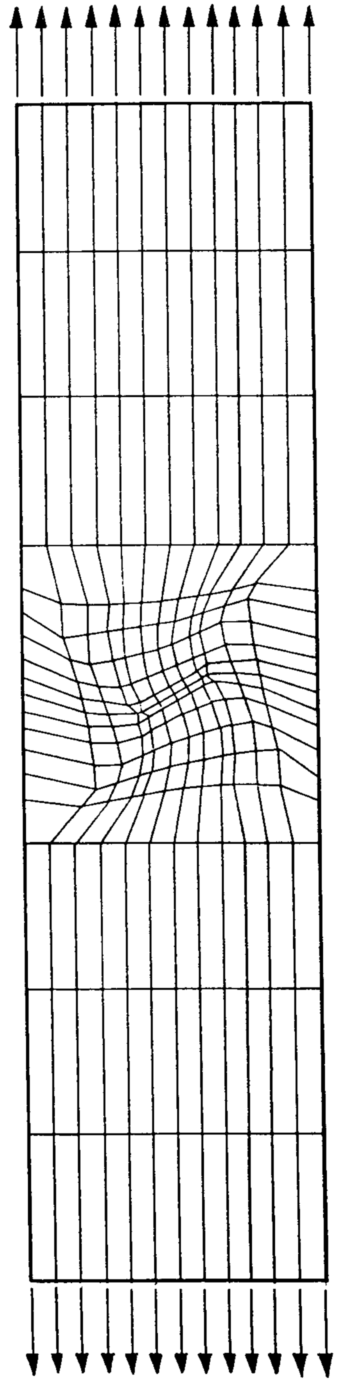

FIG. 2. Mesh adopted for simulating an angled crack.

placed by linear elements of more uniform shape. The use of a mesh with grid lines parallel to the grain in each layer was attempted, but the resulting three-dimensional elements led to complicated mathematical problems and considerable computing time. Consequently, that approach was abandoned.

The same application for dividing the solid into elements was used for crack-free specimens as for specimens with cracks. The program received as input suitable stiffness properties for the finite elements.

A Fortran program called LAMINA (Cha 1988) was written to number the nodal points and to calculate their coordinates.

Stiffness of angled laminae

Standard theory for orthotropic elasticity gives the following relationship between the elastic constants for a member stressed at an angle θ to the longitudinal (L) axis of symmetry of the material.

$$E_L = E_l\left[\cos^4\theta + \frac{E_L}{E_T}\sin^4\theta + \frac{1}{4}\left(\frac{E_L}{G_{LT}} - 2\nu_{LT}\right)\sin^2 2\theta\right] \quad (2)$$

where

- E_L = modulus of elasticity (MOE) parallel to the grain (longitudinal axis of symmetry)
- E_T = MOE parallel to the growth rings (the tangential axis of symmetry) = 0.043 E_L
- E_l = MOE parallel to the length of the specimen (the l-axis)
- G_{LT} = modulus of rigidity (G) for the LT plane = 0.069 E_L
- ν_{LT} = Poisson's ratio for strain in the T direction caused by stress in the L direction = 0.39.

The value of E_l was obtained for each lamina from stress wave tests. The values involving E_T, G_{LT} and ν_{LT} given above were obtained for yellow poplar from the Wood Handbook (USDA 1987).

Finite element stress analysis

An abbreviated version of a commercial comprehensive computer program called NASTRAN was used to perform the FEM. Tensor theory was used to transform the orthotropic elastic properties to the values appropriate to the orientation of the elements. The transformed properties and boundary conditions were readily entered into the program. The output produced by this version of NASTRAN included nodal displacements and the stresses at the centroid of each element. A plotting routine enabled the large amount of data generated by the analysis to be more easily interpreted. A plot of the deformed model was used to check the boundary conditions of the elements.

EXPERIMENTAL STUDY

Test variables

The test material was 3-layer LVL nominally 2 in. (5.1 cm) wide, 16 in. (40.6 cm) long and ⅜ in. (9.5 mm) thick made from ⅛-in.- (3.2-mm-) thick yellow polar veneers. The outer layers were straight-grained and free from significant defects. The central layer contained the test variables of crack length and slope of grain, all cracks being made parallel to the grain. For the initial experiment, the grain angles were 0°, 10°, 20°, 30°, 60°, and 90°. Crack lengths were nil for all angles for controls, 0.5 in. (12.7 mm) for 30°, 60°, and 90° angles, plus 0.7, 0.9 and 1.1 in. (17.8, 22.9 and 27.9 mm) for the 90° angle. Accordingly, the total number of variables was 12.

Later, an additional experiment was carried out with 3-in.- (7.6-cm-) long cracks in veneers with grain slopes of 10°, 20°, and 30°.

Production of veneer strips

A random procedure was used to select 25 sheets for the faces and 10 sheets for the cores from a stack of 36- by 38- by ⅛-in. (91.4- by 96.5- by 0.33-cm) sheets of clear yellow poplar veneers. Strips 3 by 16 in. (7.6 by 40.6 cm) were cut with a band saw from each sheet, those for the faces being sawn parallel to the

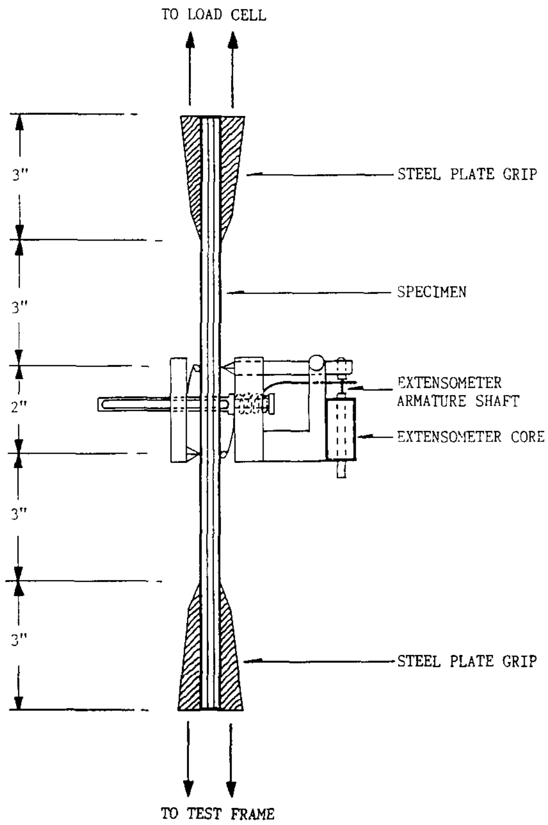

FIG. 3. Specimen with averaging LVDT extensometer.

grain, those for the cores being sawn at approximately the required grain angles. Center lines were then drawn parallel and perpendicular to the grain on all the strips to enable the grain angle to be measured carefully by a protractor. The outline of a rectangle just over 2 by 14 in. (5.1 by 35.6 cm) was then drawn on each strip at the correct grain angle. Strips with the grain at 90° were made slightly larger than the others to provide a safety margin in handling these fragile strips. The strips were then sawn with a table saw to the new dimensions.

Selection of strips for specimens

A Metrigard stress wave timer was used to determine the MOE parallel to the length of each strip. A small ball pendulum impacted the strip and the time for the stress wave to pass between two accelerometers was recorded. The MOE was computed from the following equation:

$$E_l = \rho v^2/g \tag{3}$$

where

ρ = density of the strip (lb/in.^{3})
v = speed of the stress wave (in./sec)
g = acceleration due to gravity (in./sec^2).

For the initial experiment, a total of 168 strips as straight-grained and defect-free as possible were selected for the outer layers. Each strip was ranked in ascending order of its MOE. Two groups of 84 strips were formed, one being the strips of odd-numbered rank, the other the strips of even-numbered rank so that both groups were closely matched with respect to their MOE values. Pairs of strips of corresponding rank in each group were then selected so that each strip in each pair would have approximately the same MOE. In similar manner, seven sets of twelve pairs each were selected from total number so that each set was similar in its MOE values. These sets provided the replications. The test variables of grain angle and crack length were allocated at random to the pairs in each replication.

The strips for the cores were similarly ranked in ascending order of their MOEs. A core strip with the required grain angle was matched to a pair of outer strips in order of its rank number.

A similar procedure was used for obtaining the specimens for the second experiment with the 3-in.-long cracks, but the veneers came from a different batch.

Specimen construction

Cracks were formed in the strips selected for the central layer by drilling a hole $\frac{3}{32}$-in. (2.4-mm) diameter at the center of the crack position to allow insertion of a jeweler's saw blade, which then was used to saw a slot of the required length in both directions from the hole.

A small piece of plastic film was inserted in the crack to keep it open during the spreading of the adhesive. After being glued, the three strips for each specimen were stapled together

TABLE 1. *Effect of slope of grain and crack size on tension properties of three-layer LVL specimens.*

Grain angle (°)	Crack length (in.)	Sample size	Maximum tensile stress (psi & %*)	Modulus of elasticity: Stress wave test (ksi & %*)	Modulus of elasticity: Tension test (ksi & %*)
0	0	14	11,950 (13.2)	1,410 (4.7)	1,610 (7.4)
10	0	7	11,720 (5.6)	1,285 (6.5)	1,400 (7.8)
10	3.0	5	11,630 (2.7)	1,525 (4.2)	1,410 (4.6)
20	0	7	9,690 (8.5)	1,160 (4.2)	1,325 (13.7)
20	3.0	5	9,870 (4.0)	1,300 (5.5)	1,280 (13.0)
30	0	7	8,520 (7.0)	1,060 (6.0)	1,170 (12.1)
30	3.0	6	9,460 (4.6)	1,220 (4.2)	1,130 (7.7)
30	0.5	5	8,680 (7.3)	1,070 (5.1)	1,100 (6.5)
60	0	7	8,860 (9.8)	990 (5.5)	1,140 (7.9)
60	0.5	6	8,410 (9.3)	996 (5.2)	1,145 (7.2)
90	0	7	8,240 (11.9)	976 (5.3)	1,050 (6.9)
90	All	39	8,210 (14.1)	1,010 (7.5)	1,010 (11.5)

* Values in parentheses are the coefficients of variation.

to hold them in position. The specimens were clamped together under pneumatic pressure for a least 24 hours while the adhesive cured.

Test procedure

The specimens were held by steel wedge grips in the loading heads of a Tinius-Olsen universal testing machine, the upper grip being loaded through a spherical seat to minimize eccentric loading. The deformation parallel to the length of the specimen was measured by the linear variable differential transformer (LVDT) of a Tinius-Olsen averaging extensometer as shown in Fig. 3. The LVDT was carefully positioned over the crack location with its knife edges 2 in. (5.1 mm) apart. An X-Y recorder provided a graph of load vs. extension. Loading was continued to failure at a rate of head movement of 0.05 in./min (1.3 mm/min).

RESULTS AND DISCUSSION

Effect of cracks on tensile properties of specimens

Table 1 gives the average values of the maximum tensile stress (MTS) and MOE obtained from the tension tests on the different types of specimen. The MTS was computed as the maximum load divided by the gross cross-sectional area. The stress wave values of MOE are the mean values of the MOE of the three layers comprising a specimen obtained from the stress wave tests.

The results indicate that the cracks in the central layer had little effect on either the tensile strength or modulus of elasticity, the reductions in the properties being caused by the slope of grain. As the slope of grain in the central layer increased, there was a significant reduction initially, but the magnitude of the decrease became small for a slope of grain exceeding about 30°. Table 1 makes it clear that, as expected, a central layer oriented with the grain perpendicular to the length of the specimen contributes very little to the overall strength or stiffness. For such specimens, the strength and stiffness were about two-thirds of the values for specimens with all layers straight-grained, i.e., the properties were those of the two outer layers.

Relation between tensile strength and modulus of elasticity of the specimens

Table 1 shows that the mean values of MOE, like those for MTS, decreased as the slope of grain of the core veneer increased. The values from the stress wave and the tension tests differed by less than 12%.

For the crack-free specimens, MTS was related to the mean MOE of the three layers as obtained from the stress wave tests by the following regression equation.

TABLE 2. *Comparison of experimental and FEM values of longitudinal tensile strains and stresses.*

		FEM		Experimental		Difference†	
Grain angle (°)	Crack length (in.)	(10^{-3} in./in.)	Stress* (psi)	Strain (10^{-3} in./in.)	Stress** (psi)	Strain (%)	Stress (%)
0	0	8.45	11,920	7.42	11,950	13.9	−0.3
10	0	8.73	11,220	8.31	11,630	5.1	−3.7
20	0	7.77	9,010	7.33	9,710	6.0	−7.7
30	0	7.58	8,040	7.31	8,550	3.7	−6.4
30	0.5	7.65	8,190	7.93	8,720	−3.7	−6.6
60	0	8.83	8,740	8.00	9,120	10.4	−4.3
60	0.5	8.33	8,300	7.29	8,350	14.3	−0.6
90	All	8.07	8,150	8.15	8,230	−1.0	−0.9

* Stress = Stress wave test value of MOE from Table 1 × FEM strain.
** Stress = MOE from tension test in Table 1 × Experimental strain.
† Difference = 100 × (FEM value − Experimental value)/Experimental value.

$$MTS = -136 + 8.670 \times 10^{-3} \text{ MOE.} \quad (4)$$

The coefficient of determination, r^2, was equal to 0.733. The units are psi for MTS and 1,000 psi (ksi) for MOE.

For the specimens with a crack in the core, the following equation was obtained, r^2 being equal to 0.654.

$$MTS = 1{,}990 + 6.216 \times 10^{-3} \text{ MOE.} \quad (5)$$

These equations may be used to estimate the tensile strength from a knowledge of the MOEs of the individual veneers. For example, the stress wave tests gave 1,450,000 psi as the average MOE of all straight-grained veneers without cracks and 57,000 psi as the average MOE for the veneers with the grain at 90° to the stress. From Eq. (4), the expected maximum tensile stresses of specimens with all veneers at 0° or 90° to the stress would be 12,570 psi or 494 psi, respectively. These values are 20% and 10% lower than the respective species mean values of 15,900 psi and 540 psi given in the Wood Handbook (USDA 1987) for solid yellow poplar at 12% moisture content stressed parallel and perpendicular to the grain, respectively. The MOE given by the Wood Handbook for yellow poplar is 1,580,000 psi. For comparison with the shear-free MOE of the veneers, the value of 1,580,000 psi needs to be increased by about 10%. On that basis, the MOE of the solid wood would be about 17% greater than the MOE of the veneers and so the discrepancy between the estimate of MOR given by Eq. (4) and the Handbook value is reduced to about 6%.

Comparison of predicted and test values of strains

Table 2 compares the strains at maximum load predicted by the FEM against those measured from the tension test over the 2-in. (5.1-cm) gauge length. The strains from the FEM were calculated from the displacements of two nodes 2 in. apart corresponding to the gauge length of the extensometer. Finite element strains were not obtained for the specimens with cracks at 10°, 20°, and 30° because there were no two nodes corresponding to the position of the extensometer. The FEM tended to overestimate the strains, but generally there was good agreement between the experimental and the theoretical strains.

Table 2 also compares the stresses computed from the FEM strains at maximum load and the stress wave values of the MOE of the veneers and the stresses computed from the experimental strains at maximum load and the test value of the MOE. The agreement is good, the maximum difference being 7.7%.

Effect of grain angle and cracks on stresses in the layers

Tension tests were not done on individual veneers, but two methods were used to estimate the stresses in the layers. One method was based on the strains computed by the FEM; the other was based on Hankinson's formula with Eqs. (4) or (5).

For the first method, the MTS in each layer parallel to the length of the specimen was computed by multiplying the value given by the FEM of the maximum tensile strain parallel to the length in each layer by the MOE of the respective veneer as determined from the stress wave tests.

For the second method, the MTS of the straight-grained veneers was estimated from Eq. (4) if there were no cracks in the central layer, and from Eq. (5) if there were cracks in

TABLE 3. *Comparison of FEM and Hankinson strength values.*

Ratio of FEM estimate to formula estimate of MTS									
	Crack-free central layer				Cracked central layer				
		Central layer					Central layer		
Grain angle (°)	Outer layer (%)	n = 2 (%)	n = 2.5 (%)	n = 3 (%)	Crack size (in.)	Outer layer (%)	n = 2 (%)	n = 2.5 (%)	n = 3 (%)
0	101	91	91	91	—	—	—	—	—
10	100	115	85	72	3.0	106	148	108	92
20	100	153	103	73	3.0	108	159	107	70
30	100	136	100	73	3.0	106	175	128	94
30					0.5	95	132	96	71
60	100	115	100	99	0.5	94	113	105	97
90	99	100	100	100	0.5	100	100	100	100

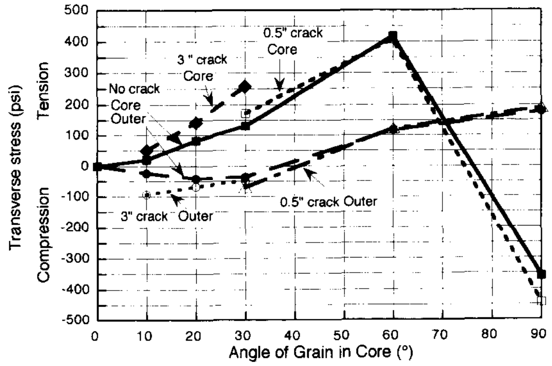

FIG. 4. The maximum values of the transverse stresses obtained from the FEM for various angles of the core grain and crack lengths. The values are joined by lines only to indicate the trends. The upper three sets of values are the stresses in the core, the lower three sets are the stresses in the outer plies. The crack and sloping grain occur in the core only.

the central layer. The value of the MOE substituted in the equation was the average value obtained from the stress wave tests on the particular veneer.

The tensile strength of a veneer with sloping grain was estimated in a more complex manner. Substitution of the stress wave MOE as E_l in Eq. (2) gave an estimate of E_L, and E_T was then taken as 0.043 E_L. Finally, these values of E_L and E_T were substituted in Hankinson's formula, Eq. (1), to obtain the estimate of the tensile strength of the veneer with the particular slope of grain. Three estimates were computed using n = 2, 2.5 and 3 in Hankinson's formula.

For ease of reference, the estimates of the MTS given by the second method will be called "formula estimates." They are compared with the estimates obtained from the FEM in Table 3, the tabulated values being the ratio of the FEM estimates to the formula estimates expressed as percentages. Ratios of 100% indicate perfect agreement. For the outer layers, the agreement is nearly perfect, and except for grain angles of 0° and 10°, the agreement is good for the inner layers for estimates obtained with n = 2.5.

The maximum values computed from the FEM of the transverse stress (the normal stress perpendicular to the direction of the applied stress) are plotted against the grain angle of the core in Fig. 4.

Figure 4 indicates that the transverse stress in the central layer was tension that increased with increase in grain angle up to some angle in the vicinity of 60° and then decreased and became compression for some angle near 90°. The converse occurred in the outer layers, the transverse stress being compression for core grain angles less than about 40° and tension for larger grain angles. For the test specimens, the highest tensile stress was 416 psi at 60° for the core of the crack-free specimens and 407 psi for the core of the specimens with an 0.5-in. crack.

Although limited in scope, the tests showed that crack size had some effect, especially for the smaller grain angles. At a grain angle of 30°, the transverse tensile stress in the core was 258 psi for a 3-in.-long crack and 172 psi for a crack only 0.5 in. long. For high grain angles, cracks would not be expected to have much effect because the material strength at those angles is so low. For a grain angle of 90°, the compressive stresses in the core were 358 psi and 444 psi for the crack lengths of zero and 0.5 in., respectively.

The transverse stresses in the outer layers were markedly less than those in the central layer. The maximum compression reached was less than 100 psi. Maximum tension of 191 psi occurred at a core grain angle of 90°.

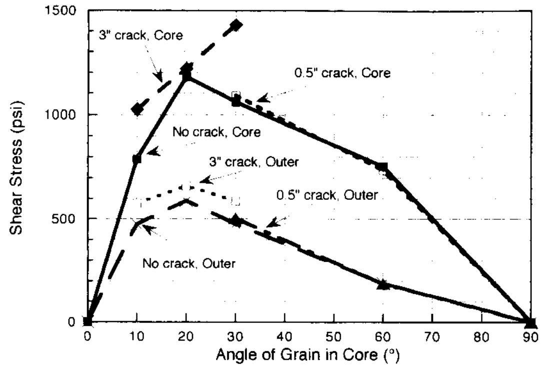

FIG. 5. The maximum values of the shear stresses obtained from the FEM for various angles of the core grain and crack lengths. The values are joined by lines only to indicate the trends. The upper three sets of values are the stresses in the core, the lower three sets are the stresses in the outer plies. The crack and sloping grain occur in the core only.

The maximum values computed from the FEM of the shear stress parallel and perpendicular to the direction of the applied stress are plotted against the grain angle of the core in Fig. 5. As expected, shear stresses were zero for grain angles of 0° and 90°, but otherwise they were high, especially in the core. The maximum values were reached for some angle near 20° for specimens without a crack and at about 30° for specimens with a 3-in.-long crack, the respective magnitudes being 1,180 psi and 1,430 psi. The maximum shear stresses in the outer layers were about half those in the central layer. The FEM did not give values of the shear stresses parallel to the grain in the central layer, but they would be expected to be somewhat higher than those parallel to the length of the specimen.

The specimen was obviously subject to a very complex stress system, which changed with the grain angle of the central layer. The shear stress in the inner layer was high when sloping grain was present in the central layer, and the presence of a crack increased it further. The shear stress decreased for large grain angles, but the transverse tension stress increased, although it changed to compression in the central layer for very steep slopes of grain. The computed maximum values of shear stress and transverse stress were comparable with the respective mean maximum values of 1,180 psi and 540 psi listed by the Wood Handbook (USDA 1987) for the species. The interaction between shear parallel to the grain and tension stress perpendicular to the grain in the layers apparently determined the strength of the specimen.

TABLE 4. *Stress concentrations in cracked specimens.*

Grain angle (°)	Crack length (in.)	Concentration factor for longitudinal stress*	
		Outer layer	Inner layer
10	3.0	1.25	1.09
20	3.0	1.29	1.18
30	3.0	1.22	1.31
30	0.5	1.16	1.24
60	0.5	1.04	1.79
90	0.5	1.02	1.01

$$* \text{Concentration factor} = \frac{\text{stress computed from FEM}}{\text{applied longitudinal stress}}.$$

Stress concentration

The FEM enabled the longitudinal stresses to be calculated at each of the elemental areas into which the layers were subdivided by multiplying the strain parallel to the length by the MOE given by the stress wave tests. The maximum stresses were in the vicinity of the crack tips as expected. A maximum stress concentration factor (MSF) was defined as:

$$\text{MSF} = \frac{\text{maximum stress computed from FEM}}{\text{applied stress}}$$

where the applied stress = maximum tension force divided by the total cross-sectional area.

Table 4 shows the variation in the MSF for the outer and inner layers with the various grain angles and crack lengths. The MSF reached a maximum of 1.79 for a grain angle of about 60° in the inner layer, but the maximum of 1.29 was reached in the outer layer when the inner layer had a grain angle of about 20°. Two crack sizes were tested for a slope of grain of 30°, and the MSF for the 3-in.-long crack was about 6% greater than that for the 0.5-in. crack.

CONCLUSIONS

1. The presence of sloping grain in the core of 3-layer LVL subjected to longitudinal tension causes a very complex system of stresses in the material. High shear stresses and transverse tension stresses occur in the core, the magnitudes of which vary with the slope of grain. The presence of a crack or split in the core increases these stresses.

2. Transverse stress (i.e., stress perpendicular to the specimen length) in the core changed from tension to compression when the slope of grain was close to 90°. In the outer layers, however, the transverse stress was compression for grain angles up to about 40°, and then it changed to tension. The presence of a crack in the core increased the transverse stress for the smaller grain angles, but had little effect for angles greater than about 40°. The transverse stress in the outer layers was numerically about one-half that in the core for the same grain angle.

3. The shear stresses in the directions parallel and perpendicular to the applied tension were zero for grain angles of 0° and 90°, but were of high magnitude for specimens with intermediate grain angles in the central layer. The shear stresses in the core were much higher than those in the outer layers. The maximum computed value was 1,180 psi in the core for a grain angle of 20°, the corresponding shear stress in the outer layer being 589 psi. A crack appeared to increase the shear stresses to some extent for grain angles less than about 30°.

4. Longitudinal stress concentrations due to cracks decreased in the outer layer as the grain angle increased, but in the central layer they increased with increase in the grain angle up to an angle of 60°.

5. Hankinson's formula with $n = 2.5$ provided the best fit to the FEM values of the longitudinal tension stresses in the core and outer layers. With $n = 2$, the formula gave a satisfactory fit for small and large grain angles but underestimated the strength at intermediate angles.

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