ORTHOTROPIC BEHAVIOR OF LUMBER COMPOSITE MATERIALS

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(Received September 2000)

ABSTRACT

Elasticity properties were evaluated with respect to the various commercial types of composite lumber. The study included laminated veneer lumber (LVL), parallel strand lumber (PSL), and laminated strand lumber (LSL). The experimental study was designed to better characterize the elasticity properties of these increasingly important structural composite lumber (SCL) materials. Experimental efforts for SCL material characterization were performed applying the five-point bending test (FPBT) and torsional stiffness measurement test (TSMT) evaluation methodologies. FPBT provided simultaneous solution for both modulus of elasticity (E) and modulus of rigidity (G). TSMT was employed to derive both the in-plane and through-the-thickness shear moduli from a singular test scheme. Further investigation focused on axial tests under tensile and compressive loading conditions for determinations of longitudinal and transverse elastic moduli (i.e., E_1 and E_2) combined with in-plane Poisson ratio (ν_{12}). Presented are the descriptive statistics of the SCL elasticity data as are comparisons to the orthotropic behavior of solid wood.

Keywords: Orthotropic, elasticity, lumber composites, modulus of rigidity, modulus of elasticity, Poisson ratio.

INTRODUCTION

Structural composite lumber (SCL) materials of increasing importance include laminated veneer lumber (LVL), parallel strand lumber (PSL), and laminated strand lumber (LSL). SCL production volume has been estimated at 850,000 m^3 (30 million ft^3) with projected increase to 2 million m^3 (70 million ft^3) over the next decade (Smulski 1997). These materials have gained remarkable acceptance in light commercial and residential construction. With variety of length and dimensional configurations, SCLs are popular and adaptive to a diverse range of structural applications. Working stresses for these composite materials are largely available for general design purposes. However, a more detailed enumeration of elasticity property values would be beneficial. Elasticity information has been limited to a single modulus term to describe longitudinal bending stiffness. Further elasticity data would be beneficial for more advanced mechanics and engineering analyses. The orthotropic behavior of SCL materials has not been thoroughly investigated nor have elasticity data widely reported.

On a comparative basis, the orthotropic be-

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Wood and Fiber Science, 33(4), 2001, pp. 580–594

havior of solid wood with respect to elastic property information is documented through numerous experimental studies. Sources that establish the orthotropic behavior of solid wood include the early published findings of Doyle et al. (1945–1946); Hearmon (1948); and USDA Forest Service (1951). Possibly the most extensive report providing elasticity data for wood is the research of Goodman and Bodig (1970). Other useful and more current studies that enhance our understanding into the elasticity characteristics of wood include those of Schniewind and Barrett (1972); Goodman and Bodig (1974); Sliker (1975, 1985, 1988, 1989); Yu (1990); Weigel (1991); Zhang and Sliker (1991); and Sliker et al. (1994). Orthotropic elasticity remains an important topic of investigative research for the wood scientist.

Careful evaluation of the scientific literature fails to reveal any investigation to assess the orthotropic nature for the different types of SCL material. Wood in itself is classified as highly orthotropic—implying substantial variation in the magnitude of elastic moduli between the respective orthogonal material directions. Bodig and Jayne (1993) provide insights on this phenomenon specific to orthotropic properties of wood material. Material orthogonality as a ratio between independent modulus values is decidedly large. Wood approaches a 24 to 1 ratio for its modulus of elasticity (MOE) in the longitudinal to orthogonal tangential plane (Bodig and Jayne 1993). Various questions arise about the elasticity characteristics of SCL materials. One is whether composite lumber products have similar elasticity to solid wood or instead exhibit higher or lower orthotropic behavior.

Reported here are some of the results from a recent test program study designed to better characterize the elasticity properties of reconstituted wood in the form of SCL materials (e.g., LVL, PSL, and LSL). This study provides new data on the load deformation resistance behavior with directed MOE (E) measurements under flexural versus axial compressive and tensile load tests. Further evaluation activities within the LVL, PSL, and LSL study included characterization of SCL elasticity properties that describe resistance to shear distortion with determinations of modulus of rigidity (G) values that define the independent orthotropic material shear moduli. Besides elastic moduli determinations, the study program collected SCL material data for in-plane Poisson ratio (ν) values under axial tensile and compressive test conditions. MOE evaluations were limited to only the two in-plane E property values without evaluation of the third independent Young's moduli term. Specifically, this paper presents the resultant SCL property information (e.g., E, G, and ν) with the material constants formatted in elastic ratios for comparison to orthogonality measures published for solid wood.

MATERIAL AND METHODS

Some differences between SCL materials

SCL materials are more or less unidirectional composites where wood fiber approximates zero angle inclinations from the principal longitudinal axis. However, LVL, PSL, and LSL composites do differ in their material composition and respective manufacture technology. Outlined in the following paragraphs are some of the major process factors and other subtle aspects that may impact properties of the individual composite lumber material.

LVL manufacture is based on the use of presorted plywood veneers of 2.5-mm ($\frac{1}{10}$-in.) up to heavy 4.2-mm ($\frac{1}{6}$-in.) thickness. Sorted veneers are rated for their relative quality with 'better' quality veneer material used on the outer portion of the LVL section. Irrespective of other quality issues, all ply veneers are rotary-peeled with lathe checks present. Lathe check frequency and micro-fracture depth do vary relative to wood veneer species and peeler block preconditioning. Bonding agents for veneer lamination are a resol type of phenol-formaldehyde (PF) adhesive formulated 30–40% solids content. Consolidation includes a heated platen press or continuous system of pressing line to control temperature and pressure profiles. With direct platen contact, composite densification may be more pronounced at LVL surfaces. Typically veneers are compacted 4 to 10% or higher, dependent on press closure and temperature elevation. Manufacturers may employ optional crossband plies in LVL composites for added dimensional stability or adjustment to transverse properties.

PSL manufacture utilizes roundup or other partial veneers 3.2 mm (⅛ in.) in thickness refined to 19-mm (¾-in.) width cut strands. Strands are screened to retain a minimum 601-mm (24-in.) length with removals of inferior material. PSL strands vis-à-vis veneer that originates from outer sapwood compared to the pith zone recovery of veneer may include a lessened amount of grain distortion and knot material inclusion. The strands are surface-coated with PF resol bonding adhesive. After coating, the strands are directionally aligned into a continuous billet mat. Adhesive cure is facilitated using an indirect heat source with strand billet densification through a specialized die press equipped with microwave unit. Adhesive amount or spread rate for strand coverage is potentially higher to account for greater interfacial area. Temperature elevation is internalized through moisture adsorption of microwave energy with possible lessened density stratification. Observations of PSL composite materials indicate macroporosity with incomplete void elimination among the compacted array of strands.

LSL production is strictly based on whole roundwood conversion to a furnish supply with strander equipment opposed to veneer generation. Strander-generated wood particles do not have lathe checks common to veneer-to-strand PSL processed raw material. LSL strands are thinner at 0.76 to 1.3 mm (0.03 to 0.05 in.) and shorter 305 mm (12 in.) as opposed to the thickness and aspect ratio geometry of PSL strands. Strands are spray-blended with an emulsified polymeric isocyanate (EPI) formulation of diphenylmethane diisocyanate (MDI) adhesive. MDI application rates tend to be lower without complete adhesive to surface spread coverage. Strands are directionally felted into mats and consolidated using a steam-injection cure applying a specialized pressing equipment design. Low-density woods are the preferred raw material, which permits property enhancement through added amounts of densification. LSL production can be conducted with incorporation of strand layering to improve transverse direction strength.

One feature common to all SCL materials is the potential of orthogonal randomization of the radial and tangential plane orientations. Strand processing and rotary peeling have the effect of partially eliminating or crossing over these directional axes. In LVL with the veneer and PSL with veneer-based strands, the fabricated composites may retain quantitative amounts of lathe checks unfilled with cured adhesive matrix. Their presence may be theorized to function as modifiers intrinsic to observed SCL elasticity. Lathe knife checks as wood fractures are known to have a dramatic influence on performance of veneers in tension perpendicular to grain (Lutz and Patzer 1966).

Inclusion of slope of grain and a single crack parallel to grain was the subject of investigation with development of a mathematical model to predict the elastic properties in tension for a simulated 3-layer laminated veneer lumber material (Cha and Pearson 1994). Despite this research, further study to experimentally quantify or numerically model the effect of lathe checks on LVL elasticity behavior is needed. Macro-voids of compacted PSL strands constitute another significant feature that may influence the differential behavior of this SCL reconstituted wood material. Ellis et al. (1994) acknowledged that macroporosity after PSL pressing can contribute both positive and negative attributes to the composite's properties. The researchers noted a potential for reduction in strength properties if voids are excessive but represent a positive attribute for enhanced material permeability.

SCL materials for experimental investigation

Materials collected for the experimental investigation involved cooperative arrangements

TABLE 1. *Summary of composite lumber materials (SCL) for experimental investigation.*

SCL identification[1]	Lumber composite type	Species composition
2.0E SP LVL	Laminated Veneer Lumber (13-ply LVL)	Southern Pine (SP)
2.2E SP LVL	Laminated Veneer Lumber (13-ply LVL)	Southern Pine (SP)
2.0E DF1 LVL	Laminated Veneer Lumber (13-ply LVL)	Douglas-fir (DF)
2.0E DF2 LVL	Laminated Veneer Lumber (18-ply LVL)	Douglas-fir (DF)
2.0E YP LVL	Laminated Veneer Lumber (13-ply LVL)	Yellow-Poplar (YP)
2.0E YP PSL	Parallel Strand Lumber (PSL)	Yellow-Poplar (YP)
2.0E SP PSL	Parallel Strand Lumber (PSL)	Southern Pine (SP)
1.5E A LSL	Laminated Strand Lumber (LSL)	Aspen (A)
1.5E YP LSL	Laminated Strand Lumber (LSL)	Yellow-Poplar (YP)

[1] First numbers in the SCL Identification denote material quality with classification of design-rated longitudinal edgewise bending MOE (E) stiffness $\times 10^6$ psi.

with several SCL production facilities. Part of the arrangements included random sampling over an extended production period. Section requirements due to the planned evaluation methods mandated procurement of sufficient width SCL to extract specimens from both directional in-plane orientations. Notably, specimens were processed from both the longitudinal (e.g., 1-direction coinciding with fiber alignment orientation) and the orthogonal 2-direction (e.g., transverse in-plane orientation). Through-the-thickness is the 3-direction as the material orientation perpendicular to glueline and fiber directions. Collected LVL, PSL, and LSL samples were supplied from the various cooperating facilities in 2.4- or 3.6-m (8- or 12-ft) lengths and greatest possible production billet width. Selection of LVL materials focused on 13-ply construction and 3.2-mm (⅛-in.) veneer material. This construction pattern is the norm for most structural LVL production. One exception was Douglas-fir (*Pseudotsuga menziesii*) supplied as 44.5-mm (1.75-in.) LVL material with an 18-ply and 2.5-mm ($\frac{1}{10}$-in.) veneer construction pattern.

SCL materials collected with the classifications of commercially rated longitudinal MOE and the parent species of wood are itemized within Table 1. LVL, PSL, and LSL materials in the test study were selected to be unidirectional composites from the respective manufacture technology. The study attempted to focus on the most common lumber composite performance with a rated 13.8 GPa (2 million lb/in.^{2}) (2.0E) longitudinal bending modulus. Table 1 reveals that the two LSL materials, manufactured from aspen (*Populus spp.*) and yellow-poplar (*Liriodendron tulipifera*), had bending stiffness modulus of 10.3 GPa (1.5×10^6 psi) (1.5E). LSL technology as state-of-the-art manufacture at the time did not permit collection of the same material stiffness classification. One rated performance exception was the higher quality 15.2 GPa (2.2×10^6 psi) (2.2E) southern yellow pine (*Pinus spp.*) LVL added to the experimental test program for special interest.

Experimental SCL material test study plan

Upon arrival of SCL billets, a series of steps were taken before testing. Efforts included the processing of longitudinal and transverse specimens. Specimens were processed to appropriate test size. Test specimens were taken from multiple locations along the billet length. Each grouping of billets per SCL material provided 16 specimens. Transverse specimen lengths were limited by billet width. Accordingly, specimens representing the different SCL materials, particularly those from PSL billets, precluded identical specimen length to depth ratio tests. LVL, PSL, and LSL specimens not being tested were maintained in environmental chambers at approximately 20°C (68°F) and 65% relative humidity. After final test completion, moisture content (%MC) and specific gravity (SG) were determined as per Method A of ASTM D 2395 (ASTM 1997a).

The SCL specimens were subjected to a

systematic series of primary flexural tests (i.e., edgewise and flatwise orientation) for bending modulus of elasticity (E_1 and E_2) with corresponding determination of shear modulus including G_{12}, G_{13}, and G_{23}. Actual flexural E and G evaluations of the reconstituted wood composites were examined, based on the five-point bending test (FPBT) methodology. This was followed in sequence by secondary torsion test analyses to also characterize the orthotropic shear resistance moduli for directional in-plane G_{12} and G_{21} values with also through-the-thickness G_{13} and G_{23}. A further objective for this SCL material study was to examine possible outcome differences between test property evaluation methodology. Hindman et al. (2001) comparatively examined experimental five-point bending versus torsion testing to characterize shear modulus properties for the nine SCL materials and two oriented strandboard (OSB) products. Torsion methodology was based on a torsional stiffness measurement test (TSMT). The sequence of FPBT and TSMT evaluations were subsequently followed with axial loading tests for tensile, then compression elastic moduli determinations and strain-gage measurements for assessment of in-plane Poisson ratio (ν_{12}) measures. For axial loading, the SCL material testing followed speed of testing and other load conditions set forth in ASTM D 198 (ASTM 1997b). ASTM D 5456 (ASTM 1997c) the test specification for LVL and PSL lumber composites recommends application of ASTM D 198 procedures.

Five-point bending followed by torsion and axial loading, using the same processed specimens, assisted in minimizing sampled material variation. Experimental activities included various precautions to avoid bias within the repeated test scheme. Assurances that materials were not stressed beyond elastic limits were verified after TSMT implementation with FPBT retesting for comparison to original flexure load-deformation data measurements. This did verify repeatability of data between test series to confirm lack of an introduced bias after torsional loading to guarantee reliable comparison of bending E to those of tensile and compressive tests. FPBT and TSMT methodologies were utilized for the experimental study because of their ability to simultaneous evaluate two elasticity terms from the same specimen. Hindman (1999) provides more in-depth discussion on the complete experimental study design.

FPBT and TSMT evaluation methodologies

The FPBT method was first proposed as a quality control tool for the wood composite OSB panel industry (Bateman et al. 1990). Bateman et al.'s research was designed to develop the five-point bending scheme as a possible shear strength test replacement to the ASTM D 1037 and D 2718 interlaminar shear procedures. More recently, various other subsequent studies have given attention to this particular shear property test method (Hunt et al. 1993; Bradtmuellar et al. 1994; Leichti et al. 1996; Tingley and Kent 1996). Reasons for interest in the FPBT method vary but include a more simplified method to reduce the cumbersomeness and labor intensity associated with other shear evaluation procedures.

Bradtmuellar et al. (1994) first reported on the FPBT method for possible shear moduli determination with experimentation conducted on OSB panel material. Hunt et al. (1993) summarized study activities devoted to investigate FPBT for determination of longitudinal shear strength of LVL material. Leichti et al. (1996) used finite element techniques to analyze the FPBT method. One conclusion reached was that compressive stress perpendicular to grain ($\sigma_{c\perp}$) from the bearing reaction or loading point can proportionally increase calculated shear stress (τ). Tingley and Kent (1996) provided insights to minimize the interaction between $\sigma_{c\perp}$ and τ with advisement that FPBT be conducted with a minimum 3.0 ratio for one-half the shear span to test specimen height. This test protocol was observed in this study to derive the various SCL material elastic moduli values.

The SCL material study utilized the FPBT procedure because of its convenient ability to provide a simultaneous solution for both E and G. Simultaneous solution is provided through a dual test procedure composed of quarter-point (QP) combined with five-point (FP) flexural loading. Load-induced deflection data (Δ_{QP} and Δ_{FP}) with the elementary QP and FP beam theory equations expanded for shear component displacement provide the computational basis for moduli determinations. The mathematical formulae used for SCL material computation of E and G values are given as follows:

$$E = \frac{66L}{\{1536I[0.5703\Delta_{QP} - \Delta_{FP}]\}} \quad \text{and}$$

$$G = \frac{66L}{\{16KA[32\Delta_{FP} - 1.75\Delta_{QP}]\}} \qquad (1)$$

where:

L = beam span, (cm)
I = beam moment of inertia, (cm^4)
K = 5/6 shape factor for rectangular cross-section, (unitless) and
A = beam cross section. (cm^2)

These formulae were derived for this experimental study specific to the QP test procedure conducted with beam deformation measured at the two quarter-point locations. This differs from single mid-span material deflection which typifies the test approach of Bradtmueller et al. (1994). Both QP and FP test procedures included SCL material deflection measured from the neutral axis of the beam specimens based on Bradtmueller et al.'s recommendation.

Beyond the applied FPBT method for assessing shear moduli values, the experimental approach utilized torsional stiffness measurements with the FPBT specimens. Experimental SCL material testing followed closely the procedures of the TSMT methodology as reported by Janowiak and Pellerin (1992). This prior research studied the torsion loading procedure as an alternate to anticlastic plate bending tests prescribed for wood composite panel materials. TSMT was implemented, as opposed to the ASTM D 198 torsion method, because it facilitates solution of two orthogonal shear moduli terms from the same material test sample. Although the TSMT approach allows a simultaneous determination, it requires that torsional stiffness measures be taken over several slenderness ratios (h/b) where specimen width (h) is reduced for a constant material thickness (b). Application of the TSMT methodology included compensation for clamping grip effects which otherwise influence free torsional deformation (Nederveen and Tilstra 1971). Actual TSMT tests were conducted on a torsion stress apparatus (TSA) converted from a 36-inch metal lathe machine carriage specially equipped with: 1) adjustable clamps for specimen grip pressure; 2) Lebow Model 2121 230 N-m torque sensor (0.11 N-m sensitivity); 3) LVDT operational system devised to monitor specimen twist angle displacements; and 4) hydraulic power supply with manual actuator controller.

The generalized formula that defines in-plane (G_{12}) and through-the-thickness shear modulus (G_{13}) terms applicable to the TSA evaluations with a longitudinal orientation SCL specimen follows:

$$\lim_{h/b \to 0} K_x = \frac{[G_{12} - 0.63025G_{12}(G_{12}/G_{13})^{0.5}(h/b)]}{(3bh^3)} = \left(\frac{bh^3}{3}\right)G_{12} \qquad (2)$$

where

K_x = TL/θ computed torsional stiffness measure term, (N-cm^2/degree)
T = torsional load about the material longitudinal 1- or x-direction (cm-N), and
θ = specimen measured angle of twist (degree).

At h/b = 0 the linear relationship shown is reduced where the y-intercept equals the quantity $G_{12} = (3/bh^3)K_x$ and $G_{13} = 0.3972G_{12}/k_s^2$

with k_s the slope for the regressed $3K_x/bh^3$ plot versus h/b line (Hindman 1999). Test evaluation for transverse orientation specimens yields the G_{21} directional in-plane shear distortion value and through-the-thickness G_{23} shear modulus term. It should be explained that the TSMT approach to characterize shear moduli terms is only valid for a relatively 'large' or 'small' slenderness ratio given the observed material anisotropy according to the following mathematical restrictions.

$$h/b < 0.25\pi(G_{12}/G_{13})^{0.5} \quad \text{or}$$

$$b/h < 4\pi(G_{13}/G_{12})^{0.5} \qquad (3)$$

Lemperiere et al (1969), Tarnoplo'skii and Kincis (1985), and Janowiak and Pellerin (1992) discuss this restriction (Eq. 3) to solve for modulus of rigidity applying the linear torsion stiffness relationship (Eq. 2). In both TSMT and FPBT methodologies, the collected response data were analyzed applying ordinary least squares regression techniques. Some test series could not be analyzed to solve for independent shear modulus terms through the TSMT protocol. Without prior shear modulus data to guide FPBT specimen preparation, an inadequacy was observed in the slenderness (h/b or b/h) needed to comply with material anisotropy consistent with the previously identified mathematical restriction. Accordingly, some collected TL/θ test measurement data could not be properly reduced to establish a shear modulus value with respect to a particular SCL material.

Tensile and compressive SCL test evaluations

Completion of the TSMT test series was followed by the final evaluations for tensile and compressive MOE measures. This activity did require further processing with specimen length adjustment to coincide with available testing machine opening height. Tensile tests met or exceeded the ASTM D 198 recommendation of eight times the greater cross-section dimension for specimen length between loading grips. Compressive loading included conversion of tensile specimens into short column specimens matching ASTM D 198 test description. Length adjustment consisted of end removals to retain the same material portion evaluated for tensile deformation measurements. Prior to axial loading tests, four sample specimens were identified for 0° and 90° placements of single element Vishay Micro-Measurement (#EA-06-500UW) 120-ohm strain gage installations (Vishay Measurements Group 1999). Sample specimen selections were based on absence of possible surface voids (i.e., PSL and LSL) or LVL veneer joints at proximity of mid-length as the position for gage installations. Shorter length 19.1-mm (0.75-in.) strain gages helped to avoid possible error from strain variations near specimen edges (Vishay Measurements Group 1999). Strain gage procedures included surface coating with low-modulus epoxy filler resin and use of looped stress relief wires soldered to tab connection terminals. Elastic moduli determinations with ASTM D 198 testing are based on averaged deformation measures using an LVDT attached to front and back specimen surfaces.

FPBT evaluations were performed on a 534 kN capacity Tinius-Oslen electromechanical universal testing machine (UTM). Five-point and quarter-point tests were measured using the lowest UTM load cell range of 5,340 N (0.4 N sensitivity). FPBT data collection included Labtech Notebook software to continuously monitor specimen load-deflection behavior. An alternate 445 kN capacity Instron-Satec electromechanical UTM with same 0.4 N measurement sensitivity was used for the tensile and compressive load tests. The Instron-Satec UTM was utilized because of its more modern operational system for analog signal acquisition and data analysis management. Strain measurements (ϵ) from installed gages were taken through the Partners Nu-Vision software of the Instron MATS II data acquisition system. The MATS II system provides a pulsed voltage for the active strain gage with internal dummy strain gage circuit for temperature compensation of microstrain readings. Longitudinal with transverse ϵ val-

TABLE 2. *Summary of flatwise flexural elastic modulus E derived from the five-point bending method (FPBT) with computed values corrected for shear.*

SCL material identification	Elasticity property	Descriptive statistics			
		Average[1,2]	Maximum	Minimum	COV
2.0E SP LVL	E_1-Longitudinal	16.5 (2.40 × 10^6)	18.2	14.4	6.8
	E_2-Transverse	0.58 (8.45 × 10^4)	0.67	0.49	8.3
2.2E SP LVL	E_1-Longitudinal	16.2 (2.35 × 10^6)	19.8	13.8	8.8
	E_2-Transverse	0.65 (9.42 × 10^4)	0.75	0.50	10.9
2.0E DF1 LVL	E_1-Longitudinal	18.3 (2.65 × 10^6)	20.6	15.6	7.7
	E_2-Transverse	0.50 (7.28 × 10^4)	0.72	0.32	21.3
2.0E DF2 LVL	E_1-Longitudinal	14.4 (2.26 × 10^6)	15.1	13.5	2.9
	E_2-Transverse	0.44 (6.21 × 10^4)	0.48	0.39	6.8
2.0E YP LVL	E_1-Longitudinal	15.2 (2.21 × 10^6)	17.1	13.9	6.2
	E_2-Transverse	0.45 (6.45 × 10^4)	0.51	0.38	9.1
2.0E YP PSL	E_1-Longitudinal	14.5 (2.10 × 10^6)	16.3	12.2	6.3
	E_2-Transverse	0.40 (5.70 × 10^4)	0.55	0.30	21.4
2.0E SP PSL	E_1-Longitudinal	15.1 (2.19 × 10^6)	17.5	12.4	12.1
	E_2-Transverse	0.48 (6.98 × 10^4)	0.62	0.34	15.1
1.5E A LSL	E_1-Longitudinal	13.4 (1.95 × 10^6)	15.4	11.6	7.7
	E_2-Transverse	1.49 (2.16 × 10^5)	1.90	1.20	11.8
1.5E YP LSL	E_1-Longitudinal	12.5 (1.81 × 10^6)	14.6	11.4	6.3
	E_2-Transverse	1.38 (2.00 × 10^5)	1.73	1.06	12.6

[1] Values shown are GPa with numbers in parentheses being psi (lbs/in^2). To convert other numerical values to psi, divide by 6.895 × 10^3.
[2] Averages are based on a total of 16 specimen test observations.

ues provided for enumeration of the in-plane Poisson's ratio values. The Poisson values reported are averages based on three measurement trials. The MATS II system software package also provided the basis to regress the linear slope of recorded load-to-deformation plots. High resolution Trans-Tek Series 350 gaging LVDTs ((0.0025 mm) (0.0001-in.) sensitivity—linear variable differential transducers) were used as the analog devices for FPBT, TSMT, and the axial load testing activities.

RESULTS AND DISCUSSION

Tables 2–6 provide the descriptive statistics for FPBT, TSMT, and ASTM D 198 test data evaluations performed on the nine SCL materials (Table 1). Only the FPBT data collected for MOE from the flatwise flexural test series are presented for reporting brevity.

FPBT results for MOE (E) and G determination

Table 2 shows as intuitively anticipated that large MOE differences do exist for bending stiffness between longitudinal (E_1) versus transverse (E_2) test orientation measures. The largest observed difference between longitudinal to transverse E value is for Douglas-fir LVL. The least difference between E values is for the aspen LSL. As an SCL material trend, the LSL reconstituted wood composites are less extreme in their orthogonal response differences. The E_1:E_2 ratios for the YP LVL and YP PSL materials equal 34.2:1.0 and 36.3:1.0, respectively. These ratios compare to only 9.1:1.0 as the orthogonality ratio with the tested YP LSL material. LVL and the PSL data indicate a definite departure from typical elasticity behavior where the orthogonal measure of wood approaches a maximum 24 to 1 ratio. The higher orthogonal behavior difference in ratio measure may be postulated as the possible influence of lathe checks and macroporosity features of the LVL and PSL composite materials. The lower observed E_1:E_2 ratio for both the yellow-poplar LSL and aspen LSL material may relate to the positive attribute of more intense composite manufacture and absence of macroporosity and lathe check features.

FPBT results (Table 3) for modulus of ri-

TABLE 3. *Summary of in-plane and through-the-thickness shear moduli values obtained from the five-point bending method (FPBT).*

SCL material identification	Elasticity property	Descriptive statistics			
		Average[1,2]	Maximum	Minimum	COV
2.0E SP LVL	G_{12}	476 (6.91 × 10^4)	702	283	25.8
	G_{13}	354 (5.14 × 10^4)	468	217	18.7
	G_{23}	64 (9.33 × 10^3)	92	46	20.7
2.2E SP LVL	G_{12}	430 (6.23 × 10^4)	696	190	29.3
	G_{13}	354 (5.14 × 10^4)	529	221	19.7
	G_{23}	69 (9.94 × 10^3)	97	42	25.6
2.0E DF1 LVL	G_{12}	405 (5.87 × 10^4)	595	245	21.3
	G_{13}	331 (4.80 × 10^4)	461	243	17.3
	G_{23}	46 (6.64 × 10^3)	73	25	36.5
2.0E DF2 LVL	G_{12}	691 (7.74 × 10^4)	767	628	4.8
	G_{13}	435 (5.12 × 10^4)	495	376	5.7
	G_{23}	48 (6.71 × 10^4)	113	24	39.6
2.0E YP LVL	G_{12}	247 (3.58 × 10^4)	411	175	23.9
	G_{13}	314 (4.56 × 10^4)	508	197	33.1
	G_{23}	96 (1.39 × 10^4)	163	45	37.9
2.0E YP PSL	G_{12}	252 (3.66 × 10^4)	346	143	21.9
	G_{13}	372 (5.39 × 10^4)	561	257	25.0
	G_{23}	99 (1.43 × 10^4)	191	36	39.4
2.0E SP PSL	G_{12}	501 (7.27 × 10^4)	700	337	21.1
	G_{13}	405 (5.87 × 10^4)	518	264	19.9
	G_{23}	85 (1.23 × 10^4)	146	44	32.7
1.5E A LSL	G_{12}	681 (9.87 × 10^4)	954	488	20.8
	G_{13}	251 (3.64 × 10^4)	421	162	22.6
	G_{23}	104 (1.51 × 10^4)	154	89	16.5
1.5E YP LSL	G_{12}	373 (5.41 × 10^4)	573	199	25.0
	G_{13}	309 (4.48 × 10^4)	539	217	34.0
	G_{23}	102 (1.48 × 10^4)	161	63	21.5

[1] Values shown are MPa with numbers in parentheses being psi (lb/in.^{2}). To convert other numerical values to psi, divide by 6.895 × 10^3.
[2] Averages are based on a total of 16 specimen test observations.

gidity indicate that SCL materials do coincide more closely with orthogonal ratio measures typically associated with wood shear distortion resistance. However, the magnitude of SCL shear distortion resistance tends to be lower compared to solid wood in terms of G_{12} and G_{13} properties. Layered veneers or deposited strands function as multiple planes for shear dislocations. Biblis et al. (1982) noted that shear deformations are enhanced for layered wood composite materials. Shear distortion behavior for the SCL composites is further confounded with the effects of adhesive coupling and fractures of the unfilled lathe checks.

Published test data of solid wood from Bodig and Goodman (1973) compared with LVL and PSL combined together as a group suggest 54.5% and 56% lower G_{12} and G_{13} shear moduli properties, respectively. In contrast to this lower shear distortion resistance, a plausible amount of property improvement may exist relative to LSL material. Quaking aspen (*Populus tremuloides*) has published shear moduli values of G_{12} = 603 MPa (87,200 psi) and G_{23} = 83.0 MPa (12,050 psi). Using these values as a basis of comparison implies the A LSL composite, evaluated applying FPBT, has roughly a 13% and 20% higher in-plane and through-the-thickness (i.e., 2–3 plane) shear distortion resistance, respectively. All other instances of SCL material test results provide G_{23} near 45% lower than the corresponding parent species of wood material. Loblolly pine (*Pinus palustris*) is assumed the primary wood represented in the SP LVL and SP LVL com-

TABLE 4. *Summary of in-plane and through-the-thickness shear moduli values derived applying the torsional stiffness measurement test (TSMT) method.*

SCL material identification	Elasticity property[1]	Descriptive statistics			
		Average[2]	Maximum	Minimum	COV
2.0E SP LVL	G_{12}	636 (9.22 × 10⁴)	847	536	13.1
	G_{13}	282 (4.10 × 10⁴)	718	182	47.2
	G_{23}	29 (4.15 × 10³)	49	20	26.3
2.2E SP LVL	G_{12}	403 (5.84 × 10⁴)	456	341	8.0
	G_{13}	754 (1.09 × 10⁵)	1,921	329	55.6
2.0E DF1 LVL	G_{12}	642 (9.32 × 10⁴)	914	553	13.8
	G_{13}	440 (6.38 × 10⁴)	649	267	27.5
	G_{23}	48 (6.90 × 10³)	67	35	15.0
2.0E DF2 LVL	G_{12}	805 (1.17 × 10⁵)	980	689	10.4
	G_{13}	86 (1.24 × 10⁴)	113	63	14.3
	G_{23}	61 (8.77 × 10³)	108	43	26.0
2.0E YP LVL	G_{12}	416 (6.04 × 10⁴)	516	333	9.9
	G_{13}	779 (1.13 × 10⁵)	1,936	277	58.2
	G_{23}	49 (7.11 × 10³)	113	29	52.7
2.0E YP PSL	G_{23}	116 (1.68 × 10⁴)	189	83	21.7
2.0E SP PSL	G_{23}	26 (3.78 × 10³)	71	43	31.7
1.5E A LSL	G_{12}	913 (1.33 × 10⁵)	1,013	814	5.1
1.5E YP LSL	G_{12}	719 (1.05 × 10⁵)	944	347	15.9
	G_{13}	675 (9.80 × 10⁴)	1,283	428	37.2

[1] Values for directional in-plane shear modulus G_{21} are reported elsewhere (Hindman et al. 2001).
[2] Values shown are MPa with numbers in parentheses being psi (lb/in.²). To convert other numerical values to psi, divide by 6.895 × 10³.

posite manufacture. Actual LVL and PSL manufacture is a somewhat random mix of the major southern pine species.

TSMT results for orthotropic shear moduli determination

TSMT results (Table 4) for shear moduli values are of different magnitude then those from FPBT. Some variation is to be expected with test dependence to define material behavior. Of the SCL materials successfully evaluated applying the TSMT methodology, the aspen and yellow-poplar LSL materials rank highest in observed G_{12} test values. The A LSL material again shows some potentially improved in-plane shear deformation resistance. In-plane shear resistance of this aspen LSL material exceeds the quaking aspen value (553 MPa (80,720 psi)) on the order of 53%. Also the YP LSL material may have a modestly higher G_{12} value compared with yellow-poplar (e.g., 724 MPa (105,000 psi) vs. 717 MPa (104,000 psi)). This modestly higher shear stiffness performance is likely less than significant. However, YP LSL surpassed YP LVL for in-plane shear distortion resistance by a substantial 84% margin. This is contrary to the potential for enhanced shear deformation with the vast number of strands deposited as discrete planes compared with limited veneer layer construction for LVL.

Poisson ratio and MOE determinations from axial loading

Table 5 provides the Poisson ratio values obtained from axial loading tests for the nine SCL materials. Further summary data for elastic moduli E determinations from compressive versus tensile test evaluation conditions are presented in Table 6. Examination of summary data (Table 5) shows Poisson ratio greater than assumed as the elasticity property measure of solid wood. Also it is observed (Table 6) that slightly higher elastic moduli measures coincide with the tensile test series for at least five out of nine SCL materials (Table 6). These test outcome differences suggest that some SCL

TABLE 5. *Strain gauge measurement[1] results for Poisson ratio (ν_{12}) from tensile and compressive test loading.*

SCL material identification	Elasticity property	Descriptive statistics			
		Average[2]	Maximum	Minimum	COV
2.0E SP LVL	ν_{12}-Tensile	0.743	0.847	0.622	12.5
	ν_{12}-Comp.	0.644	0.759	0.528	15.4
2.2E SP LVL	ν_{12}-Tensile	0.853	0.901	0.788	6.8
	ν_{12}-Comp.	0.521	0.696	0.435	22.7
2.0E DF1 LVL	ν_{12}-Tensile	0.767	1.178	0.507	37.5
	ν_{12}-Comp.	0.580	0.808	0.446	27.2
2.0E DF2 LVL	ν_{12}-Tensile	0.718	0.995	0.385	39.4
	ν_{12}-Comp.	0.804	1.062	0.501	29.5
2.0E YP LVL	ν_{12}-Tensile	0.620	0.720	0.502	16.0
	ν_{12}-Comp.	0.604	0.911	0.436	36.8
2.0E YP PSL	ν_{12}-Tensile	0.985	1.389	0.593	37.9
	ν_{12}-Comp.	0.611	1.001	0.129	68.8
2.0E SP PSL	ν_{12}-Tensile	0.762	1.007	0.528	30.9
	ν_{12}-Comp.	0.894	1.570	0.203	65.5
1.5E A LSL	ν_{12}-Tensile	0.556	0.732	0.396	29.4
	ν_{12}-Comp.	0.446	0.797	0.160	59.1
1.5E YP LSL	ν_{12}-Tensile	0.671	0.821	0.576	16.3
	ν_{12}-Comp.	0.819	0.914	0.642	15.6

[1] Maximum 90° strain gauge installation measurement inaccuracy attributable to transverse sensitivity effects is a 0.2% error.
[2] Values shown are average of four individual specimens with three independent test measurement trials.

materials may have a slight tendency toward bimodular elastic behavior.

The maximum observed Poisson ratio value is for the tensile test of the YP PSL material with ν_{12} equaling 1.389. This reported value at first glance may seem extreme. However, composite materials can have Poisson ratio's greater than unity (Lempriere 1968). The extreme measure of Poisson ratio for an isotropic material is between -1.0 to $+0.5$ as governed by thermodynamic considerations (Jones 1975). For materials of orthotropic nature, the in-plane Poisson ratio is limited by the following inequality statement.

$$\nu_{12} < \left\{\frac{E_1}{E_2}\right\}^{0.5} \qquad (4)$$

Applying Eq. (4) to compute limits from the collected tension and compression moduli, the absolute magnitude of ν_{12} without violation of elasticity theory would correspond to a Poisson ratio less than 2.85 or 3.01, respectively.

Overall the tested SCL materials show very limited equivalence to the Poisson ratio of a parent wood species. Bodig and Goodman (1973) provide the principal in-plane Poisson ratios ν_{LR} and ν_{LT} for quaking aspen at 0.458 and 0.202; Douglas-fir at 0.285 and 0.504; loblolly pine at 0.328 and 0.292; and yellow-poplar at 0.32 and 0.39 (after Hearmon 1948), respectively. Subscripts L, R, and T denote longitudinal, radial, and tangential wood directions. Zink et al. (1997) recently reported the Poisson ratio for yellow-poplar at 0.35 (ν_{LR}) and 0.40 (ν_{LT}). Zink et al.'s values are based on exploratory digital imaging and correlation technique approach to measure compressive strains. Compressive SCL evaluations with YP LVL, YP PSL and YP LSL are 73%, 75%, and 134% greater than assuming a 0.35 Poisson ratio value. YP PSL from tensile evaluation exceeds this value by 181%.

SCL materials compared to orthogonal measures of solid wood elasticity

Table 7 provides a summary of parent (actual or assumed) wood species for comparison to the orthogonal elasticity ratio prepared from the SCL material study data. Included (Table 7) for experimental reporting are the ASTM D 2395 (ASTM 1997a) test results conducted to evaluate SCL specific gravity. Specific

TABLE 6. *Summary results from axial tensile and compressive loading evaluations with respect to longitudinal and transverse in-plane test specimens.*

SCL material identification	Elasticity property	Descriptive statistics			
		Average	Maximum	Minimum	COV
2.0E SP LVL	E_1-Tensile	16.6 (2.41 × 10^6^)	19.0	14.1	9.0
	E_2-Tensile	0.46 (6.71 × 10^4^)	0.58	0.30	13.0
	E_1-Comp.	15.7 (2.28 × 10^6^)	17.9	13.8	7.6
	E_2-Comp.	0.54 (7.86 × 10^4^)	0.63	0.47	9.3
2.2E SP LVL	E_1-Tensile	16.6 (2.41 × 10^6^)	19.1	14.1	0.4
	E_2-Tensile	0.49 (7.06 × 10^4^)	0.63	0.36	14.3
	E_1-Comp.	16.1 (2.33 × 10^6^)	18.5	12.8	9.9
	E_2-Comp.	0.57 (8.27 × 10^4^)	0.71	0.46	14.0
2.0E DF1 LVL	E_1-Tensile	15.9 (2.30 × 10^6^)	19.6	11.6	15.1
	E_2-Tensile	0.39 (5.70 × 10^4^)	0.55	0.29	17.9
	E_1-Comp.	15.7 (2.27 × 10^6^)	20.2	12.2	14.7
	E_2-Comp.	0.47 (6.76 × 10^4^)	0.57	0.37	12.8
2.0E DF2 LVL	E_1-Tensile	14.5 (2.10 × 10^6^)	16.5	13.1	6.3
	E_2-Tensile	0.41 (5.95 × 10^4^)	0.50	0.36	0.9
	E_1-Comp.	15.1 (2.19 × 10^6^)	18.2	12.3	9.9
	E_2-Comp.	0.43 (6.24 × 10^4^)	0.50	0.37	0.7
2.0E YP LVL	E_1-Tensile	14.3 (2.07 × 10^6^)	16.6	11.9	11.9
	E_2-Tensile	0.44 (6.32 × 10^6^)	0.94	0.34	31.8
	E_1-Comp.	14.3 (2.07 × 10^6^)	16.4	12.9	0.6
	E_2-Comp.	0.43 (6.27 × 10^4^)	0.50	0.33	0.9
2.0E YP PSL	E_1-Tensile	15.0 (2.17 × 10^6^)	18.8	10.9	1.9
	E_2-Tensile	0.33 (4.82 × 10^4^)	0.52	0.17	27.3
	E_1-Comp.	15.0 (2.17 × 10^6^)	18.5	10.8	14.0
	E_2-Comp.	0.39 (5.62 × 10^6^)	0.58	0.29	2.3
2.0E SP PSL	E_1-Tensile	15.4 (2.23 × 10^6^)	20.0	12.5	12.3
	E_2-Tensile	0.45 (6.56 × 10^4^)	0.69	0.19	31.1
	E_1-Comp.	15.0 (2.17 × 10^6^)	18.9	12.1	10.0
	E_2-Comp.	0.46 (6.62 × 10^4^)	0.54	0.37	0.9
1.5E A LSL	E_1-Tensile	13.0 (1.89 × 10^6^)	14.7	10.2	10.0
	E_2-Tensile	1.42 (2.06 × 10^5^)	17.4	11.2	11.3
	E_1-Comp.	12.6 (1.83 × 10^6^)	17.1	9.28	13.5
	E_2-Comp.	1.39 (2.01 × 10^5^)	0.17	0.11	1.4
1.5E YP LSL	E_1-Tensile	11.9 (1.72 × 10^6^)	15.9	10.0	12.6
	E_2-Tensile	1.46 (2.11 × 10^5^)	2.0	1.1	16.4
	E_1-Comp.	12.0 (1.74 × 10^6^)	14.4	9.61	11.7
	E_2-Comp.	1.28 (1.86 × 10^5^)	0.16	0.10	13.3

[1] Values shown are GPa with numbers in parentheses being psi (lb/in.^{2}). To convert other numerical values to psi, divide by 6.895 × 10^3Pa.

gravity (SG) provides some indication of the relative amount of lumber composite densification. Review of SG numbers indicates that aspen LSL is highly densified during steam-injection pressing. LVL and PSL composites have SG values that deviate much less from the parent wood species.

On average, the LVL materials exhibit fairly similar elasticity behavior to wood material with respect to orthogonal ratios between the independent shear moduli terms. Contrasting this is a greater orthogonal response difference for the elastic moduli in observed MOE material constants. The E_1:E_2 ratios for the LVL and PSL material definitely establish these two lumber composite types as more highly orthotropic than solid wood. This enhanced orthotropic behavior has various practical implications with respect to localized stress concentration and interactive stress fields when materials are subjected to concentrated point or other loading configurations.

TABLE 7. *Generalized comparison of solid wood to the varying SCL material elastic constant ratios obtained based on the FPBT evaluation results.*

Wood material[1]	SG	$E_L:E_R$	$G_{LR}:G_{LT}$	$G_{LR}:G_{RT}$	$G_{LT}:G_{RT}$	$E_L:G_{LR}$
P. menziesii	0.47	17.7	0.93	6.55	7.01	22.4
P. palustris	0.47	8.8	1.01	6.34	6.31	12.3
P. tremuloides	0.30	10.6	1.35	7.24	5.38	13.1
L. tuliperifera	0.38	10.9	1.07	6.50	6.06	13.5
Average:	0.41	12.0	1.09	6.66	6.19	15.3
SCL material	SG[2]	$E_1:E_2$	$G_{12}:G_{13}$	$G_{12}:G_{23}$	$G_{13}:G_{23}$	$E_1:G_{12}$
2.0E SP LVL	0.58	28.4	1.34	7.41	5.52	34.7
2.2E SP LVL	0.59	24.9	1.21	6.27	5.17	37.7
2.0E DF1 LVL	0.52	36.4	1.22	8.84	7.22	45.1
2.0E DF2 LVL	0.49	32.7	1.59	14.39	9.06	29.2
2.0E YP LVL	0.52	34.2	0.79	2.52	3.20	61.7
Average:	0.54	31.3	1.23	7.89	6.03	41.7
2.0E SP PSL	0.67	31.3	1.24	5.91	4.77	30.0
2.0E YP PSL	0.59	36.3	0.68	2.56	3.77	57.4
Average:	0.63	33.8	0.96	4.24	4.27	43.7
1.5E A LSL	0.66	9.04	2.71	6.54	2.41	19.8
1.5E YP LSL	0.64	9.05	1.21	3.67	3.04	33.4
Average:	0.65	9.05	1.96	5.11	2.73	26.6

[1] Based on Bodig and Goodman (1973) data with elasticity constants derived from plate bending tests.
[2] SG values are oven-dry volume basis with weight at conditioned MC averages for LVL = 10.3%, PSL = 9.8% and LSL = 8.7%.

PSL and LVL also exhibit substantially greater MOE to in-plane shear modulus ratio ($E_1:G_{12}$), while for LSL materials this elasticity characteristic tends to be somewhat minimized. The extreme case is YP LVL where $E_1:G_{12}$ equals a 61.7 ratio measure, while the YP PSL materials equal only 33.4. The lowest ratio occurs for A LSL with a ratio of only 19.8, but still exceeds that for aspen wood with a 13.1 $E_L:G_{LR}$ ratio. A higher E:G measure indicates that shear displacements contribute a greater role in the total deformation where the material acts as a structural member.

SUMMARY

The results of this study provide new insights into the elasticity characteristics for the three types of composite lumber material. Experimental test data strongly indicate that composite lumber can exhibit orthotropic properties that differ from those of solid wood. Data collected show that reconstituted SCL materials can possess elastic moduli of magnitudes that exceed the orthogonal measures typical of solid wood. It can be stated with some certainty that LVL and PSL composites tend to behave as more highly orthotropic materials. In contrast, the LSL composites tested show a lessened orthotropic response difference between elasticity terms for longitudinal to transverse MOE. Though not completely analyzed, some differences were observed between tensile versus compressive derived MOE measures. Should differences in tensile versus compressive E be significant, some SCL composites will then exhibit a tendency toward bimodular material behavior. Poisson ratio measures also differed from tensile to compressive test evaluation. More importantly, it is evident that this elasticity term in general deviates from values published for solid wood material. It can be concluded that an SCL material will have a limited similarity to the elasticity behavior corresponding with a parent species of wood.

ACKNOWLEDGMENTS

The research was supported by USDA NRICRP grant No. 9802713 and Pennsylvania

State University Agricultural Experiment Station. The authors wish to specially thank the cooperation provided by Boise Cascade Corp., Georgia-Pacific, Inc. and Trus Joist–Weyerhaeuser, formerly Trus Joist MacMillan.

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