In-Plane Shear Properties of Laminated Wood from Tension and Compression Tests of Angle-Ply Laminates

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Abstract: Experimental methods for the characterization of shear strength and stiffness of both wood-based and glass-based or carbon-based composite materials are highly contested because shear properties are difficult to isolate experimentally. A comprehensive literature review on the subject is presented, considering methods for both structural composite lumber and traditional composite laminates. The researchers present a novel method for calculating shear strength, stiffness, and interaction parameters of laminated wood-veneer panels by coupling experimental data from tension and compression tests of multiaxial laminates with an optimization routine for two failure criteria theories from the literature. Optimal shear parameters are reported for both theories. **DOI:** 10.1061/(ASCE)MT.1943-5533.0002063.

Author keywords: Wood laminate; Shear strength; Shear stiffness; Tsai-Wu failure theory; Hashin failure theory.

Introduction

Experimental methods for the characterization of shear strength and stiffness of both wood-based and glass-based or carbon-based composite materials are highly contested because shear properties are difficult to isolate experimentally. Meanwhile, in-plane shear properties of laminated wood are needed in applications such as diaphragms, shear webs, and plates and shells under combined loading. The researchers involved in the present study are particularly interested in the design of large wind-turbine blades incorporating laminated wood-veneer panels. With the size of turbine blades surpassing 60 m in length, these panels could exceed thicknesses of 100 mm. Like many advanced composite structures, a wind-turbine blade uses multiaxial laminates in order to optimize for complex combined loading conditions. Combined shear failures are especially common under such conditions, so the accurate measure of shear properties is especially important.

The authors present a novel method for calculating the in-plane shear strength and stiffness based on uniaxial tension and compression tests of symmetric angle-ply wood laminates. The test data were compared with predictions from the Tsai-Wu and Hashin failure criteria, for which shear parameters were determined using genetic optimization.

Literature Review

There has been considerable research into test methods for determining in-plane shear strength of both wood products and fiber-reinforced composites, with no clear consensus among researchers regarding the best method for thin wood laminates in plate or shell structures. This review summarizes the most popular and promising test methods.

±45° Tension Test

This methodology was developed for polymer-matrix composites and is presented in ASTM D3518 (ASTM 2013a). Small test coupons of continuous-fiber ±45° angle-ply laminates were tested in tension. Rosen (1972) developed expressions that allow the in-plane 0° shear stress-strain curve to be generated from the longitudinal and transverse stress-strain curves from uniaxial tension tests of 45° angle-ply laminates. Rosen also suggested the presence of an edge effect and highlighted the importance of specimen size and fabrication. The benefits of this test include that the coupon is small and easy to fabricate, and that the results are easily reproducible. The main drawback is a complex, coupled stress state that makes it difficult to isolate the shear-stress property. Based on a comparison among six methods for evaluating shear properties for an aramid-epoxy composite, Chiao et al. (1977) recommended the ±45° tension test because it gives the closest stress-strain response to the torsion tube test (which is hailed for its accuracy but difficult to perform) while remaining simple, inexpensive, and reliable.

Off-Axis Test

The 10° off-axis tension test was first proposed by Chamis and Sinclair (1976), who found through theoretical and experimental investigations that this test is promising for unidirectional laminates and single plies; it has advantages of small test coupons, simple testing, no laminate residual stresses from multiaxial laminates, and uniform shear through the test section. The main drawback is that the method is very sensitive to small misorientation errors. Chiao et al. (1977) found that in comparison with the ±45° tension test, the 10° off-axis test gave consistently higher shear modulus, lower failure stress, and lower failure strain. Clouston et al. (1998) used off-axis tension testing to determine the interaction term of the Tsai-Wu failure theory for Douglas-fir laminated veneer. The study compared 15°, 30°, 45°, and 60° off-axis test data and found that the 15° data were most reliable because they were less sensitive to experimental variations. Clouston and Lam (2001) went on to propose a minimization approach to estimate simultaneously three

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parameters (shear strength, modulus of rigidity, and the interaction parameter) based on the compression properties of 15 angle-ply laminates.

Rail Shear Test

The rail shear test method outlined in ASTM D4255 (ASTM 2007) covers both two-rail and three-rail shear. In two-rail shear testing, laminates were clamped between two pairs of rails; when loaded in tension, the rails introduced shear forces in the specimen. In three-rail testing, laminates were clamped on opposite edges while a third rail in the center applied a tensile or compressive force. Whitney and Stansbarger (1971) did an extensive theoretical stress analysis, concluding that the method is valid for finding shear modulus when the length-to-width ratio is at least 10. For shear strength, there is an additional criterion, namely that the effective laminate's Poisson's ratio must be less than 1, which is not the case for 45° angle-ply specimens. Garcia et al. (1980) showed that the aspect ratio of the specimen can have a major effect on the stress distribution, depending on the laminate. Subsequently, an ASTM round-robin review (Lockwood 1981) concluded that the variation in averages across different studies was great enough to cast doubt on the validity of the data from these tests.

Iosipescu Shear Block Test

Iosipescu, also called the V-notched beam method, is the most common test methodology for isotropic materials and has been adapted for composite materials as described in ASTM-D5379 (ASTM 2012). In this method, a small specimen with symmetrical center-span v-notches is tested in a special fixture that translates compressive forces from a Universal Testing Machine to act on opposite ends of the specimen, shearing the specimen in the notched center section. Walrath and Adams (1983) extended the test to fibrous composites with some success. However, finite-element analyses have since shown that because of the highly nonuniform stress distribution through the cross section, it is very hard to accurately determine the stress and strain that caused failure (Wang and Socie 1994). Another major limitation is that shear strength is affected by geometry of the notches and gripping systems. The main advantages to this method are that the test is easy to conduct and uses small test specimens.

Torsion of Thin-Walled Tubes

Many researchers have agreed that torsion tests of thin-walled tubes are both precise and accurate in determining shear strength of composite laminates, with many citing this as the most accurate method for determining in-plane shear strength. The methodology is presented in ASTM D5448 (ASTM 2011a). Thin hoop-wound (90°) cylinders were bonded to two end fixtures and tested in pure torsion. The main drawback of this methodology is that specimens are difficult to fabricate, especially for natural materials like wood. The tests both require a more labor-intensive fabrication processes and are sensitive to defects that may result from those processes. Still, Lee and Munro (1986) argued that this is the test to which other, simpler tests should be compared.

Torsion Tests of Full-Size Beams

The testing protocol for determining the shear properties of full-size lumber is given in ASTM D198 (ASTM 1999). Full-size structural beams were tested in pure torsion using a torsion test machine or adapting a Universal Testing Machine. Riyanto and Gupta (1998) compared full-beam torsion tests with three-point, four-point, and five-point bending tests on solid wood in structural sizes. The researchers found that the torsion test gave the highest shear strength of all methods and concluded that the torsion test is a good method to determine shear stress in structural lumber because of its ability to isolate pure shear. Gupta and Siller (2005) went on to compare the shear strength of structural composite lumber (SCL) using torsion and shear block tests and found that torsion tests gave a lower shear strength compared with shear block tests. They recommended the torsion test as the best practical method for determining pure shear strength of SCL as well as full-size structural lumber (Gupta et al. 2002). Yang et al. (2014) further used the torsional test to establish shear strength of full-size eastern species laminated-veneer lumber (LVL).

Other Methods

Duggan et al. (1978) proposed a cross-beam sandwich method, wherein a cross-shaped specimen is loaded in bending on two opposite arms and supported on the remaining two arms. This method was found to produce significantly different strength values compared with the ±45° tension test, so is not widely used. Later, Duggan (1980) proposed a biaxial slotted-tension shear test, where the specimen is under biaxial tension-compression loading with slots used to control loading. The slots were causing stress concentrations, and failures in this test were in tension, so it is not a good measure of shear strength. Wang and Socie (1994) expanded on the biaxial tension-compression test method by creating flexible end reinforcements of aluminum, which do not transfer transverse loads. The concept was that this configuration would eliminate stress concentrations caused by tensile grips and prevent laminate edges from being crushed in compression. Shear failures as predicted by failure criteria were not observed in this test method, with maximum stress/strain failures observed instead.

The short beam method is promising and has been reviewed in ASTM D2344 (ASTM 2013b). The method allows the calculation of the apparent interlaminar shear strength of fiber-reinforced plastic composites. The failure mode in this test will depend upon layup, size parameters, and manufacturing. Thus, the method is not recommended for strength determination, but is a simple method that can be used for screening. Finally, the plate twist test, outlined in ISO-15310 (ISO 1999), is often used to determine shear modulus of composite laminates. The procedure was modified by Yoshihara (2012) to calculate apparent shear strength, but the results varied with plate thickness, and the researchers suggested future work in order to evaluate the accuracy of this method.

Methods

Experimental Methods

The source material used in this study was rotary peeled, 1.22×2.44 m $(4 \times 8$ ft) spruce-pine-fir (SPF) veneer sheets in 3.175 mm (1/8 in.) thickness donated to the study by Louisiana Pacific (Nashville, Tennessee). They are high-quality veneers used in the production of laminated-veneer lumber. These veneers were laminated and machined as detailed in Fig. 1. T-88 (System Three Resins, Auburn, Washington) structural epoxy was used as the adhesive because of its ability to cure in ambient room temperatures. The veneers were glued in ambient room conditions, leading to a moisture content of 7–10%. Specimens were laminated in a hydraulic press with uniform pressure of approximately 690–970 kPa (100–140 psi). The specimen geometry and testing procedure were determined according to ASTM D3500 (ASTM 2009) (tension) and ASTM D3501 (ASTM 2011b) (compression). The gauge

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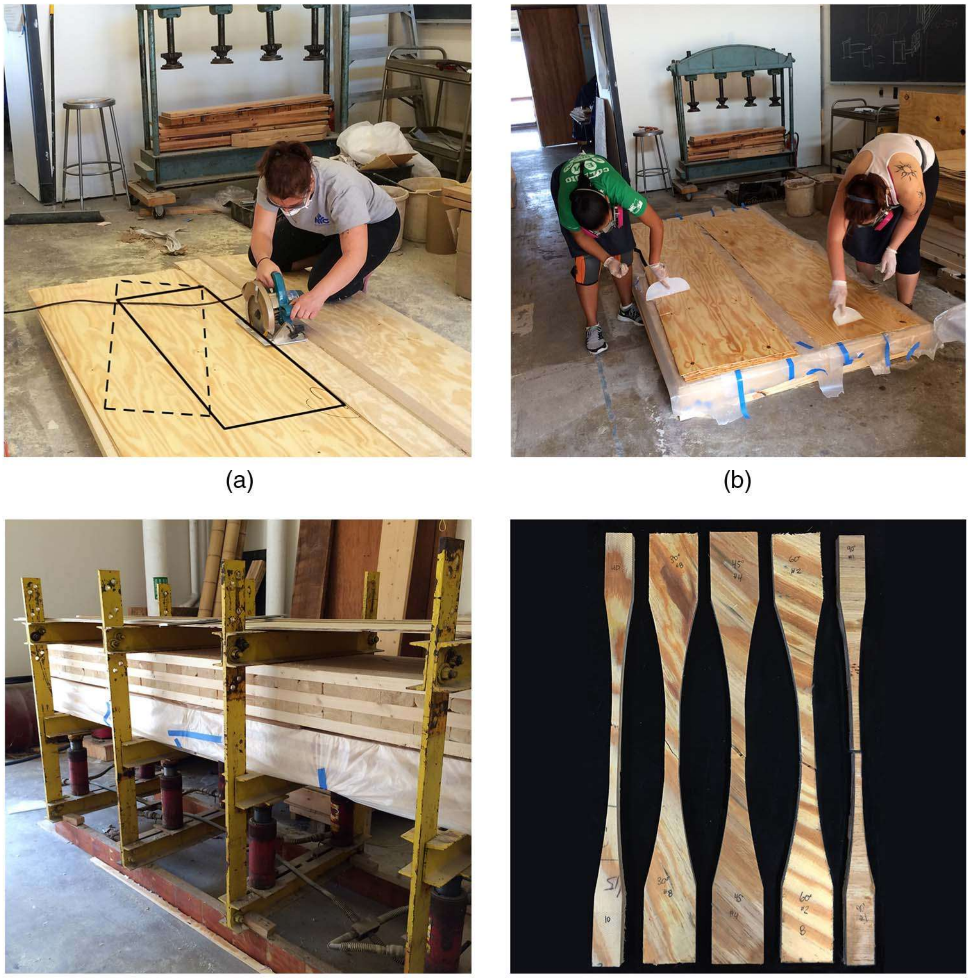


(a) (b) (c) (d)

Fig. 1. Manufacturing process for angle-ply laminates: (a) veneer is cut into panels corresponding to the desired grain angles; solid rectangle is a sketch of a unidirectional (UD) panel, whereas the dashed rectangle is a sketch of a panel at approximately 30°; (b) adhesive is applied manually to both sides of each lamina; (c) laminate is pressed at room temperature using a hydraulic press and cross-laminated timber panels to distribute the load from the press; (d) dog-bone-shaped tension specimens and rectangular compression specimens (not pictured) are cut using a computer numerical control (CNC) router

sections for the unidirectional and transverse tension specimens were 6.35×12.7 mm ($1/4 \times 1/2$ in.); gauge sections for the multiaxial tension specimens were 12.7×12.7 mm ($1/2 \times 1/2$ in.); and gauge sections for all compression specimens were 25.4×12.7 mm ($1 \times 1/2$ in.). Specimens were fabricated at 0°, 30°, 45°, 60°, and 90° in symmetric, four-ply layups. Ten specimens were tested for each tension and compression, in each of five layups, for a total of 100 experiments.

The specific gravity measurement was taken in accordance with ASTM D2395 (ASTM 2014), and moisture content measurement was taken using the oven-dry method, specified by ASTM D4442 (ASTM 1997). The specific gravity of the laminated specimens was 0.73 ± 0.045 g/cm^3 with no significant variation between treatments. The moisture content was $7.1 \pm 0.35\%$ with no significant variation between treatments.

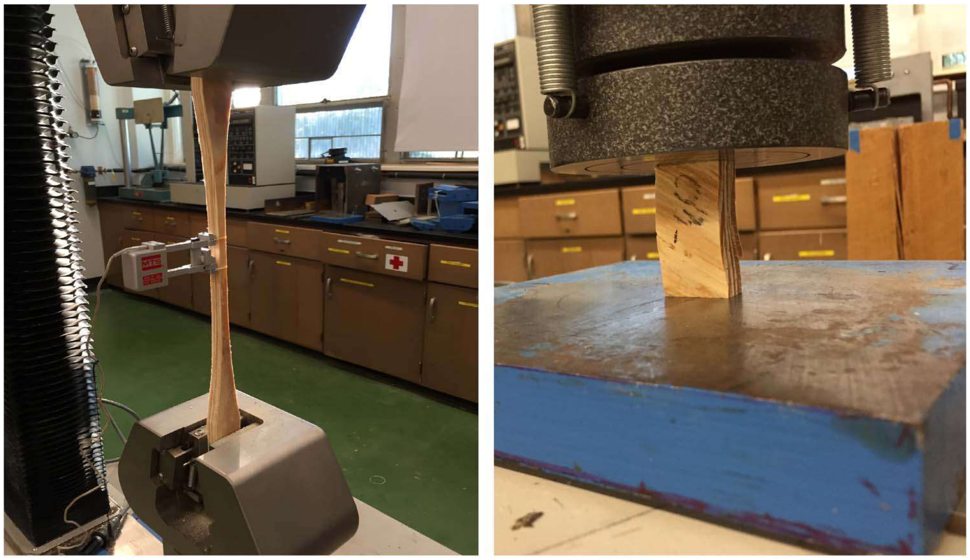
Tensile and compression tests were performed at room temperature on a MTS (Eden Prairie, Minnesota) universal testing system, pictured in Fig. 2. Tensile strain was measured using a single extensometer centered on the face of the test specimen. The strength was defined as the maximum stress recorded during testing, and the stiffness is taken from the low-strain, linear portion of the stress-strain curve. Elastic moduli E_1 and E_2 were measured from the unidirectional, 0°, and 90° specimens. The reported values reflect the mean across the 10 specimens.

Numerical Methods

From experimental data, global stresses and strains were transformed into those in the local material coordinates of the ply following the assumptions of classical lamination theory (CLT), as in Fig. 3. It is these lamina-level stresses and strains that are used in failure criteria. The global coordinate system is defined by (σ_x, ϵ_x) where x is the testing direction. The lamina coordinate system is defined by (σ_1, ϵ_1) representing the parallel-to-grain direction, and (σ_2, ϵ_2) representing the perpendicular-to-grain direction. For a symmetric, balanced laminate using only one angle (e.g., $\pm 30_s$), the lamina-level stresses and strains are of the same magnitude for each lamina in the stackup.

Shear Modulus G_{12}

Shear modulus was determined through least-squares minimization of error between the experimentally obtained laminate stiffness and analytically obtained laminate stiffness. The latter used CLT with shear modulus as the inherent unknown to be optimized.



(a) (b)

Fig. 2. (a) Tension tests; (b) compression tests were performed on a MTS universal test system

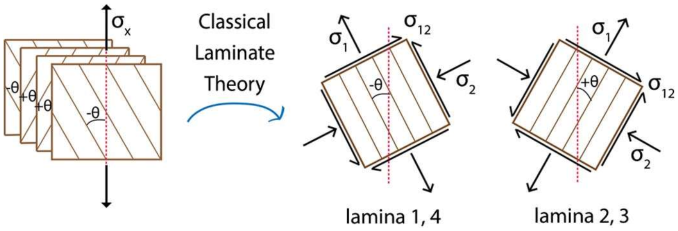


Fig. 3. Global stresses and strains are transformed into lamina stresses and strains

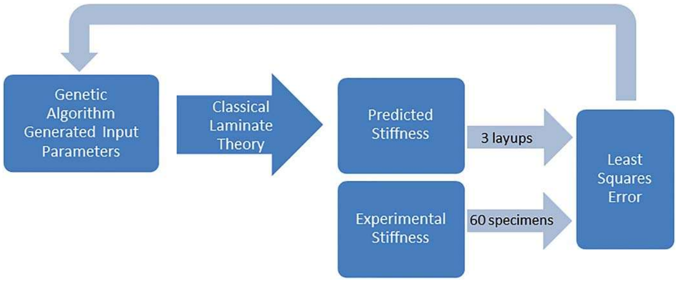


Fig. 4. Optimization routine for shear stiffness minimizes the least-squares error between classical laminate theory and test data from 30°, 45°, and 60° symmetric laminates in tension and compression

Stiffness was calculated for each of the 60 multiaxial specimens (at 30°, 45°, and 60°) and the optimization routine was performed using *MATLAB* as depicted in Fig. 4. The optimization boundaries (presented in Table 1) were estimated from Janowiak et al. (2001), who determined G_{12} for several structural composite lumber products using the torsion test.

It is well known that a dependency exists between the Poisson's ratio ν_{12}, elastic moduli E_1 and E_2, and shear modulus G_{12}. Therefore, to arrive at an accurate characterization of G_{12}, the remaining parameters must be defined. E_1 and E_2 were determined by testing uniaxial wood laminates in the 0° and 90° orientations. The ν_{12} values for several similar materials (e.g., clear eastern species and several types of LVL) were reported by Ross (2010) and Janowiak et al. (2001), but the variation in reported values from these sources is substantial. The authors chose to use the value reported by Janowiak et al. (2001) for 2.0E southern pine LVL, but tested a range of values to illustrate that the dependency of G_{12} on ν_{12} is quite small.

Shear Strength S_{12} and S_{21}

Lamina-level stresses are used to inform a parametric optimization of two failure theories: the Tsai-Wu failure criterion and Hashin criterion. The Tsai-Wu theory (Tsai and Wu 1971) was chosen because of its prevalence in the industry, its use by other researchers for wood composites (Clouston and Lam 2002; Oh 2011; Mascia and Nicolas 2012), and its ability to consider tensile and compressive strengths separately. The theory is summarized in Eqs. (1*a*)–(1*c*). Eq. (1*a*) shows the general three dimensional (3D) formulation, and Eq. (1*b*) is the plane stress formulation. Eq. (1*c*) defines the combined strength parameters used in the in-plane formulation. The Hashin criterion (Hashin 1980) is a semiempirical theory that considers specific failure modes, and has been shown by Koh and Clouston (2016) to better fit experimental data for multiaxial wood laminates. The piecewise theory, shown in Eqs. (2*a*)–(2*d*), was originally formulated for fiber-reinforced composites. It considers four distinct modes of failure and the combined stress states that contribute to each

Table 1. Optimization Boundaries

Parameter	Lower boundary	Upper boundary
G_{12} (MPa)	200	800
S_{12} (MPa)	0	50
S_{21} (MPa)	0	50
f_{12} (MPa^{-2})	−0.0021	0.0021

$$f_i\sigma_i + f_{ij}\sigma_i\sigma_j = 1 \quad \text{for} \quad i,j = 1,2,3,4,5,6 \tag{1a}$$

$$f_1\sigma_1 + f_2\sigma_2 + f_{11}\sigma_1^2 + f_{22}\sigma_2^2 + f_{66}\sigma_6^2 + 2f_{12}\sigma_1\sigma_2 = 1 \tag{1b}$$

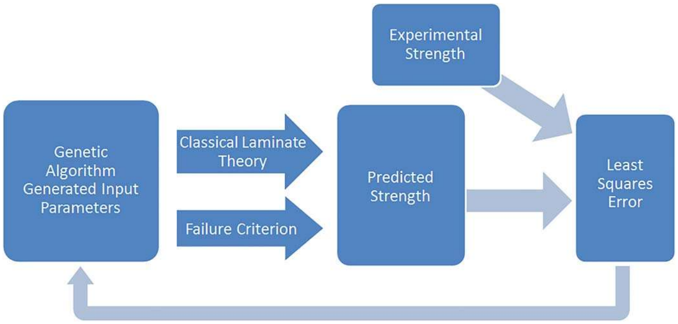


Fig. 5. Optimization routine for shear strength minimizes the least-squares error between predicted and test data from 30°, 45°, and 60° symmetric laminates in tension and compression

$$f_1 = \frac{1}{S_{1T}} - \frac{1}{S_{1C}}; \qquad f_2 = \frac{1}{S_{2T}} - \frac{1}{S_{2C}}; \qquad f_{11} = \frac{1}{S_{1T}S_{1C}};$$
$$f_{22} = \frac{1}{S_{2T}S_{2C}}; \qquad f_{66} = \frac{1}{S_{12}^2} \tag{1c}$$

The Tsai-Wu theory contains an interaction parameter f_{12} that characterizes the interaction between parallel-to-grain and perpendicular-to-grain stresses, as in Eq. (1*b*). Theoretically, this parameter can vary for each quadrant of the loading regime (σ_1–σ_2 in tension-tension, tension-compression, compression-tension, and compression-compression). However, it is common practice to use a single interaction parameter, and the authors have done so in this study. Although there was at least one treatment in each regime, there were not sufficient treatments in each regime to create four separate optimized surfaces. The interaction parameter was optimized concurrently with shear strength S_{12} in the Tsai-Wu case. The boundaries of f_{12}, presented in Table 1, are calculated by a stability criterion (Tsai and Wu 1971) that forces the failure surface to converge as follows:

Tensile fiber mode

$$\left(\frac{\sigma_1}{S_{1T}}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 = 1; \qquad \sigma_1 > 0 \tag{2a}$$

Fiber compressive mode

$$\sigma_1 = -S_{1C}; \qquad \sigma_1 < 0 \tag{2b}$$

Tensile matrix mode

$$\left(\frac{\sigma_2}{S_{2T}}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 = 1; \qquad \sigma_2 > 0 \tag{2c}$$

Compressive matrix mode

$$\left(\frac{\sigma_2}{S_{21}}\right)^2 + \left[\left(\frac{S_{2C}}{2S_{21}}\right)^2 - 1\right]\frac{\sigma_2}{S_{2C}} + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 = 1; \qquad \sigma_2 < 0 \tag{2d}$$

Optimization Routine

A *MATLAB* genetic algorithm solver was used to optimize the shear strength and interaction parameters concurrently. A schematic for the parametric optimization for strength is depicted in Fig. 5. CLT and the failure criterion are coupled to solve for a single failure point in 3D space (σ_1, σ_2, σ_{12}), the predicted strength. The fitness function minimizes the least-squares error between the predicted and actual (experimental) strength for each treatment (orientation angle and test direction). In the Tsai-Wu case, the fitness function optimizes parallel-to-grain shear strength S_{12} and interaction parameter f_{12}. In the Hashin case, the fitness function optimizes parallel-to-grain shear strength S_{12} and perpendicular-to-grain shear strength S_{21}.

Results

Axial tension and compression tests were performed on 0°, 30°, 45°, 60°, and 90° symmetric angle-ply wood laminates. The results of these tests are reported in Fig. 6, with error bars showing one standard deviation ($n = 10$ tests for each treatment).

Shear Modulus G_{12}

The optimal shear stiffness from tension and compression tests of multiaxial laminates was found to be 566 MPa. This is in good agreement with Janowiak et al. (2001), who used torsion tests to determine G_{12} for southern pine, Douglas fir, and yellow poplar laminated-veneer lumber. All elastic parameters are presented in Table 2. E_1 and E_2 were determined by preliminary experiments, and Poisson's Ratio ν_{12} was taken as the manufacturer-reported value for a similar material (LVL). Because of the known interaction between ν_{12} and G_{12}, the variation of G_{12} in response to a range of possible ν_{12} values was also examined. The result is shown in Fig. 7. In comparison with the variation of G_{12} among different

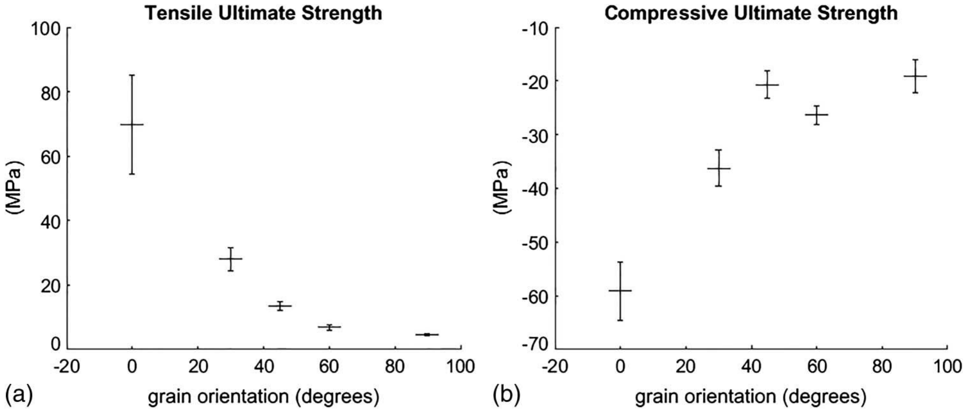


Fig. 6. Strength of angle-ply wood laminates in (a) tension; (b) compression

Table 2. In-Plane Elastic Properties

Parameter	Value
E_1 (GPa)	14.8
E_2 (GPa)	1.15
ν_{12}	0.743
G_{12} (MPa)	567

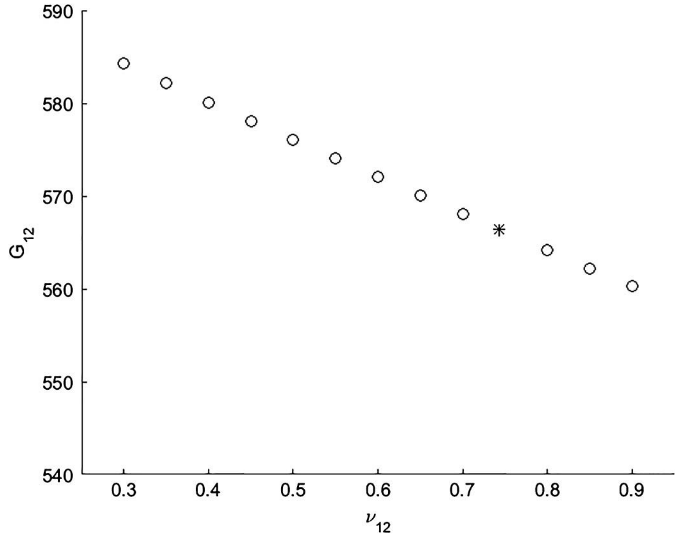


Fig. 7. Relationship between shear modulus G_{12} and Poisson's ratio ν_{12}; asterisk indicates the value selected in this study

studies on similar materials, the variation resulting from Poisson's Ratio was relatively small.

Shear Strength S_{12} and S_{21}

Strength parameters X_t, X_c, Y_t, and Y_c determined by tests of 0° and 90° specimens are reported in Table 3. The optimal shear strength values for the Tsai-Wu and Hashin criteria are reported in Table 3, along with interaction parameter f_{12} for the Tsai-Wu theory. Resulting failure surfaces are graphed in Fig. 8 with experimental averages denoted by an asterisk. For S_{12}, shear parallel-to-grain, there is quite good agreement between the two criteria and reasonable agreement with what little data are available in the literature. Whereas the present study reports S_{12} values of 7.10 MPa (Tsai-Wu) and 7.33 MPa (Hashin), Gupta and Siller (2005) reported a value of 4.90 MPa from the shear block test and 6.99 MPa from the torsion test for a similar material. For clear wood, an expected range for S_{21} is 5–10 MPa (Ross 2010). The present study reports S_{21}, perpendicular-to-grain shear, to be 18.4 MPa per the Hashin criterion. This parameter is not commonly reported in the literature (and has not been verified experimentally) because it tends not to be a limiting factor when designing with wood, but is known to be higher than parallel-to-grain shear.

Table 3. In-plane Strength Properties of Wood Laminate

Source	Strength parameter	Value
Experiment	X_t (MPa)	69.8
Experiment	X_c (MPa)	59.1
Experiment	Y_t (MPa)	4.55
Experiment	Y_c (MPa)	19.2
Tsai-Wu criterion optimization	f_{12} (MPa^{-2})	−0.0010
Tsai-Wu criterion optimization	S_{12} (MPa)	7.10
Hashin criterion optimization	S_{12} (MPa)	7.31
Hashin criterion optimization	S_{21} (MPa)	18.4

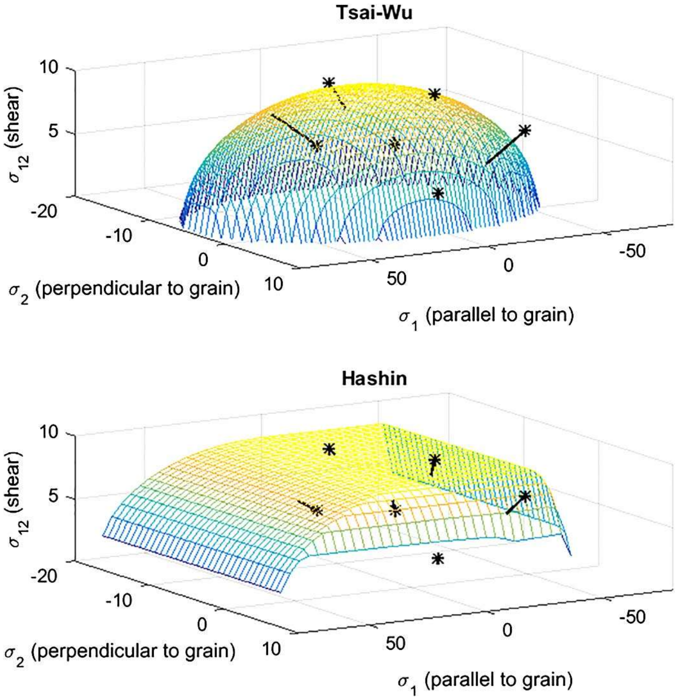


Fig. 8. Three-dimensional failure surfaces for Tsai-Wu and Hashin criteria; surface parameters were optimized to fit the experimental data, shown by an asterisk

Tsai-Wu Interaction Parameter f_{12}

The optimal interaction parameter f_{12} for the Tsai-Wu theory is -0.0010 MPa^{-2}. Clouston et al. (1998) showed that this parameter varies by orientation angle, reporting values from -0.00053 to 0.0409 MPa^{-2} in laminates tested from 15° to 60° off-axis in tension and ultimately recommending the value of $+0.00003$ MPa^{-2} for Douglas-fir LVL based on a probabilistic minimization using 15° test data. By comparison, the present study used balanced, symmetric laminates in both tension and compression, and the optimization results account for all angles. The value of -0.0010 MPa^{-2} is comparable with the range of values reported by Clouston (1996) and falls within the boundaries of the stability criterion.

Conclusions

This paper presented a novel method for determining shear properties of laminated wood by coupling tension and compression tests of angle-ply laminates with a failure criterion optimization routine. Shear strength, stiffness, and Tsai-Wu interaction parameter f_{12} were presented for four-ply wood laminates. The results were in relatively good agreement with those found by other test methods in the literature for similar materials. They are especially close to torsion test results from Gupta and Siller (2005), which is promising because the torsion test is widely considered to be among the best methods to determine shear strength. Importantly, rather than trying to isolate pure shear strength, which is uncommon in plate and shell structures, this study examined the shear properties using a testing program that more closely mimics real-life applications and failure modes.

Acknowledgments

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Notation

The following symbols are used in this paper:

f_{12} = Tsai-Wu interaction parameter;
G_{12} = in-plane shear modulus;
S_{1C} = parallel-to-grain compressive strength;
S_{1T} = parallel-to-grain tensile strength;
S_{2C} = perpendicular-to-grain compressive strength;
S_{2T} = perpendicular-to-grain tensile strength;
S_{12} = in-plane shear strength (MPa);
S_{21} = in-plane shear strength (MPa);
ϵ_X = global strain in the testing direction;
ϵ_1 = parallel-to-grain strain;
ϵ_2 = perpendicular-to-grain strain;
ϵ_{12} = shear strain;
σ_X = global stress in the testing direction;
σ_1 = parallel-to-grain stress;
σ_2 = parallel-to-grain strain; and
σ_{12} = shear stress.

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