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ABSTRACT

This study investigates the effect that specimen depth has on the torsional shear strength of full-size Eastern Species Laminated Veneer Lumber (LVL). Characterization of this effect is valuable for structural design purposes as well as for use in constitutive modeling when predicting member strength of one depth based on member strength of a different depth derived from testing. To this end, torsion tests were carried out on three depths (140, 184, and 235 mm) of 1.98 m long by 44 mm thick 1.9E Eastern Species LVL. The shear strength of each depth was determined based on homogeneous, orthotropic theory for beams of rectangular cross-section. Despite a perceptible trend of slightly decreasing shear strength with increasing depth, an analysis of variance test indicated that no statistically significant depth effect exists as it relates to torsional shear strength. Further, a three dimensional finite element model of the 44 mm by 140 mm specimen indicated that stresses are uniform within the shear span of 2 times the depth plus the grip distance away from each end of the specimen. The predicted average maximum shear stress in this region compared well to the maximum shear stresses obtained experimentally.

Keywords

torsion, shear strength, laminated veneer lumber, size effect, wood composite

Introduction

Size effect is a well-known phenomenon in which the strength of a material decreases with increasing stressed volume. It has been characterized and incorporated into the structural design of many building materials, particularly those with brittle failure mechanisms including concrete, advanced composites, wood and structural composite lumber [1–5].

The impetus of this study is a larger on-going project which is focused on developing a constitutive model to predict full-size member strength of Structural Composite Lumber (SCL), of which Laminated Veneer Lumber (LVL) is one type. LVL is comprised of thin layers of wood veneers that are laminated together with structural adhesives and are used extensively in light-frame construction in lumber-like applications such as beams, columns, and scaffolding.

An important implication of size effect comes about when using a multi-axial strength theory in a constitutive model. The uniaxial (or pure) strengths that are needed as input for the strength theory must be representative of the volume of material to which the strength theory is being applied. For LVL, the uniaxial strengths are tension and compression, both parallel and perpendicular to grain, and shear. If size significantly affects any one of these strengths, one should first adjust the strength that is derived based on a test specimen volume to a strength that is representative of the model element size [6–8].

The shear strength of LVL, as with solid wood, is experimentally determined based on small shear block tests, with a shear area of 2581 mm^2, in accordance with ASTM D143 [9]; however, several recent research studies have asserted that the shear block method is not appropriate for establishing *pure* shear strength of structural lumber or structural composite lumber. Riyanto and Gupta [10] conducted a comparison test to evaluate the shear strength of dimensional lumber (38 by 89 mm^2 by 3.6 m long Machine-Stress-Rated lumber) by using three-point bending, four-point bending, five-point bending, and torsion tests. A Duncan multiple-comparison test showed that shear strengths from all test methods were significantly different from one other. The torsion test produced the highest shear strength and appeared to be the best test method for determining shear strength of dimensional lumber because it was the only one able to produce a pure shear stress state (i.e., free of stress interactions). In a later study, Gupta et al. [11] evaluated the torsion test using five different lengths and five different depths of full-size structural lumber. They concluded that the torsion method was the best and most practical approach to determine pure shear strength for lumber but also found no evidence of a length or depth effect using this method. Gupta and Siller [12,13] conducted torsion tests and comparison shear block tests on Structural Composite Lumber (SCL) and recommended it as a standard method, as did Khokhar et al. [14] who did tests on Sitka spruce and Norway spruce.

The effect of member size on strength has been thoroughly researched for structural composite lumber for bending and tension scenarios [2,5] but not for torsional shear. In fact, with the exception of the study done on structural lumber by Gupta et al. [11], no literature was found that focused on the relationship between size and torsional shear strength. Interestingly, from previous studies that did torsional testing of structural composite lumber [12,13,15], it appears that a correlation between size and shear strength may exist, though not scientifically proven. Moreover, the torsional shear strength of 1.9E Eastern Species LVL is not reported in the literature—with the exception of a technical note focused on the machine test setup that extends from the first author's graduate thesis [16,17]. The aim of this paper is, therefore, to establish the torsional shear strength of 1.9E Eastern Species LVL, and to investigate potential dependence of the torsional shear strength on member size.

Experimental Procedures

MATERIALS

The materials tested in the study were 2600Fb-1.9E Eastern Species LVL boards manufactured by iLevel by Weyerhaeuser. In general, Eastern Species LVL is a product manufactured out of any one, or combination of, the species in the Southern Pine group (e.g., Longleaf pine, Loblolly pine), Yellow Poplar, and/or Red Maple. The product is made at any one time from different species considering veneer cost and availability to the mill. Consequently, the actual mix of species used for the specimens tested was unknown.

Thirty-six pieces of 1980 mm by 44 mm wide LVL were tested in this project, breaking down into 12 pieces for each depth studied (140, 184, and 235 mm). Before the experimental test, the beams were stacked and conditioned for 6 weeks to reach equilibrium with ambient temperature and humidity. Specimens for moisture content (MC) and specific gravity (SG) were extracted from the main beams near the shear crack zone after completion of the torsional tests following the guidelines of ASTM D2395 [18]. The average MC and SG values were not significantly different between depth groups and gave a pooled value of 7.7 % (COV 7.8 %) and 0.50 (COV 3.3 %) for MC and SG, respectively.

The minimum length requirement of eight times the larger cross-sectional dimension per ASTM D198 [19] was followed to ensure a long enough shear span to allow shear stress uniformity and to avoid end effect. A grip length of 76 mm was used at both ends of the specimen, which produced a gauge length of 1828 mm for all the specimens, as shown in **Fig. 1**.

TEST METHOD

The torsional tests were conducted using a Universal-type test machine (150 kN capacity MTS) for which a general procedure is described in ASTM D198 [19]. The test specimen was clamped symmetrically about the longitudinal axis by two steel bracket assemblies on either end of the specimen as shown in **Fig. 2**. The deformation rate was 0.11 rad per meter of length per minute (rad/m/min), producing maximum torque in approximately 10 min. The test setup and test protocol for this lesser known approach have been presented in Yang et al. [17] and readers are directed to this study for more detailed information on the test procedure.

FIG. 1
Torsion test setup and dimensions of LVL specimen.

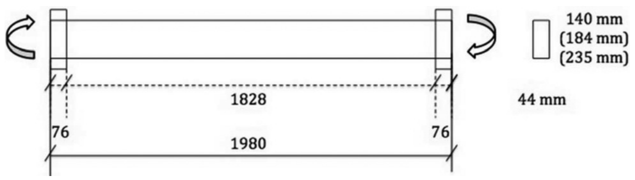


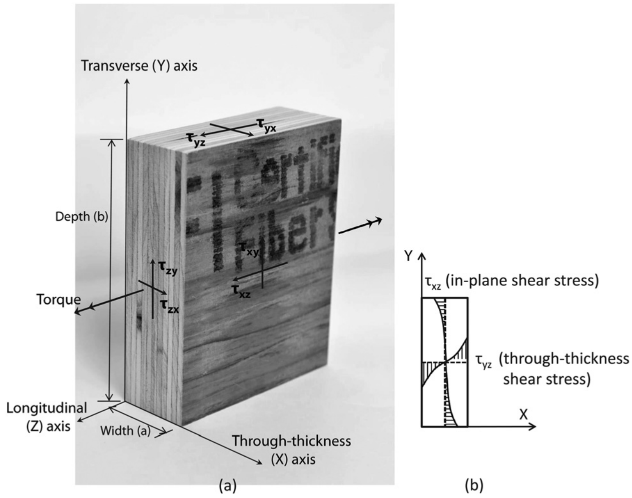
FIG. 2
Torsion test with a universal test machine.

Results and Discussion

TORSION TEST

Upon failure of the specimens (i.e., post peak load), cracking sounds were heard and shear cracks were observed on both the Transverse–Longitudinal (T–L) and Through-Thickness–Longitudinal (TT-L) planes parallel to the longitudinal direction. Shear failure reliably occurred parallel to grain at mid-depth (for τ_{yz}) or mid-thickness (for τ_{xz}), as expected; referencing **Fig. 3(*b*)**, torsional shear stress is maximum at the surface of the beam and zero at the center of the cross section. A failed

FIG. 3
Shear stress block (a) three-dimensional coordinate system and (b) idealized torsional shear stress distribution over the cross section.



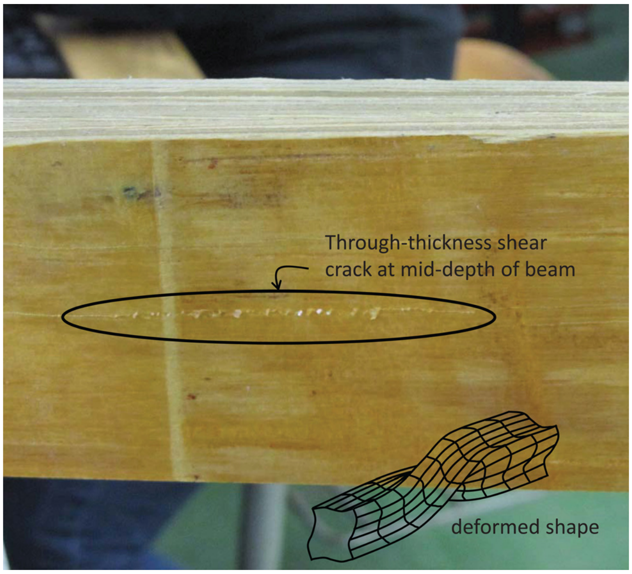


FIG. 4 Shear crack on tangential–longitudinal (T–L) face of LVL.

torsion specimen is depicted in **Fig. 4** showing a through-thickness shear crack at mid-depth of the specimen.

A typical load-displacement plot is given in **Fig. 5**. It displays a brittle shear failure, as expected; however, there is some abnormal increase in slope near peak load. This was due to slippage between the loading blocks and the steel moment arms which was evident during testing. It was reasoned that the slippage did not affect the ultimate strength of the specimen and so, maximum shear stress was calculated based on the maximum torque produced in the specimen at peak load.

MAXIMUM SHEAR STRESS BASED ON ORTHOTROPIC MATERIAL BEHAVIOR

Gupta and Siller [12] explored two different approaches to evaluate shear stress in SCL: (1) assuming isotropic behavior, which is the procedure outlined in

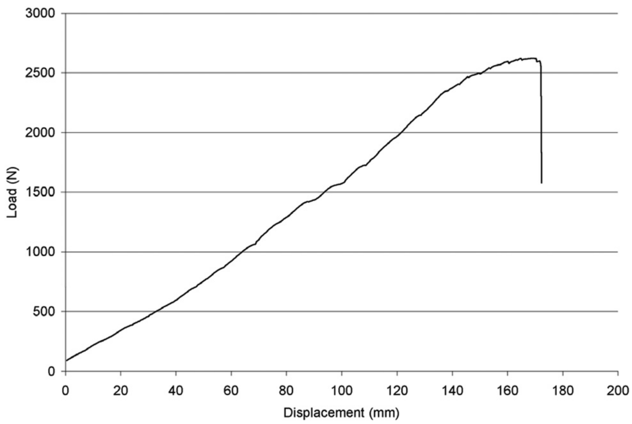


FIG. 5 Typical load-crosshead displacement plot from torsion test.

ASTM D198 [19] based on work by Trayer and March [20], and (2) assuming orthotropic behavior per Lekhnitskii [21]. Although the latter approach was more complex, they found it to be justified in that incorporating realistic orthotropic properties proved to be influential; in particular, the shear moduli in the two longitudinal planes, G_{xz} and G_{yz}, significantly influenced the results for shear strength.

Thus, for this study, maximum shear stress was calculated in accordance with Lekhnitskii's approach [21]. The formulas are for homogeneous orthotropic beams of rectangular cross section as follows:

$$\tau_{xz} = \frac{T}{a^2 b} k_1 \tag{1}$$

$$\tau_{yz} = \frac{T}{\mu a^2 b} k_2 \tag{2}$$

where:

τ_{xz} = maximum in-plane shear stress (on the T–L plane in the L direction),

τ_{yz} = maximum through-thickness shear stress (on the TT–L plane in the L direction),

a = width,

b = depth,

T = twisting moment (or torque) at peak load (twice the product of the normal component of the maximum applied vertical load and the corresponding moment arm), and

k_1, k_2 = factors that depend on aspect ratio and shear moduli.

$$\mu = \sqrt{G_{yz} G_{xz}}$$

The factors k_1, k_2 need to be interpolated separately from a Table given in Lekhnitskii [21]. They depend not only on the dimensions, a and b, but also on the ratio of the two shear moduli in the longitudinal direction, G_{yz} and G_{xz}.

While values for G_{yz} and G_{xz} for some LVL products exist in the literature, no information has been found specifically for 2600Fb-1.9E Eastern Species LVL. According to Janowiak et al. [22], the test protocol to derive these values from a torsional test requires that torsional stiffness measurements be taken over various slenderness ratios—a separate procedure from that of the current study. Therefore, for the purposes of this study, shear moduli of a similar product (2.0E Southern Pine LVL) was employed. Taken from Janowiak et al. [22], the shear moduli are 636 MPa and 282 MPa for G_{yz} and G_{xz}, respectively, and the corresponding μ value is 1.5.

Using Lekhnitskii's approach, the orthotropic shear stresses at failure, τ_{xz} and τ_{yz}, were calculated. Mean values and corresponding COVs are presented in **Table 1**.

Since the COVs appear different across groups, the data was analyzed for homoscedasticity (equal variances) using Bartlett's test. The test concluded that, with a p-value of 0.285 and a significance level of 0.05, the variances are not significantly different and the data is homoscedastic.

Regarding size effect, there is a visible trend of slightly decreasing shear strength with increasing depth in the values shown in the cumulative distribution plots in **Fig. 6**. However, an Analysis of Variance (ANOVA) test, conducted at a 5 % level of significance, indicated that no significant difference exists between the mean of the

TABLE 1

Mean shear strength results.

	Dimensions (mm)	Mean (MPa)	COV[a] (%)
τ_{xz}	44 by 140	11.2	18.8
	44 by 184	10.9	12.3
	44 by 235	10.7	13.0
τ_{yz}	44 by 140	5.9	18.9
	44 by 184	5.5	12.2
	44 by 235	5.3	13.0

[a]Homoscedastic data at a 5 % level of significance.

three size groups. Consequently, it is concluded that depth effect on shear strength of 2600Fb-1.9E Eastern Species LVL, within the range of depths from 140 to 235 mm, was deemed statistically insignificant.

Based on a pooled set of data of 36 specimens, the mean shear strengths on the T–L plane (τ_{xz}) and the TT–L plane (τ_{yz}) were calculated to be 10.9 MPa (16.2 % COV) and 5.6 MPa (16.8 % COV), respectively. These results compare reasonably well with mean strength values published for a similar product from a different species, 1.9 E Douglas Fir LVL, where τ_{xz} and τ_{yz} were determined to be 7.96 and 4.9 MPa, respectively [12].

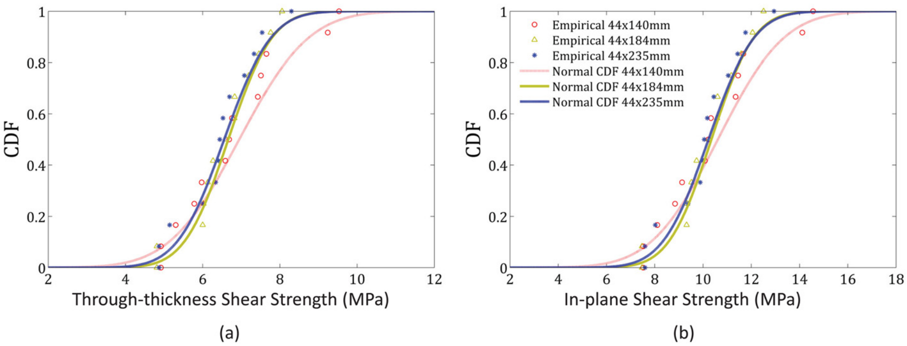
Finite Element Model

A three dimensional, linear elastic, orthotropic finite element model was created using the commercially available finite element program ADINA to analyze the shear stress distribution of the torsional specimens. The analysis was performed with orthotropic properties for the 44 mm by 140 mm by 1980 mm LVL specimen so that comparisons could be made between the FE model and the experimental results.

FE MESH AND BOUNDARY CONDITIONS

Three dimensional, eight-node brick elements were used to model the specimen as an orthotropic continuum. To ensure a suitable mesh size, a convergence study was

FIG. 6 Cumulative Distribution Function of Orthotropic Torsional Shear Strength:(a) Through-thickness Shear Strength; (b) In-plane Shear Strength



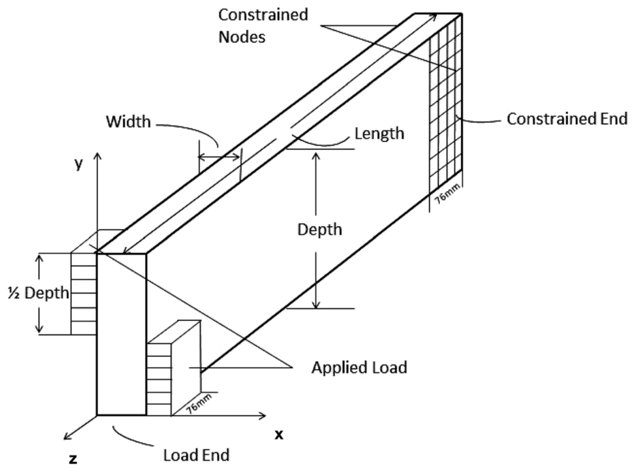


FIG. 7
Boundary conditions of torsional finite element model.

conducted, whereupon the beam was discretized evenly into 12 elements in the through-thickness (x) direction, 24 elements in the in-plane (y) direction, and 52 elements in the longitudinal (z) direction with 14 976 elements in total.

The specimen was modeled assuming one end constrained while the other end was subjected to opposing transverse loads (i.e., a force couple) to create a torsional moment. **Figure 7** shows the boundary conditions and loading applied to the specimen. A 76 mm long boundary length was designated on both ends of the specimen. On the constrained end, all nodes on both wide faces were fixed in all directions. On the loaded end, opposing transverse surface loads were uniformly distributed on both wide faces over $^1/_2$ the specimen height.

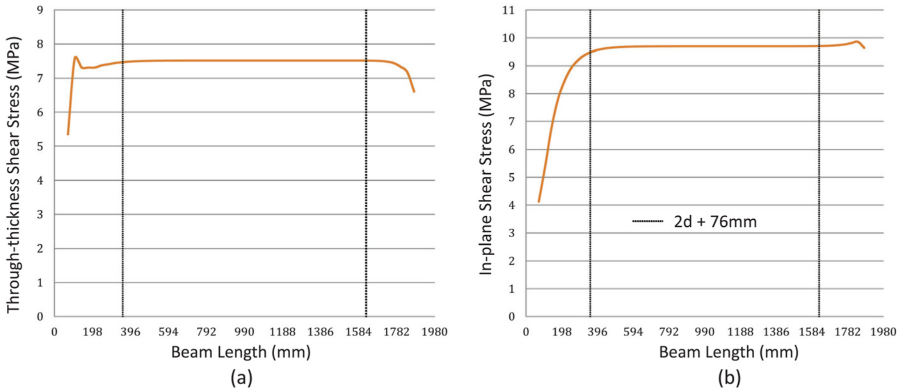
The mean value of the maximum torque from the experimental test, 750 N·m, was used to calculate the applied surface loads. These loads were adjusted accordingly for each mesh size such that force was applied per node on the surface (analogous to an applied pressure).

The orthotropic elastic properties of 2.0 E SP LVL (taken from Janowiak et al. [22]), were used in the FE model to provide a basis of comparison to the experimental results. Given the modulus of elasticity in the longitudinal direction (E_z) to be 13 700 MPa, the moduli of elasticity in the other directions were deduced using theoretical elastic ratios for longleaf pine (one of several possible species in Eastern Species LVL) published in the Wood Handbook [23]. Poisson ratios were also taken from this source. The resulting elastic properties used in the FE model are listed in **Table 2**.

TABLE 2
Elastic properties used in FE model.

E_z	E_y	E_x	G_{yz}	G_{xz}	G_{xy}	ν_{xz}	ν_{yz}	ν_{xy}	μ
		—— (MPa) ——							
13 700	460	585	636	282	29	0.017	0.023	0.481	1.50

FIG. 8 Plot of shear stress distribution along longitudinal direction of beam: (a) through thickness shear stress, τ_{yz}; (b) in-plane shear stress, τ_{xz}.



MODEL RESULTS

Figures 8(*a*) and **8(*b*)** illustrate the distribution of maximum shear stress as it varies along the length of the specimen. Consistent with theory, maximum in-plane shear stress (τ_{xz}) occurred at mid-depth and maximum through-thickness shear stress (τ_{yz}) occurred at mid-width.

The vertical dotted lines denote the distance of 2 times the depth plus the clamp length (76 mm) away from each end of the beam. Within this range, between the loaded and constrained ends, the shear stresses are nearly uniform. The average shear stress matches well the theoretical stress for a rectangular specimen under torsion as found from in experimental results of the study: the average in-plane stress from the model is 12.15 MPa, and the average through-thickness stress is 6.25 MPa compared with the experimentally obtained values of 11.2 (8.48 % difference) and 5.9 MPa (5.9 % difference), respectively.

Outside of this range (i.e., in the grip zone), the graphs do not match the theoretical shear stresses due to the effects of the model boundary conditions. Gupta et al. [24] found the same end effect on their torsion model of structural lumber. They reported the same range of uniform stresses (2 times the depth plus the clamp length) and showed similar stress distribution in the grip zones.

Conclusions

Recent research studies have concluded that pure shear strength of dimensional lumber and structural composite lumber is most accurately determined using torsion tests as opposed to the ASTM shear block method or three or five point bending test methods. This research study involved torsional shear stress tests on 1.9E Eastern Species Laminated Veneer Lumber (LVL) of three different depths to evaluate pure shear strength and any related depth effect on shear strength. The key findings of the study are as follows:

The results indicated a slightly decreasing trend with increasing depth dimension. However, an Analysis of Variance (ANOVA) test result proved no significant difference between the means of the results and hence it was determined that depth does not affect torsional shear strength in 1.9E Eastern Species LVL within the range of depths tested (140, 184, and 235 mm).

The orthotropic shear stresses for 1.9E Eastern Species LVL on both in-plane and through-thickness directions were calculated based on the shear moduli of 2.0E Southern Pine. From a pooled data set of 36 specimens, the mean values were found to be 10.9 and 5.6 MPa for the in-plane and through-thickness shear strengths, respectively. Future tests to determine the shear moduli, G_{xz} and G_{yz}, specifically for 1.9E Eastern Species LVL, may benefit the accuracy of these results.

A Finite Element Study of a torsional shear test was carried out and the results compared favorably with the experimental results. Excluding the effects of boundary conditions, shear stresses were constant in a range of 2 times the depth plus the clamp length (76 mm) away from each end of the beam. Within this shear zone, the model was successful in predicting the shear stresses in both planes for laminated veneer lumber.

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