Holzforschung, Vol. 66, pp. 655–658, 2012 • Copyright © by Walter de Gruyter • Berlin • Boston. DOI 10.1515/hf-2011-0031

Short Note

Effect of grain angle on shear strength of Douglas-fir wood

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Abstract

The effect of grain angle (GA) on shear strength of Douglas-fir has been evaluated. Shear block specimens with a GA varying from 0 to 90° was loaded in the shear plane, resulting in failure mode transitioning from parallel to grain shear to rolling shear. As expected, shear strength decreased as the GA increased from 0° to 90°. A root-mean-square equation was found to be suitable to predict the relationship between GA and shear strength. Traditional Hankinson formula and the Tsai-Wu criteria were less effective with this regard.

Keywords: mechanical properties; rolling shear; timber mechanics; wood design; wood technology.

Introduction

Wood is an orthotropic material with longitudinal (L), tangential (T) and radial (R) planes of symmetry over which the properties differ significantly (Kretschmann 2011). Shear failure (ShF) may coincide with one of these planes; hence, six distinct modes of ShF are possible: TL, RL, LT, LR, RL and TR (Figure 1a). These six modes may be classified into one of the three groups of ShF: shear parallel ($\mathrm{Sh}_{\perp}$), perpendicular ($\mathrm{Sh}_{\perp}$) to grain and rolling shear ($\mathrm{Sh}_{\odot}$) (Figure 1a).

$\mathrm{Sh}_{\perp}$ occurs in the tangential- radial plane (TR) and, because a large number of primary bonds must be broken for its initiation, $\mathrm{Sh}_{\mathrm{str.}\ \perp}$ is very high (~30 MPa) (Schniewind 1979). However, $\mathrm{Sh}_{\mathrm{str.}\ \perp}$ occurs seldomly, as other modes of failure tend to supersede it. Therefore, $\mathrm{Sh}_{\perp}$ is generally not a concern for design (AFPA 2007a). Most often tested and documented is Sh, which occurs in longitudinal planes (LR and LT), and consists of wood fibers sliding past each other in the L direction, i.e. parallel to grain (G‖) (Figure 1a). Its magnitude is around 10 MPa depending on the species and other variables. As Sh‖ is relevant in members subjected to changing bending moments, it must be considered in calculations. The weakest forces are active, however, in $\mathrm{Sh}_{\odot}$ (3.5–5 MPa). $\mathrm{Sh}_{\odot}$ occurs in the TR plane, while the failure plane is $\mathrm{G}_{\perp}$; however, it induces $\mathrm{Sh}_{\mathrm{str.}}$ in a plane $\mathrm{G}_{\perp}$ direction (Schniewind 1979). Owing to low $\mathrm{Sh}_{\odot}$ stiffness of wood, significant shear deformation occurs. $\mathrm{Sh}_{\odot}$ is quite different from that of Sh‖; it consists of fibers rolling past one another and is preceded by large distortions of wood cell cross sections (Schniewind 1979).

The geometrical axes of wood members do not necessarily correspond with the local axes of the wood fiber as a result of cross grain or other natural defects. This can lead to conditions where Sh force is applied at a certain angle to wood fiber. For this reason, the relationship between angle of applied load with respect to grain angle (GA) and $\mathrm{Sh}_{\mathrm{str.}}$ in structural members is important. The literature is scarce in this regard.

Liu and Floeter (1984) determined $\mathrm{Sh}_{\mathrm{str.}}$ variation in the LT plane of Sitka spruce by Arcan shear test specimens (Iosipescu method). $\mathrm{Sh}_{\mathrm{str.}}$ was determined for the GAs 0° (Sh‖), 30°, 60° and 90° ($\mathrm{Sh}_{\odot}$). Although a close agreement with the strength theory (Tsai and Wu 1971) was observed, the $\mathrm{Sh}_{\mathrm{str.}}$ values were somewhat lower than those from the shear block test. Liu and Floeter (1984) demonstrated that as the GA increased from 0° to 30°, $\mathrm{Sh}_{\mathrm{str.}}$ decreased by over 43%. Reconsideration of a formula initially presented by Cowin (1979) closely predicted $\mathrm{Sh}_{\mathrm{str.}}$ at 30° and 60°. Xavier et al. (2009) analyzed failure modes qualitatively by Iosipescu (Arcan) Sh tests and observed a crack initiating at the notch root and propagating G‖ in LR specimen. The RT specimen failed in a brittle mode with crack propagating at about 45° to the horizontal axis. These observations were in agreement with the predicted finite element analyses results (Xavier et al. 2004).

Liu et al. (1999) studied $\mathrm{Sh}_{\mathrm{str.}}$ of Sitka spruce in planes ⊥ to LR and observed a weak relationship between $\mathrm{Sh}_{\mathrm{str.}}$ and GA. Liu and Ross (1997) presented a formula (similar to that of Hankinson) relating Sh modulus to GA. It showed that Sh modulus increases with a GA increment, from 0° to 45°. Similar results were observed for Southern pine lumber by Kretschmann (2008), while Gorlacher (2002) observed similar results for $\mathrm{Sh}_{\odot}$ modulus.

Various methods were developed to transform the GA-dependent properties (Bodig and Jayne 1982) in 2D (Hankinson 1921; AFPA 2007a) and in 3D (Goodman and Bodig 1970; Hermanson et al. 1997). Goodman and Bodig (1970) performed unconstrained, uniaxial compression tests on several wood species at different GA-to-load orientations and demonstrated a strong influence of GA on the effective modulus along the loading axis. Their theory was adequate when the principal material directions aligned with the loading direction. However, Hermanson et al. (1997) found an error in the equations of Goodman and Bodig and developed another algorithm for transformation of measured GAs and ring angles. Riyanto and Gupta (1996) conducted shear test G‖ on Douglas-fir with varying angles of ring orientation to

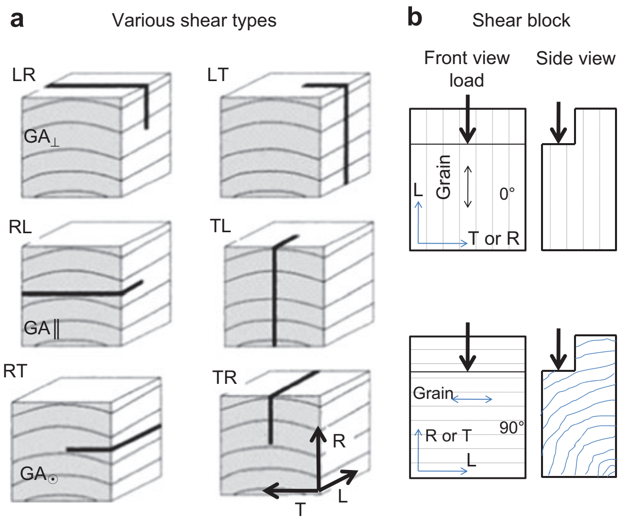

Figure 1 Abbreviations concerning the relation of shear load and grain (a) and shear block for tests illustrating two extreme angles between shear load and grain.

shear plane ranging from 0° (LT plane) to 90° (LR plane), with a 10° increment. While average $\text{Sh}_{\text{str.}}$ at the R Sh plane was 5% greater than that at the T Sh plane, no significant difference was observed between $\text{Sh}_{\text{str.}}$ values G at different ring angles.

$\text{Sh}_{\text{str.}}$ of wood is an important design-governing property and there is a pressing need to characterize quantitatively the $\text{Sh}_{\text{str.}}$ of wood as it varies with the GA. Literature is on this subject is limited. The objective of this study was to evaluate quantitatively $\text{Sh}_{\text{str.}}$ of wood in relation to shearing direction as failure mode transitions from Sh|| to $\text{Sh}_{\odot}$ of Douglas-fir. An expression will be presented to predict the relationship between GA and $\text{Sh}_{\text{str.}}$. Furthermore, the characteristic of the failure surfaces appearance between grain orientation and shear plane changes from 0° (G||) to 90° ($G_{\perp}$) should be investigated.

Materials and methods

Douglas-fir samples 38 mm×89 mm (nominal 2×4 inches) were prepared. Specimens were cut in such a manner that the Sh plane was always LR or LT, but the sliding direction changed from L (0°) to R or T (90°). The GA varied at 10° increments from G|| (0°) to $G_{\perp}$ (90°) (Figure 1b, 2a). In this manner, the theoretical mode of ShF was varied correspondingly from Sh|| (0°) to $\text{Sh}_{\odot}$ (90°). Between seven and 10 specimens for each Sh orientation were cut. A total of 85 specimens were fabricated for 10 different GAs (see Figure 2a).

Owing to the dimensions of the available lumber, specimens were cut so that the dimension ⊥ to Sh plane measured only 38 mm (1½ in) across. This produced a Sh specimen with a Sh plane area of 2581 mm^2 (4 in^2) and with identical geometry to the ASTM Sh block test specimen (ASTM 2009) with the exception that the ⊥ to Sh plane dimension measured 38 mm (1.5 in) rather than 51 mm (2 in). However, based on data from the literature, it can be assumed that the thinner specimens will have little impact on $\text{Sh}_{\text{str.}}$ (Kretchmann 1991, Gorlacher 2002). After cutting, the specimens were conditioned at 20°C and 65% relative humidity for approximately 1 week.

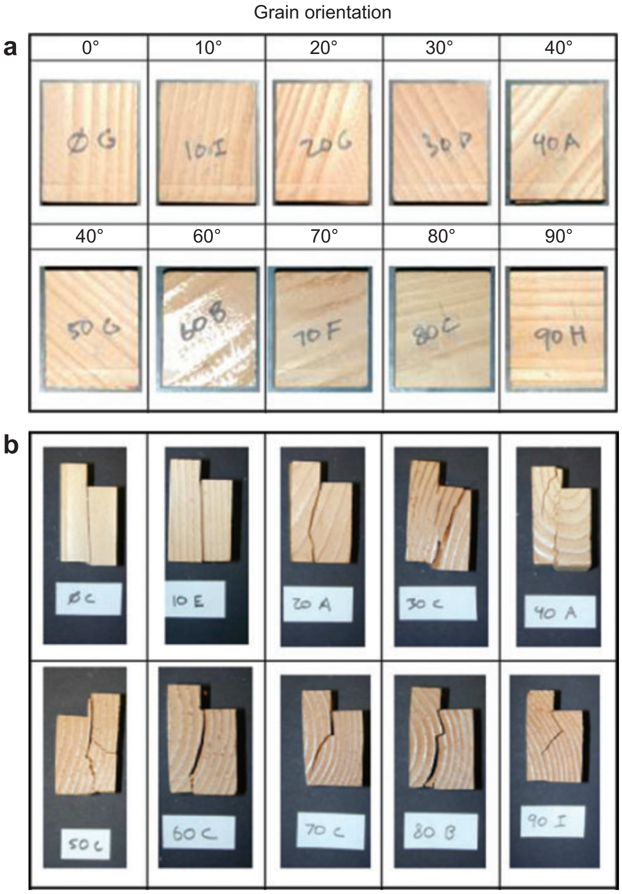

Figure 2 Shear block specimens with 0°, 45° and 90° grain orientation (a) and examples for failure modes for various grain angles (b).

Testing was performed in shear test jigs according to the ASTM standard D143 (ASTM 2009). Before testing, the dimensions and masses of each conditioned specimen were measured. Force was applied by an Instron machine at a rate of 1 mm min^{-1}. The $\text{Sh}_{\text{str.}}$ was determined by dividing the maximum load by the theoretical Sh plane area of 2581 mm^2 (4 in^2).

After failure, MC and specific gravity (SG) of each specimen was determined based on ASTM standards D4442 (ASTM 2007b) and D2395 (ASTM 2007c), respectively (Table 1).

Results and discussion

The mean $\text{Sh}_{\text{str.}}$ of each GA group is listed in Table 1. Irrespective of the failure mode, all strength values were included in the data analysis because the objective of the study was to find a relationship between strength as one of the inherent characteristics of the specimen and the GA. As expected, Table 1 reveals a decreasing trend in $\text{Sh}_{\text{str.}}$ with increasing GA, i.e. the failure mode is changing from Sh|| to $\text{Sh}_{\odot}$ with increasing GA. As indicated in the "Introduction" above, $\text{Sh}_{\odot}$ is about half to one third of Sh||. Figure 3 shows $\text{Sh}_{\text{str.}}$ as a function of GA for all specimens tested based on the fitted data of the following three failure theories: (i) Hankinson's theory (AFPA 2007a) described by Eq. (1); (ii) the Tsai and Wu (1971) theory

Table 1 Summary of test results depending on grain angle (GA).

GA (°)	*n*	$\text{Sh}_{\text{str.}}$ (MPa)	SG (g cm^3)	MC (%)	$\text{Sh}_{\text{str.}}$ predicted (MPa)
0	8	6.57±09	0.41	13.0	6.57
10	10	6.88±12	0.41	13.0	6.48
20	10	5.82±14	0.39	12.9	6.22
30	8	5.72±20	0.41	12.8	5.80
40	8	5.61±11	0.43	12.7	5.24
50	9	4.86±12	0.41	12.6	4.56
60	8	4.05±07	0.43	12.8	3.82
70	8	3.07±24	0.44	12.8	3.08
80	7	2.36±14	0.42	12.9	2.48
90	9	2.24±30	0.40	12.9	2.24

n, number of specimens; $\text{Sh}_{\text{str.}}$, shear strength; SG, specific gravity; MC, moisture content; $\text{Sh}_{\text{str.}}$ predicted by Eq. (3).

described by Eq. (2); and (iii) a root-mean-square (RMS) approach developed in this study, described in Eq. (3).

$$N=\frac{PQ}{PSin^2\theta+QCos^2\theta} \tag{1}$$

$$N=\sqrt{\frac{P^2Q^2}{PSin^2\theta+QCos^2\theta}} \tag{2}$$

$$N=\sqrt{P^2Cos^2\theta+Q^2Sin^2\theta} \tag{3}$$

where N is the estimated $\text{Sh}_{\text{str.}}$ at a GA of θ, P is the mean strength G‖ (θ=0°), Q is the mean strength $\text{G}_{\perp}$ (θ=90°) and θ=GA in degrees.

The performance of Eq. (1) is a poor predictor, with R^2=0.503 the $\text{Sh}_{\text{str.}}$ (GA from 10° to 70°). Similarly, Eq. (2) was also a poor predictor (R^2=0.313) of $\text{Sh}_{\text{str.}}$. The possible reason for the poor performance may be that the state of stress in shear block is not a pure shear, as will be explained later. However, the RMS approach (Eq. 3), provided an excellent agreement (R^2=0.811) with the experimental data through all GAs (Table 1).

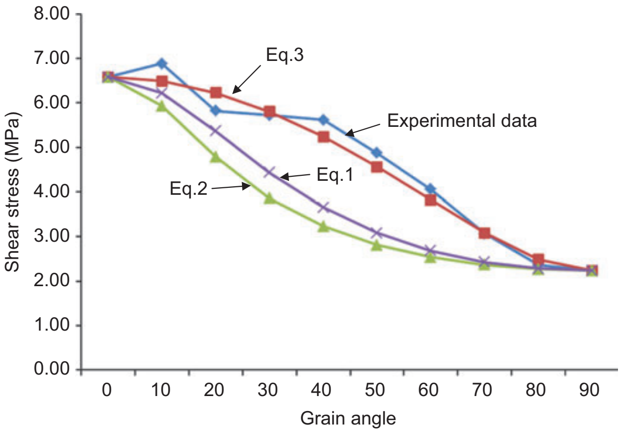

Figure 3 Relationship between shear strength and grain angle.

There are large discrepancies in the relationship between $\text{Sh}_{\text{str.}}$ and GA from our data and those of the literature. Liu and Floeter (1984) and Gorlacher (2002) found a decrease in $\text{Sh}_{\odot}$ of over 43% and 30%, respectively, between 0° and 30°. Over the same range, our specimens showed a 13% decrement. Liu and Floeter (1984) reported a decrease in $\text{Sh}_{\text{str.}}$ of 18% as opposed to our data of 44.7%. However, the total decrease in $\text{Sh}_{\text{str.}}$ from 0° to 90° of 65.2% (Liu and Floeter 1984) agrees with our findings (65.9% decrease). Xavier et al. (2009) observed, on average, a 71% decrease in $\text{Sh}_{\text{str.}}$ for maritime pine from 0° to 90°, which is slightly higher than our data. Similarly, Liu and Floeter (1984) reported lowering in $\text{Sh}_{\text{str.}}$ of 27.5% (30°–60°) compared with our results of 29%. Taking into consideration that the effect of varying GA on $\text{Sh}_{\text{str.}}$ is species dependent (Xavier et al. 2009) and that partly different methodology was used (shear block vs. Arcan), the deviations between the results of the quoted studies and those in the present study are not large.

Figure 2b shows typical failed specimens for each group. Failure in most specimens occurred to a large degree along the earlywood-latewood interface; the stronger latewood was seldom crossed. This type of failure mode is similar to the one observed by Riyanto and Gupta (1996) for varying GAs. Group 0° (Sh G‖) specimens typically exhibited ShF occurring more or less along the theoretical 2581 mm^2 (4 in^2) Sh plane. As the angle between applied load and wood grain increased, successive specimens exhibited increasingly irregular fracture patterns, which tended to zigzag across the theoretical shear plane. Xavier et al. (2009) reported a 45° crack propagation for $\text{G}_{\perp}$ loading. The difference is primarily a result of methodology (Shear block vs. Arcan). In group 70°, non-ShF began to be induced and such failures continued to increase through group 90° specimens. Two of the seven group 80° specimens reached maximum strain limit without attaining a definable maximum stress value. Of the nine group 90° specimens, at least seven exhibited non-ShF. In general, large strains typical of compression $\text{G}_{\perp}$ in combination with apparent $\text{G}_{\perp}$ tension failure at the re-entrant corner of the notch in the shear specimen, as well as multiple fracture paths of non-ShF modes was observed in groups 70°, 80°, and 90°.

Conclusions

ASTM D143 shear test specimen produces stress concentrations at the re-entrant corner of the specimen, which creates peak shear stresses greater than average shear stress. The ASTM method induces a moment that further detracts from measurement of pure $\text{Sh}_{\text{str.}}$. It is possible that more elaborated tests will better reflect the true effect of varying GA on $\text{Sh}_{\text{str.}}$. A 3D transformation could also be useful in case of species with multi-axial stresses.

Acknowledgements

The assistance of John Bannister in the conducting the tests, Craig Basta and Scott Kent in analyzing the data, and Milo Clauson in instrumentation is appreciated.

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Received February 23, 2011. Accepted February 16, 2012.