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° were 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 (Sh∥) perpendicuar (Sh⊥) to grain and rolling shear (Shθ) (Figure 1a).

Sh∥ occurs in the tangential-radial plane (TR) and, because a large number of primary bonds must be broken for its initiation, Sh∥ is very high (~30 MPa) (Schniwewind 1979). However, Shθ occurs seldomly, as other modes of failure tend to supersede it. Therefore, Shθ 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 (GIl) (Figure 1a). Its magnitude is around 10 MPa depending on the species and other variables. As Shθ is relevant in members subjected to changing bending moments, it must be considered in calculations. The weakest forces are active, however, in Shθ (3.5–5 MPa). Shθ occurs in the TR plane, while the failure plane is G∥; however, it induces Sh∥ in a plane G∥ direction (Schniwewind 1979). Owing to low Sh∥ stiffness of wood, significant shear deformation occurs. Shθ is quite different from that of Shθ; it consists of fibers rolling past one another and is preceded by large distortions of wood cell cross sections (Schniwewind 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 Shθ in structural members is important. The literature is scarce in this regard.

Liu and Floeter (1984) determined Shθ variation in the LT plane of Sitka spruce by Arcan shear test specimens (Iosipescu method). Shθ was determined for the GAs 0° (Shθ), 30°, 60° and 90° (Shθ). Although a close agreement with the strength theory (Tsai and Wu 1971) was observed, the Shθ 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°, Shθ decreased by over 43%. Reconsideration of a formula initially presented by Cowin (1979) closely predicted Shθ 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 GIl 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 Shθ of Sitka spruce in planes ⊥ to LR and observed a weak relationship between Shθ 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 Shθ 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 GIl on Douglas-fir with varying angles of ring orientation to
shear plane ranging from $0^\circ$ (LT plane) to $90^\circ$ (LR plane), with a $10^\circ$ increment. While average $S_{str}$ at the R Sh plane was 5% greater than that at the T Sh plane, no significant difference was observed between $S_{str}$ values at different ring angles.

$S_{str}$ of wood is an important design-governing property and there is a pressing need to characterize quantitatively the $S_{str}$ of wood as it varies with the GA. Literature is on this subject is limited. The objective of this study was to evaluate quantitatively $S_{str}$ of wood in relation to shearing direction as failure mode transitions from Sh|| to Sh/ as GA varies from $G_{\|}$ ($0^\circ$) to $G_{\perp}$ ($90^\circ$). An expression will be presented to predict the relationship between GA and $S_{str}$. Furthermore, the characteristic of the failure surfaces appearance between grain orientation and shear plane changes from $0^\circ$ ($G_{\|}$) to $90^\circ$ ($G_{\perp}$) 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 ($0^\circ$) to R or T ($90^\circ$). The GA varied at $10^\circ$ increments from $G_{\|}$ ($0^\circ$) to $G_{\perp}$ ($90^\circ$) (Figure 1b, 2a). In this manner, the theoretical mode of ShF was varied correspondingly from Sh|| ($0^\circ$) to Sh/ ($90^\circ$). 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 $\perp$ to Sh plane measured only 38 mm (1 ½ 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 $\perp$ 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 $S_{str}$ (Kretchmann 1991, Gorlacher 2002). After cutting, the specimens were conditioned at 20°C and 65% relative humidity for approximately 1 week.

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 $S_{str}$ 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 $S_{str}$ 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 $S_{str}$ with increasing GA, i.e. the failure mode is changing from Sh|| to Sh/ with increasing GA. As indicated in the “Introduction” above, Sh/ is about half to one third of Sh||. Figure 3 shows $S_{str}$ 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).

<table>
<thead>
<tr>
<th>GA (°)</th>
<th>n</th>
<th>Sh_{str} (MPa)</th>
<th>SG (g cm⁻³)</th>
<th>MC (%)</th>
<th>Sh_{str} predicted (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8</td>
<td>6.57±09</td>
<td>0.41</td>
<td>13.0</td>
<td>6.57</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>6.88±12</td>
<td>0.41</td>
<td>13.0</td>
<td>6.48</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>5.82±14</td>
<td>0.39</td>
<td>12.9</td>
<td>6.22</td>
</tr>
<tr>
<td>30</td>
<td>8</td>
<td>5.72±20</td>
<td>0.41</td>
<td>12.8</td>
<td>5.80</td>
</tr>
<tr>
<td>40</td>
<td>8</td>
<td>5.61±11</td>
<td>0.43</td>
<td>12.7</td>
<td>5.24</td>
</tr>
<tr>
<td>50</td>
<td>9</td>
<td>4.86±12</td>
<td>0.41</td>
<td>12.6</td>
<td>4.56</td>
</tr>
<tr>
<td>60</td>
<td>8</td>
<td>4.05±07</td>
<td>0.43</td>
<td>12.8</td>
<td>3.82</td>
</tr>
<tr>
<td>70</td>
<td>8</td>
<td>3.07±24</td>
<td>0.44</td>
<td>12.8</td>
<td>3.08</td>
</tr>
<tr>
<td>80</td>
<td>7</td>
<td>2.36±14</td>
<td>0.42</td>
<td>12.9</td>
<td>2.48</td>
</tr>
<tr>
<td>90</td>
<td>9</td>
<td>2.24±30</td>
<td>0.40</td>
<td>12.9</td>
<td>2.24</td>
</tr>
</tbody>
</table>

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

There are large discrepancies in the relationship between Sh_{str} and GA from our data and those of the literature. Liu and Floeter (1984) and Gorlacher (2002) found a decrease in Sh_{str} 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 Sh_{str} of 18% as opposed to our data of 44.7%. However, the total decrease in Sh_{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 Sh_{str} for maritime pine from 0° to 90°, which is slightly higher than our data. Similarly, Liu and Floeter (1984) reported lowering in Sh_{str} of 27.5% (30°–60°) compared with our results of 29%. Taking into consideration that the effect of varying GA on Sh_{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 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 G_{||} 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 G_{⊥} 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 Sh_{str}. It is possible that more elaborated tests will better reflect the true effect of varying GA on Sh_{str}. A 3D transformation could also be useful in case of species with multi-axial stresses.

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References


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