RELATIONSHIP BETWEEN COMPRESSION STRENGTH PERPENDICULAR TO GRAIN AND RING ORIENTATION

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ABSTRACT
This study described the effect of ring angle on the stress at 0.04-inch (1.02-mm) deformation in compression perpendicular to grain for dahurian larch (Larix dahurica). Ring angle is the angle between direction of load and direction of growth rings. Results indicated that compressive strength perpendicular to the grain depends on orientation of the growth rings. When stress at 0.04-inch deflection is used as the strength property, we found that it related to grain angle in an approximately quadratic way.

Published reports of strength in compression perpendicular to grain1 as a function of orientation of growth rings are limited. The Wood Handbook,2 in its several editions, explains that the proportional limit (PL) in compression perpendicular to grain varies with angle between growth rings and direction of applied stress. The Wood Handbook has evolved in how it quantifies that observation, from the first edition (circa 1935) to the current 1987 edition. The current edition indicates that the PL is about equal when ring angle is 0 and 45 degrees, but higher at 90 degrees. It notes that for some species, the PL at 0 and 90 degrees will be about equal, but lower at 45 degrees.

In the 1970s, interest developed in a design strength property higher than the PL.3 Eventually, the stress at 0.04-inch (1.02-mm) deflection (S0.4) measured in the ASTM D 143 test was studied and adopted for such uses as establishing allowable design properties for stress-graded lumber.4 To our knowledge, how this newly defined property behaves as a function of growth ring angle has not been studied. In the work reported here, we examined the relationship of S0.4 to ring angle as part of a larger effort on stress grades and allowable properties of dahurian larch (Larix dahurica) lumber.

Our study involved specimens 1-1/2 inches (38.1 mm) thick, taken from nominal 2- by 4-inch (standard 38- by 89-mm) lumber. They were thinner than the ASTM D 143 specimen. We did not test specimens at the standard 2-inch (50.8-mm) thickness and do not have direct evidence that S0.4 is unaffected by specimen thickness. However, Kunesh5 tested specimens according to ASTM D 143 specifications. The specimens were 1/4 inch (6.35 mm), 1 inch (25.4 mm), and 2 inches thick. He noted the effect of thickness on stress at PL, on a stress somewhat above PL but less than S0.4, and on a stress considerably above S0.4. He reported no effect of specimen depth on stress at PL or at the intermediate deflection level. He also noted no effect on maximum load between 1- and 2-inch-deep specimens. Thus, the Kunesh results suggest there would be no significant difference in stress at 0.04-inch deflection for standard 2-inch-thick specimens and for our 1-1/2-inch-thick specimens.

EXPERIMENTAL
Our sample consisted of 323 specimens of larch, 1-1/2 by 2 by 6 inches (152.4 mm), each taken from a clear, straight-grained portion of a separate 2 by 4, 12 feet (3.66 m) long. The larch was obtained north of Vladivostok, Russia, in equal numbers from two stands about 50 miles (80.5 km) apart. Trees ranged from 160 to 200 years old. On the average, the specimens had 29 growth rings per inch (11.4 per cm) and were 39 percent summerwood.

The specimens were conditioned to 15 percent equilibrium moisture content and tested in compression perpendicular to grain. The results for each angle were analyzed with an analysis of variance. The null hypothesis was that there was no significant difference among the mean stress values. The data from the test showed that stress at 0.04-inch deflection was significantly influenced by ring angle, and the value of S0.4 increased as ring angle increased from 0 to 90 degrees. The study also showed that the relationship between stress and ring angle was quadratic, with the highest stress occurring at a ring angle of 45 degrees.
to the 2-inch-wide face according to ASTM D 143. Loads and corresponding deflections were recorded with a computer-controlled data acquisition unit. An approximately 1-inch cross-sectional slice was taken immediately after testing and used to measure moisture content at time of test, specific gravity (SG) with volume at time of test, growth rate, percent summerwood, and growth ring angle (Fig. 1).

A single operator drew a representative radial line on the slice. This line was used to estimate ring angle; therefore, the angles measured depended on the selection of the radial line. The angle between the radial line and the 2-inch face of the specimen was measured with a protractor. Although we could easily estimate the angle within 2 or 3 degrees, we recorded it in 5-degree increments. The complement of the measured angle is the angle between direction of load and tangent to the growth rings (Fig. 1).

There was no effort to select ring angle when the specimens were made, and unlike the standard ASTM D 143 specimen, the angle between growth ring and load direction was uncontrolled. Figure 2 is a histogram of ring angle, showing that all 5-degree classes were well represented, with a greater frequency of occurrence in the classes from 20 to 60 degrees.

Stress at 0.04-inch deflection was determined by fitting a straight line by least squares to the linear portion of the load-deflection curve for each specimen (Fig. 3). Selection of the straight line portion was subjective and was done by a single operator. The line was extrapolated back to zero load to establish an origin. The load at 0.04-inch deflection, measured from that origin, was divided by bearing area to give $S_{0.04}$.

**RESULTS**

Table 1 summarizes the test statistics. When regressed on SG, $S_{0.04}$ was significantly, but not strongly, related with a coefficient of determination of 0.18 (sample value of Student's $t$-test $= 7.11$). Examination of a scatter plot gave no reason to use other than a straight line. Using that regression, all values of $S_{0.04}$ were adjusted to the average SG of 0.539 to remove the effect of SG variation. In the discussion that follows, all values of $S_{0.04}$ are the adjusted values.

Figure 4 is a plot of $S_{0.04}$ as a function of ring angle for the 232 specimens. It would clearly be represented by a curvilinear function, however, the visual representation is somewhat misleading. Some of the plotted points represent multiple specimens, and with such a large sample size, it is difficult to visualize the distribution of strengths at any selected ring angle.

We looked at a freehand fit of a curve to the data in Figure 4, at a curve fit to the average $S_{0.04}$ by ring angle class, and at Hankinson's formula. Each is subjective, however, and especially so when

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**TABLE 1.** Properties of 232 dahurian larch samples.  

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td></td>
</tr>
<tr>
<td>Average (%)</td>
<td>15.1</td>
</tr>
<tr>
<td>COV (%)</td>
<td>6.8</td>
</tr>
<tr>
<td>Specific gravity</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.539</td>
</tr>
<tr>
<td>COV (%)</td>
<td>11.7</td>
</tr>
<tr>
<td>Stress ($S_{0.04}$)</td>
<td></td>
</tr>
<tr>
<td>Average (psi)</td>
<td>857</td>
</tr>
<tr>
<td>COV (%)</td>
<td>25.2</td>
</tr>
</tbody>
</table>

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1 COV = coefficient of variation.  
2 Based on oven-dry weight and moisture content at time of test.
Figure 4. — Stress at 0.04-inch (1.02-mm) deflection plotted against ring angle for 232 specimens. The fitted quadratic equation is superimposed.

data points represent multiple specimens. Believing that Hankinson's formula had some boundary characteristics that made it appealing, we attempted to develop a least-squares and a least-deviations representation that would be more objective. Both of those pursuits, however, became mathematically onerous. Finally, we simply fit a third-order polynomial by least-squares and found that the coefficient of determination increased from 0.15 to 0.31 by adding the second power to the first, but did not increase at all by adding the third power. Thus, we settled on the second-order polynomial expressed as:

$$S_{04} = 886 - 7.43 \text{ (RA)} + 0.117 \text{ (RA)}^2$$

where RA is the ring angle in degrees and $S_{04}$ is in psi.

The polynomial is superimposed over the data plot in Figure 4 for visual comparison. At the extremes, it has values of $S_{04}$ of 886 psi (6.109 MPa) and 1,165 psi (9.357 MPa) for 0 and 90 degrees, respectively. The standard error of any predicted value of $S_{04}$ depends on ring angle but is on the order of 164 psi (1.131 MPa). If divided by ordinates of the curve, it gives a sort of rolling coefficient of variation, which ranges from 14 to 20 percent.

Looking back at the rules of thumb relating strength to ring angle found in the Wood Handbook, this larch seems to display a hybrid of those rules (recognizing that the Wood Handbook observations had to do with PL and our observations deal with $S_{04}$). That is, we clearly have the property at 90 degrees exceeding that at 0 degrees. However, the property at 45 degrees is lower than either boundary value. The property at 45 degrees is calculated at 789 psi (5.440 MPa), 68 percent of that in the radial or 90-degree direction and 89 percent of that in the tangential or 0-degree direction.

Although we should not rely too heavily on our equation, which is fitted to only one data set, it is easy to determine that the minimum occurs at 31.8 degrees and the corresponding property is 768 psi. What can be safely said, based on the scatter diagram as well as the function, is that the lowest property is found for ring angles in the range of about 30 to 50 degrees. The minimum property for the function is approximately 750 psi (5.171 MPa) and is 65 to 85 percent of the property perpendicular and parallel to the growth rings.

CONCLUSIONS

Our study of dahurian larch supports the concept that compressive strength perpendicular to grain depends on the orientation of growth rings in the test specimen. When stress at 0.04-inch deflection is used as the strength property, we found that it is related to grain angle in an approximately quadratic way. The property is highest with load at 90 degrees to the growth rings (radial stress), lowest with stress at some intermediate angle of roughly 30 degrees to 50 degrees, and intermediate at 0 degrees (tangential stress). At any ring angle, strength is variable, on the order of ±15 to 20 percent.