Abstract
When logs of three diameter classes and two specific gravity classes were sheared with a 3/8-inch-thick knife travelling at 2 inches per minute, shearing force and work averaged greatest for dense 13.6-inch logs cut with a knife having a 45° sharpness angle (73,517 pounds; 49,838 foot-pounds). Force and work averaged least for 5.1-inch bolts of low density when cut with a knife having 22-1/2° sharpness angle (9,975 pounds; 2,885 foot-pounds). Values for 9.7-inch bolts were intermediate. Shear force reached a maximum about three-fourths the way through the log; it then dropped rapidly as the knife travelled the remaining distance. Momentary peaks of force commonly occurred near the three-quarter point. The greatest observed force to shear was 92,000 pounds required for a 13.6-inch log of 0.51 specific gravity (oven-dry weight and green volume) when cut with a knife having 45° sharpness angle. When sheared logs were viewed in radial section, each annual ring showed a check at the earlywood-latewood boundary. Checks were least severe in small logs sheared with the 22-1/2° knife, where they averaged 0.8 inch deep; they were most severe in large logs of low density sheared with the 45° knife, where they averaged 1.4 inches deep. Each sheared log generally also had one to several rather lengthy checks that formed just prior to emergence of the knife. Regression expressions were developed to predict force and work to shear as well as average and maximum check depth—all in terms of sharpness angle, wood specific gravity, and log diameter.

The work reported here is an extension of a general study of orthogonal cutting of southern pine wood (12).

When a knife is arranged to cut across the grain against an anvil or opposing knife, and the chip and the workpiece are of about equal thickness (visualize rose stems cut with pruning shears), the process is described as shearing (Fig. 1). Shears to fell trees or reduce long logs to pulpwood lengths are in common use. Published research is chiefly on species other than southern pine, but it defines principles that probably are widely applicable (1, 3, 4, 5, 6, 7, 8, 10, 11).

In general, shear forces are less in warm than in frozen wood, less in clear than in knotty wood, less in heartwood than in sapwood, less in low-density than in dense wood, and less where the shearing direction is perpendicular rather than parallel to the annual rings. Above the fiber saturation point, moisture content apparently makes little difference in the force required to shear.

The work reported here is an extension of a general study of orthogonal cutting of southern pine wood (12).

When a knife is arranged to cut across the grain against an anvil or opposing knife, and the chip and the workpiece are of about equal thickness (visualize rose stems cut with pruning shears), the process is described as shearing (Fig. 1). Shears to fell trees or reduce long logs to pulpwood lengths are in common use. Published research is chiefly on species other than southern pine, but it defines principles that probably are widely applicable (1, 3, 4, 5, 6, 7, 8, 10, 11).

In general, shear forces are less in warm than in frozen wood, less in clear than in knotty wood, less in heartwood than in sapwood, less in low-density than in dense wood, and less where the shearing direction is perpendicular rather than parallel to the annual rings. Above the fiber saturation point, moisture content apparently makes little difference in the force required to shear.

The friction coefficient between a steel knife and green wood is approximately 0.2. Greasing the knife does not reduce shearing forces greatly; Teflon surfaces on the cutter are more effective. Axial loads (simulating the weight of a standing tree) do not appreciably increase shearing forces. Lateral vibration of the cutter reduces shear forces required, as does tapering the cutter plate (Fig. 2A) to give clearance between the plate and the wood. In a review of Russian work, Kubler (9) reported that vibration in the feed direction also reduces shear forces required.
For parallel-sided cutters (Fig. 2B), thin blades shear with less force than thick blades. Blades tapered so that the plate near the cutting edge is thin and the root thick (Fig. 2C) require forces intermediate to thin and thick plates without taper. Sharp blades shear with less force than dull blades. In comparison with a straight edge, an edge in the shape of an open V does not appreciably lessen forces. Shear force is least when the specimen is cut between opposing knives; if cutting is by a single knife against an anvil, a narrow anvil requires less force than a wide one.

The quality of sheared ends is impaired—i.e., knife-induced splits tend to be deep—if the wood is frozen, the knife dull, or the blade thick. McIntosh and Kerbes (10) found that lumber losses from splitting were less than 1 percent when lodgepole pine (Pinus contorta Dougl.) and white spruce (Picea glauca var. glauca) trees less than 14 inches in diameter were sheared at 45°F. Prior to shearing, the green logs had been stored for several months under a water spray; moisture content was determined immediately after each log was sawed. As has been noted, cutting velocity was 2 inches per minute. The literature indicates that cutting velocity apparently has little effect on shear. Hoel (2) has reported that the portion of loblolly pine bolts, 8-1/2 feet long, was obtained in central Louisiana. Factors in the experiment were:

1) Diameter class: 12, 9.7, and 13.6 inches inside bark
2) Specific gravity (green volume and oven-dry weight): 0.40-0.46 and 0.47-0.52 as determined by averaging the values of disks sawn from both ends of each bolt
3) Sharpness angle: 22-1/2 and 45°
4) Replications: three

A stratified random sample of green southern pine bolts, 8-1/2 feet long, was obtained in central Louisiana. Factors in the experiment were:

1) Diameter class: 5.1, 9.7, and 13.6 inches inside bark at midlength
2) Specific gravity (green volume and oven-dry weight): 0.40-0.46 and 0.47-0.52 as determined by averaging the values of disks sawn from both ends of each bolt
3) Sharpness angle: 22-1/2 and 45°
4) Replications: three

Thus, the experiment required 36 bolts: (three diameters) (two specific gravities) (two sharpness angles) (three replications). Each log was sheared at midlength regardless of knot locations, with bark in place, and at wood temperatures in the range 60 to 80°F. Prior to shearing, the green logs had been stored for several months under a water spray; moisture contents were determined immediately after each log was sheared. As has been noted, cutting velocity was 2 inches.
per minute. The mild-steel knife was 3/8-inch thick with parallel sides; anvil width was 10-3/4 inches (Figs. 1, 3). The knife was sharpened by grinding to 22-1/2° at the beginning of the experiment and became progressively duller as half the logs were sheared; it was then resharpened to 45°, and the remaining logs were sheared.

Cutting force was continuously graphed in relation to knife position as the knife passed through each log. After each log had been sheared, the two pieces were split on a diameter line parallel to the knife travel, and the sheared end stained to reveal checks and splits caused by the knife. Average and maximum check depths were determined.

<table>
<thead>
<tr>
<th>Average Log Diameter Inside Bark and Specific Gravity</th>
<th>22-1/2° Sharpness Angle</th>
<th>45° Sharpness Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force (pounds)</td>
<td>Work (foot-pounds)</td>
<td>Check Depth (inch)</td>
</tr>
<tr>
<td>9,975</td>
<td>2,885</td>
<td>0.8</td>
</tr>
<tr>
<td>12,533</td>
<td>4,506</td>
<td>.8</td>
</tr>
<tr>
<td>22,900</td>
<td>13,618</td>
<td>1.0</td>
</tr>
<tr>
<td>36,300</td>
<td>20,637</td>
<td>1.0</td>
</tr>
<tr>
<td>0.40 - 0.46</td>
<td>55,933°</td>
<td>.9</td>
</tr>
<tr>
<td>0.47 - 0.52</td>
<td>47,967°</td>
<td>1.1</td>
</tr>
</tbody>
</table>

*Cutting velocity 2 inches per minute. Each value is an average of three replications.

*Based on green volume and oven dry weight.

*Values are high because these three low-gravity logs averaged 15.1 inches in diameter, whereas the three high-gravity logs cut with the 22-1/2° knife averaged only 13.3 inches in diameter.
Results

Data for logs of the three diameters and two specific gravity classes are shown for each sharpness angle in Table 2. In Table 3 the effects of primary variables are tabulated. Values found significantly different (0.05 level) by analysis of variance appear below an asterisk. The values in Table 3 are derived from the data in Table 2; i.e., under the heading Diameter of bolt, each value is a 12-log average; those under the headings of Specific gravity and Sharpness angle are 18-log averages.

Check depth was unaffected by log diameter, but interacted with specific gravity and sharpness angle. Thus with the 22½° knife, specific gravity of the wood had little effect on check depth (Table 2); with the 45° knife, check depth was significantly greater in low-gravity wood (1.4 inches) than in high-gravity wood (1.2 inches).

Table 3. — TABULATION OF THE EFFECTS OF PRIMARY VARIABLES (FROM TABLE 2).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Maximum Force (pounds)</th>
<th>Work to Shear (foot-pounds)</th>
<th>Average Check Depth (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12,569</td>
<td>3,980</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>33,121</td>
<td>18,594</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>57,338</td>
<td>39,415</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30,885</td>
<td>18,275</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>37,800</td>
<td>23,051</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30,935</td>
<td>19,409</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>37,750</td>
<td>21,918</td>
<td>1.3</td>
<td></td>
</tr>
</tbody>
</table>

Shearing force and work to shear averaged greatest for dense 13.6-inch logs cut with a knife having a 45° sharpness angle (73,517 pounds, 49,838 foot-pounds), and were least for low-density, 5.1-inch bolts cut with a knife having 22½° sharpness angle (9,975 pounds, 2,885 foot-pounds). Shear force built to a maximum about three-fourths the way through the log; it then dropped rapidly as the knife travelled the remaining distance. A momentary peak of force commonly occurred near the three-quarter point (Fig. 4, top).

At a cutting velocity of 2 inches per minute and with cutter thickness constant at 3/8-inch, shearing force (F, pounds) of green southern pine at 60 to 80°F. can be expressed in terms of bolt diameter inside bark (inches), sharpness angle (θ, degrees), and wood specific gravity (oven-dry weight and green volume).

For green southern pine logs sheared with bark in place, shearing force is:

\[ F_\text{s} = -76,268 + 5,173 \times \text{diameter} + 104,485 \times \text{specific gravity} + 373 \times \text{sharpness angle} \]

Figure 4. — Force to shear green southern pine logs. (Top) Force related to knife travel when shearing green southern pine logs in three diameter classes (5.1, 9.7, and 13.6 inches). Circles defining curves each represent information from 12 logs; i.e., data from both high- and low-gravity logs and from both 22½° and 45° knife angles were pooled. The solid point above each curve shows the average (and position of occurrence) of maximum peak forces that lasted only momentarily; the peaks tended to occur when the knife was about three-quarters through each log. (Bottom) Relationships between maximum shearing force and factors of log diameter, specific gravity (basis of green volume and oven-dry weight), and sharpness angle. Curves were plotted from regression equation 1 by holding all factors but the one of interest at average value. Average log diameter was 9.51 inches; average specific gravity was 0.467.

Figure 5. — Relationships between work to shear and factors of log diameter, specific gravity (basis of green volume and oven-dry weight), and sharpness angle. Graphs were plotted from regression Equation [2] by holding all factors but the one of interest at average value. Average log diameter was 9.51 inches, and average specific gravity was 0.467.
This equation is graphed in Figure 4 (bottom). Within the range of the factors tested (sharpness angles 22-1/2 to 45°, bolt diameters 5 to 15 inches, and specific gravity on oven dry weight and green volume basis 0.40 to 0.52), Equation [1] accounted for 81 percent of the variation. Standard error of the estimate was 9,680 pounds.

Work to shear (foot-pounds) is expressed:

\[
\text{Work} = -71,538 + 4,048 \text{ (diameter)} + 102,589 \text{ (specific gravity)} + 171 \text{ (sharpness angle)} \tag{2}
\]

Within the range of the study, Equation [2] accounted for 93 percent of the variation. Standard error of the estimate was 4,500. The equation is graphed in Figure 5.

Because machine builders must design for the maximum shear force expected, it is of interest that, with a knife having 45° sharpness angle, one 13.6-inch-diameter log of 0.51 specific gravity required 92,000 pounds to shear through a knot cluster. To shear 20-inch southern pine logs of high density with this—or a thicker—knife, it is likely that forces in excess of 100,000 pounds would occasionally be required.

When sheared logs were viewed in radial section, each annual ring showed a check at an earlywood-latewood boundary (Fig. 6B). Checks were least severe in the smallest logs sheared with the 22-1/2° knife, where they averaged 0.8 inch deep; they were most severe in the larger logs of low density sheared with the 45° knife, where they averaged 1.4 inches deep.

In addition to the shallow checks shown in Figure 6B, one to several rather lengthy checks (Fig. 6C) generally formed in each sheared log just prior to emergence of the knife.

At a cutting velocity of 2 inches per minute, with cutter thickness constant at 3/8-inch, average check depth (inches) of green southern pine sheared at 60 to 80°F. can be expressed in terms of bolt diameter inside bark (inches) and sharpness angle (°, degrees). Wood specific gravity proved to be not significant.

\[
\text{Average check depth} = 0.411 + 0.0147 \text{ (diameter)} + 0.0172 \text{ (sharpness angle)} \tag{3}
\]

Within the range of factors tested, Equation [3] accounted for 55 percent of the variation with standard error of the estimate of 0.19 inch.
In an equation for maximum check depth in inches (ignoring the large splits occurring near knife emergence), only sharpness angle was significant:

\[
\text{Maximum check depth} = 0.0944 + 0.0588 \times \text{sharpness angle} \quad [4]
\]

Equation [4] accounted for 39 percent of the variation with standard error of the estimate of 0.85 inch.

Equations [3] and [4] describe checks illustrated in Figure 6B; the check (or checks) found near knife emergence were much longer, as illustrated in Figure 6C.

Literature Cited