THE INFLUENCE OF SMALL GRAIN ANGLE VARIATION ON TOUGHNESS

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ABSTRACT

Toughness of solid wood as determined by ASTM D143-52 is known to be sensitive to slope-of-grain in the specimen. Although samples with observed sloping grain are routinely rejected, localized grain deviations in the center of nominally straight-grained specimens may escape detection. The acceptance of this sample is often aided by the difficulty in identifying the grain orientation at a point and by the usual large number of toughness tests that are conducted in any one experiment. In this study 226 standard toughness specimens of redwood were carefully machined to be straight-grained. However, close scrutiny of the center of the specimens (often after they had been failed) showed that only 10 of the 226 samples had truly straight grain and that localized grain deviations ranged from zero to 15°. Regression analysis showed that the slope-of-grain on the specimen face parallel to the impact direction explained a significant amount of variation in toughness. If this slope was accounted for, the coefficients of variation of toughness were reduced from 33 and 30% to 22 and 18% for impact in the radial and tangential direction, respectively. The results of the study showed that toughness was very sensitive to small localized grain deviations and that truly straight-grained toughness samples are rare. A significant amount of the usual high variation in toughness data could be attributed to these small grain deviations.

Keywords: Toughness, redwood, slope-of-grain.

INTRODUCTION

The shock resistance of wood is often evaluated with a single-blow impact test of a 2- × 2- × 28-cm specimen as outlined in ASTM D143-52 (ASTM 1980). The quantitative result of this test is toughness, which is a measure of the energy required to cause rapid failure in a simply supported, centrally loaded beam. Of the many properties of wood, toughness or shock resistance has been found to be the most sensitive to effects of fungal or chemical attack or prolonged exposure to elevated temperature. Because of this sensitivity, the toughness test has served as a rapid and inexpensive means of assessing the influence of a wide variety of stimuli on the strength of wood (Sinclair et al. 1979). Toughness has also served as the basis for selecting wood requiring a high degree of shock resistance (Gerhards 1968; USDA 1974).

Although wood is an inherently variable material, the modulus of rupture (MOR) or ultimate bending strength of defect-free, straight-grained wood, evaluated according to the methods of ASTM D143, exhibits a coefficient of variation (CV) of less than 20% (ASTM 1980). However, toughness, which is essentially an impact bending test and should be related to MOR, consistently exhibits a much higher degree of variability. For example, Gerhards (1968) reports values of the CV near 30%, and the Wood Handbook (USDA 1974) suggests 34% as a representative value.

This variability may be explained by the very sensitivity of the property to subtle changes in the anatomical structure or chemical composition of the material.

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Additionally, other authors have cited moisture content (Gerhards 1968), density (Wengert 1979), annual ring orientation (Keith 1966), size variation and test procedures (Gerhards 1968) as contributing factors.

The effect of grain angle on the bending strength of wood is well known and documented (USDA 1974). Ghelmeziu (1937/38) (as reported in Kollman and Côté 1968) has shown that there was a very significant influence of grain angle on the shock resistance of beech. Additionally, a sigmoidal-shaped empirical relationship (similar to Hankinson 1921) described the relationship between impact work and the increase in angle between the specimen axis and fiber direction. Ghelmeziu indicated that a 5 degree deviation in grain angle resulted in a very significant reduction in impact bending resistance.

From this information the hypothesis was formed that small deviations in grain angle in the immediate area of the impact point on the ASTM specimen may contribute to the overall variability in toughness. These deviations from straight grain could be due to the inherent variability of wood or to slight mismanufacturing of a relatively small specimen. The latter is more likely if the angle is on the tangential face where the grain is less distinguishable in many species. If these defects were localized and were relatively small, they might be overlooked in specimen manufacture. In many cases it is quite likely that a sloping grain would not be detected without a close examination of the failed surface of the sample after the test. A confounding factor is the large number of toughness samples usually tested in any one experiment, which may facilitate the acceptance or overlooking of relatively small angle deviations.

There are two possible grain angles or slopes on a toughness sample as shown in Fig. 1. For the purpose of this discussion, the slope S1 is defined as the slope-of-grain on the face of the sample parallel to the direction of impact. Slope S2 is the slope-of-grain on the face normal to the impact. All slopes are relative to the machined edges of the specimen. It is not immediately apparent which of these two angles would have the greatest impact on toughness or if a combination of the two is a key factor. Therefore, the objectives of this study were to assess the localized slope-of-grain in the center of nominally straight-grained toughness samples and to examine the influence of these small deviations on radial and tangential toughness.

METHODS AND MATERIALS

The test materials used in the study came from five pieces of redwood dimension lumber. Initially, the study was limited to samples tested in the radial direction (impact on the tangential face), and later tests in the tangential direction (radial face impact) were added. Hence, the samples tested in the two directions were not matched. However, the lumber was all of similar quality, and the density variation between pieces was minimized in the selection process. Redwood was selected because of its availability, even texture, and relative straight grain. The latter qualities facilitated measurement of the grain angle and specimen manufacture. The specimens were machined to the standard ASTM dimension and the growth rings oriented in each sample such that the orthotropic axes were aligned with the principal axes of the cross section. The samples were machined so that they were nominally straight-grained—that is, to the naked eye, the samples did not contain a general grain deviation.

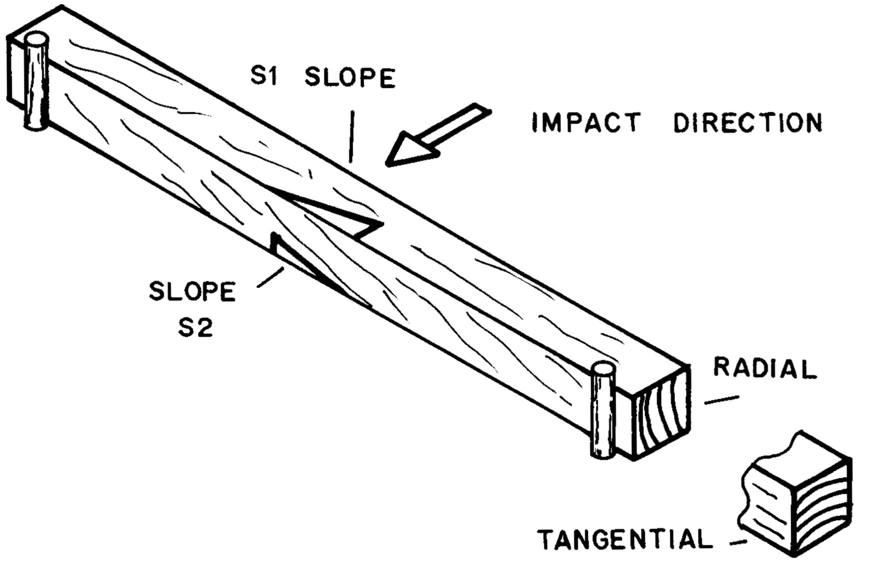

FIG. 1. The orientation of toughness specimens tested in the radial and tangential directions illustrating the two measured slopes.

The angular variations in grain were measured on the radial and tangential surfaces of each sample with a finely graduated protractor to ±0.125° and were converted into fractional slopes (or tangents), S1 and S2. The slopes measured were the largest deviations of S1 and S2 from the specimen edge within the center three inches of each piece. Since local grain deviations were observed in even the most straightly grained specimens, it was felt that deviations near the point of impact would be most critical.

Measurements on the radial surfaces were relatively easy to make as the fiber direction was usually aligned with the growth ring. However, slope measurement on the tangential surface was often a difficult and time-consuming process. Several techniques using magnification and staining were used to obtain a satisfactory measurement. A scribe was not used because any induced marking might have altered the test results and have yielded only a general specimen grain angle.

After the specimen had been tested, the failed portion was examined to confirm that the measured surface slope was representative of the slope of grain at the impact point. In several instances this examination yielded a more realistic measurement of the angle on the tangential plane.

Initially, an attempt was made in the manufacturing process to limit the study to specimens with local angles from zero to 9°. However, this was found to be impractical because of the variability of local grain deviations in nominally straight-grained specimens. In many instances a grain angle greater than 9° (tangent of the angle or slope of 0.158) was identified in the central area of a sample that was straight-grained to the unaided eye. Consequently, the limit was expanded to 15° (slope of 0.268), which was found to be a reasonable upper limit for a localized deviation that would escape all but the most intense scrutiny. Often these angles were identified only after the specimen had failed. Although an angle of 15° appears

TABLE 1. *Summary of the results of toughness test unadjusted for moisture content and specific gravity.*

Load direction	N	Toughness (in.-lb)		Moisture content (%)		Specific gravity		Slope-of-grain[2]					
								S1		S2		CS	
		Mean	CV[1]	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Radial	111	156	32.9	8.46	6.5	0.39	8.9	0.0542	104.0	0.0267	72.5	0.0663	79.6
Tangential	115	113	30.6	9.40	11.6	0.46	13.0	0.0951	78.9	0.0400	80.0	0.1063	73.6

[1] CV = Coefficient of variation (%).

[2] Fractional slope of the grain relative to the specimen edge.

excessive, the small specimen size precludes easy measurement of a localized grain deviation.

Of the 226 usable samples tested, only ten specimens had a zero slope on either the tangential or radial surface and none had zero slope on both surfaces. The lack of flat-sloped specimens, despite deliberate attempts to manufacture them, supports the premise that truly straight-grained toughness samples are rare.

Before testing, the specimens were equilibrated for several weeks to reduce moisture content variation. Each sample was tested on an FPL Toughness Machine in accordance with ASTM D143-52 (ASTM 1980). A total of 111 samples were tested in the radial direction and 115 samples in the tangential direction. After testing, the moisture content and specific gravity (OD weight/OD volume) were measured on cross sections cut near the point of failure.

The toughness, T, in inch-pounds was calculated according to ASTM D143-52 and a combined slope-of-grain (CS) was computed according to (Panshin and DeZeeuw 1970):

$$CS = \sqrt{S1^2 + S2^2}$$

RESULTS AND DISCUSSION

Table 1 summarizes the results obtained from the toughness tests. The radial impact toughness was substantially greater than that of the tangential tests, which is consistent with other published results. The values obtained are also similar to those found in the Wood Handbook (USDA 1974), and the coefficients of variation are in line with the earlier discussion. It should be reiterated that the samples came from five different boards and that the radial and tangential samples were not matched. This accounts for slight differences in moisture contents and specific gravities of the samples in the two orientations and may preclude direct comparison between the radial and tangential tests. Additionally, it was reasonable to expect that there was some density variation within each of the initial pieces of lumber. However, an analysis of covariance of the data partitioned by impact direction showed that neither the specific gravity nor moisture content was a

TABLE 2. *The fraction of explained variation, r², from single and multiple linear regression of toughness and slope-of-grain.*

Impact direction	N	Independent variables			
		S1 alone	S2 alone	S1 + S2	SC
Radial	111	0.54	0.00	0.54	0.48
Tangential	115	0.66	0.23	0.66	0.64

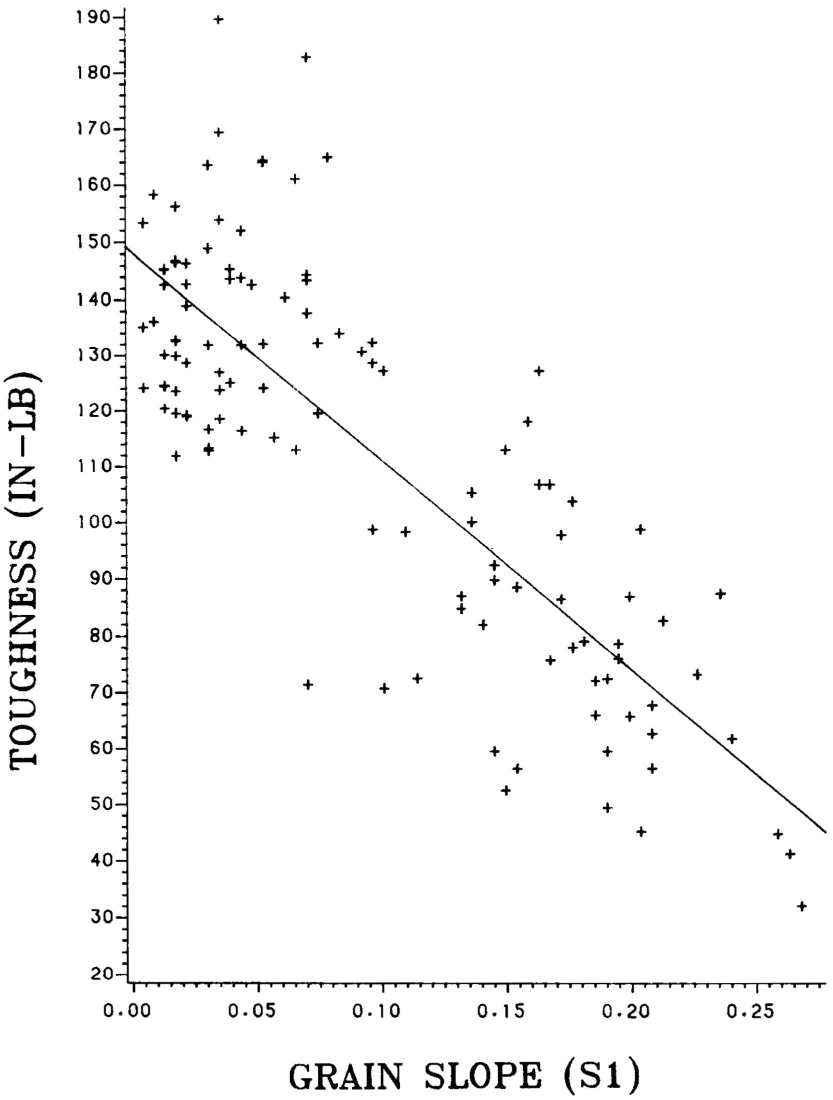

FIG. 2. The relationship between toughness and slope S1 for specimens tested in the tangential direction.

significant covariable in any of the relationships between toughness and the slope variables.

Toughness data for each impact direction were regressed against the slope variables. The coefficients of determination of these single and multiple linear regressions are shown in Table 2. The results show that the S1 slope was the more significant of the two slopes in explaining the variation in toughness. When both slopes were combined in the model ($T = b_0 + b_1S1 + b_2S2$), there was no improvement over the model with only S1. The combined slope, CS, was somewhat less effective in explaining the variation in toughness because in the calculation of CS, S1 and S2 are weighted equally.

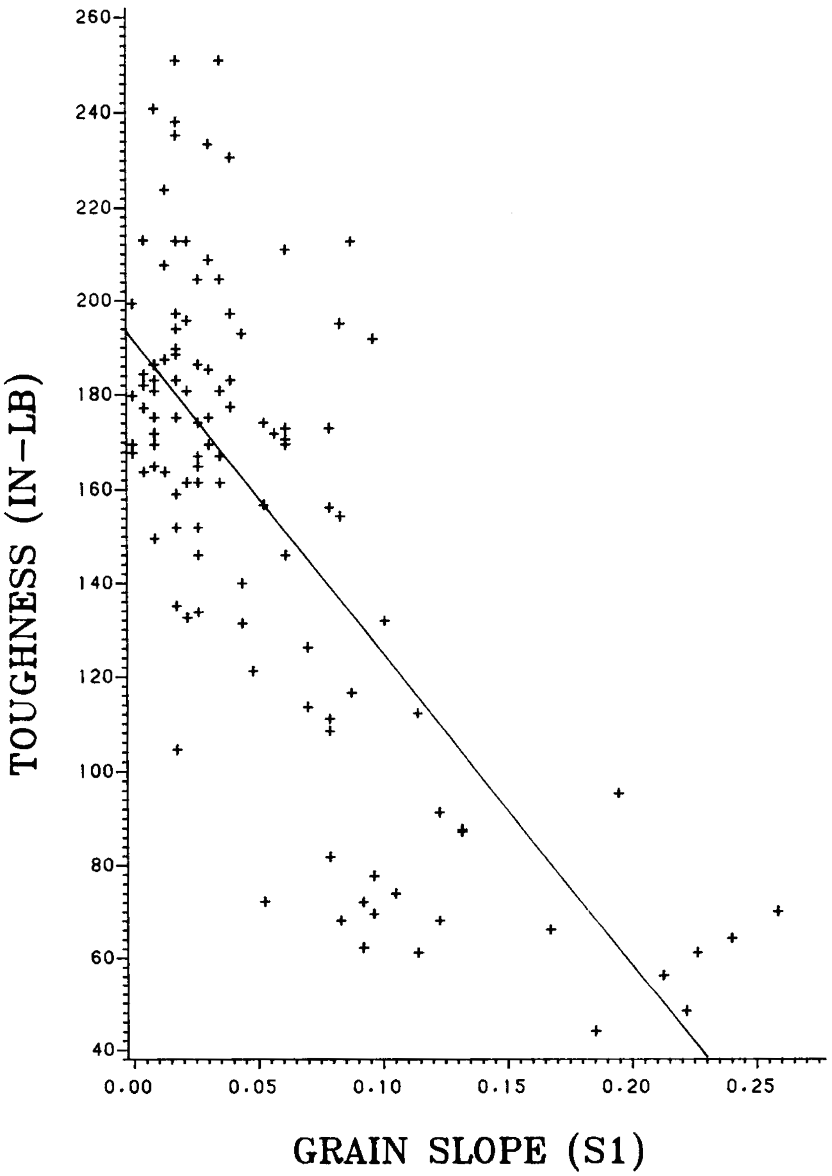

FIG. 3. The relationship between toughness and slope S1 for specimens tested in the radial direction.

Figures 2 and 3 indicate the relationship between toughness and the measured slope of grain. The data in Fig. 3 indicate that a curvilinear function may provide a better fit than the straight line. However, several attempts to fit a simple function to these data failed to yield improvement over the simple linear regression.

The best regression equations fitted to the data within the range of slopes from 0.0 to 0.267 were (angle: 0° to 15°):

Radial Impact	$T = 191.8 - 666.4\,(S1)$
Tangential Impact	$T = 148.3 - 371.8\,(S1)$

The coefficients of variation (CV) of the data about the mean when the variation in S1 was accounted for were 22 and 18% for the radial and tangential directions, respectively. These values are more consistent with published coefficients of variation for the modulus of rupture as discussed earlier. When compared to the CV for the unadjusted data (Table 1), a 36–40% reduction in the variation is realized by accounting for S1.

The slopes of the regression equations indicate that there was an 11.61 in.-lb/degree reduction in radially impacted toughness and a 6.5 in.-lb/degree reduction for tangential impact. Thus, a deviation in S1 of only 5 degrees resulted in reductions of 30 and 16% for radial and tangential toughness, respectively.

The toughness of a specimen depends on its ability to absorb and dissipate energy and is not solely a function of bending strength. However, toughness is somewhat related to the modulus of rupture, so it is not surprising that it is very sensitive to slope-of-grain. The S1 slope is an indication of the amount of open grain that is exposed on the surface of the specimen that has the greatest bending stress. Consequently, this may be a preferential factor. Additionally, the slope S2 was in the face of the surface in the cross section in which there was zero shear stress. As a result, S1 may be more important than S2 in explaining toughness variation since the shear stress at some point in the specimen depth may interact with the bending stress to precipitate failure. Another contributing factor may have been the fact that S2 was generally smaller than S1 and had somewhat less variation.

CONCLUSION

Redwood toughness samples were manufactured to be nominally straight-grained in accordance with ASTM standard procedures. Careful examination of the localized slopes-of-grain on the specimen faces parallel (S1) and perpendicular (S2) showed that only 10 of 226 samples had a truly zero slope on one face and none were truly flat-sloped on both faces. The localized grain deviation found in nominally straight-grained samples ranged from zero to 15° (fractional or tangent slopes: 0 to 0.268). Regression analysis showed that the S1 slope explained the greatest amount of variation in toughness data from samples impacted in both the radial and tangential directions. Coefficients of determination were 0.54 and 0.66 for the radial and tangential data, respectively. Accounting for the variation in S1 reduced the coefficients of variation about the mean from 32.9 and 20.6% to 22 and 18% for radial and tangential impact, respectively. The slopes of the regression lines indicated that a deviation in S1 of 5° resulted in reductions in toughness of 30 and 16% for radial and tangential tests, respectively.

These results lead to the conclusion that truly flat-grained toughness specimens are relatively rare and that local grain deviations may result in significant reductions in toughness. These easily overlooked grain deviations represent a sizeable proportion of the high variability of toughness data.

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