Crush Performance of Redwood for Developing Design Procedures for Impact Limiters[*]

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INTRODUCTION

Containers for the transportation of hazardous and radioactive materials incorporate redwood in impact limiters. Redwood is an excellent energy absorber, but only the most simple information exists on its crush properties. The stress-strain interrelationship for any wood species subject to three-dimensional stresses is largely unknown and wood behavior at both high strains and high strain-rates is known only in general terms. Both stress-strain and crush failure theories have been developed based only on uniaxial load tests. The anisotropy of wood adds an additional complexity to measuring wood response and developing suitable theories to describe it. A long history of wood utilization in the building industry has led to design procedures and property information related to simple uniaxial loadings that do not inflict damage to the wood. This lack of knowledge may be surprising for a material that has a long history of engineered use, but the result is difficulty in utilizing wood in more sophisticated designs such as impact limiters.

This study provides a step toward filling the information gap on wood material response for high-performance applications such as impact limiters. The load-deformation responses of redwood at temperature conditions corresponding to ambient (70°F), 150°F, and -20°F conditions were measured for crush levels leading to material densification. Confined compression tests of redwood cubes were conducted at low strain-rates, since earlier research by others suggests that crush performance of wood is relatively insensitive to changes in strain-rate, but further work will be needed to fully establish the strain-rate effect.

A major obstacle to the use of wood in many applications is the perception of its high

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variability in material property values. This perception is countered in this research with the hypothesis and supporting data that wood crush behavior depends on at least several interacting parameters. Measurement and control of these parameters explain much of the apparent variable nature of wood. Key parameters to define redwood crush behavior include specific gravity, growth rings per inch, grain angle, moisture content, and temperature.

EXPERIMENTAL METHODOLOGY

Triaxial tests of 4-inch redwood cubes were conducted at ambient, 150° F, and -20° F conditions. These conditions will be called *ambient*, *hot*, and *cold* conditions, respectively. The tests consisted of applying vertical load to each redwood cube in an instrumented, steel confining box. Loads were applied to the onset of densification. Lateral loads and deformations resulting from the restrained lateral expansion of the redwood cube were measured. General fiber (grain) orientation with respect to the applied vertical load was controlled and varied from 0 to 90 degrees in predetermined increments.

The angle between load application and grain direction is known to strongly influence mechanical behavior of wood specimens because of the assumed orthotropy of the material. Figure 1 shows the assumed material axes system for wood. The longitudinal direction corresponds to the parallel to grain direction and the radial and tangential directions correspond to what is generally simplified for engineering design as a single perpendicular to grain direction. The redwood specimens consisted of 4 inch cubes in which the grain orientation was targeted to a value between 0 and 90 degrees as shown in Table 1. Four to five specimens were taken for each grain angle/temperature condition. The test data provide trends and new information but are not complete enough to quantify statistically valid effects of each parameter that can influence redwood crush response. Although it was not possible to maintain constant specific gravity, moisture content, and rings per inch for each specimen in the test program, these parameters were measured and used in the analysis of data. Table 2 shows that the key parameters were maintained closely across

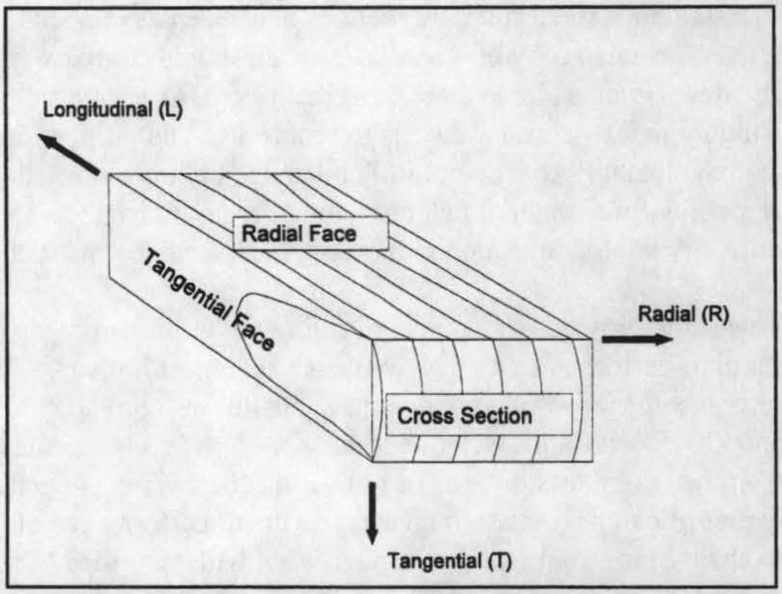

Figure 1. Radial, Tangential, and Longitudinal Axes System for Wood Materials

the different data sets, except for moisture content during the hot tests. Specimens were allowed to experience some drying during the hot tests as would likely occur during application. As a result the effect of temperature and moisture content change could not be explicitly distinguished. Consistency in parameters could not be rigorously maintained within and between each grain angle test group.

Table 1. Specimens Tested for Target Grain Angles

Target Surface Grain Angle degrees	Ambient Condition Test Specimens	150° F Test Specimens	-20° F Test Specimens
0	5	5	4
5 - T Face	5	4	4
10 - T Face	4	4	4
30 - T Face	4	4	4
90	4	4	6
5 - R Face	4	4	4
10 - R Face	5	4	4
30 - R Face	5	4	4
Tests Conducted=>	36	33	34

Table 2. Average Values of Wood Parameters for Different Data Sets

Data Set	Average/Range of Specific Gravity	Average/Range of Moisture Content	Average/Range of Growth Rings per Inch
All Data	0.37 (0.29-0.45)	11% (2%-16%)	13.3 (2.3-23.8)
Ambient Data	0.37 (0.29-0.45)	14% (13%-14%)	13.6 (2.3-23.8)
150° F Data	0.37 (0.30-0.45)	5% (2%-10%)	13.9 (2.3-23.8)
-20° F Data	0.37 (0.29-0.45)	14% (12%-16%)	12.6 (2.3-22.5)

Each test consisted of application of vertical load on a 4-inch redwood cube confined by very rigid side plates of steel. The vertical load was applied at two quasi-static displacement rates of 0.014 inches per minute for the first 10 minutes of the test and 0.263 inches per minute thereafter until the onset of material densification. As shown in the cut-away view in Fig. 2, the side plates of steel were restrained from movement by a 24-inch steel ring that encompassed the wood cube and side plates. The side plates were instrumented such that the expansion and resultant lateral loads were measured. The complete test device was placed in a convection oven for the hot tests and a freezer for the cold tests. The test specimens were conditioned to a uniform moisture content of approximately 14% before testing, but no special humidity controls were employed within the test chamber.

RESULTS AND DISCUSSION

Redwood crush behavior can be idealized into three general regions of material response: linear and elastic, crush or plastic, and densification as shown in Fig. 3. The elastic region occurs over only a small portion of the total volumetric crush. Once the significant effect of boundary conditions is addressed, the elastic response follows property trends as influenced by grain angle, temperature, moisture, and specific gravity as developed from uniaxial tests for general engineering design (Forest Products Laboratory 1987).

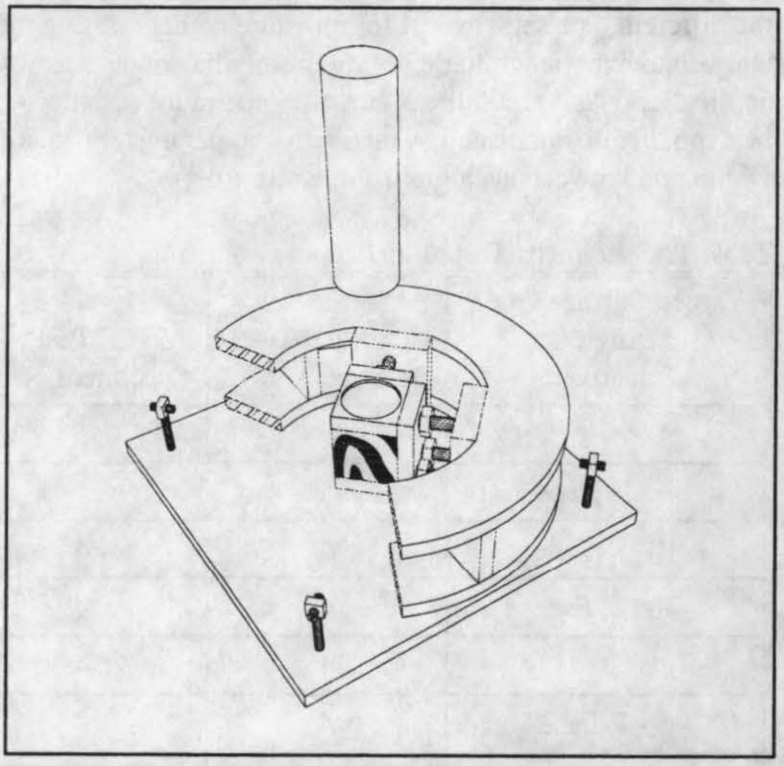

Figure 2. Triaxial Redwood Test Device

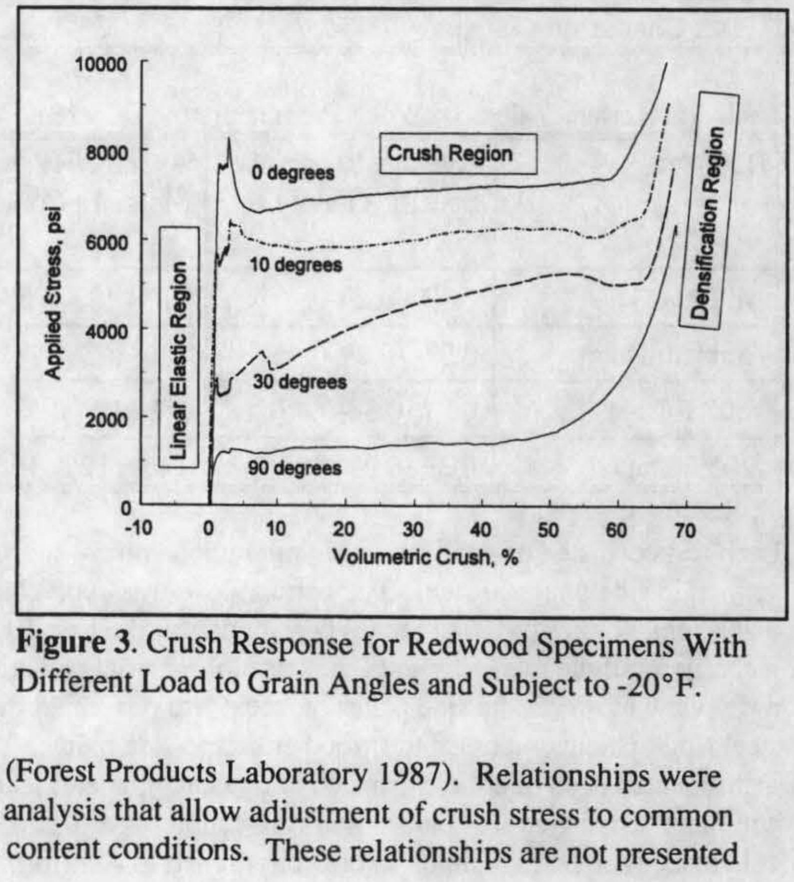

Figure 3. Crush Response for Redwood Specimens With Different Load to Grain Angles and Subject to -20°F.

Package deceleration is based upon the crush region characteristics and thus it is most important for impact limiter design. The region is denoted by the crush stress and for 0 degree grain angle that corresponds closely to published compressive strength values for redwood (Forest Products Laboratory 1987). Relationships were developed as part of the data analysis that allow adjustment of crush stress to common specific gravity and moisture content conditions. These relationships are not presented here , but the separate influences of specific gravity, temperature, and moisture content on redwood crush stress were found to approximately follow adjustments published in the literature for parallel to grain compressive strength of several wood species. These adjustments are shown in Table 3. As revealed in Table 3, decrease in crush stress associated with elevated temperature of 150°F is more than offset by increase associated with drying that naturally occurs at the elevated temperature.

As indicated in Fig. 3, the influence of angle of load to grain has a dramatic influence on crush strength. Although Hankinson's formula (Forest Products Laboratory 1987) is a common approach for predicting properties at angles to grain, our investigation shows it tends to underpredict crush strength at intermediate grain angles (not shown) and does not distinguish between the radial and tangential directions. As angle of load to grain increases, local material resistance induces large amounts of shear stress and the resulting triaxial stress states in the material coordinates become complex. A complete failure theory that accounts for complex triaxial stress states would be the most versatile approach for predicting grain angle effects on crush stress, but such a theory has not been fully developed and verified for wood. Table 4 summarizes the crush stress values obtained in the test program. Although angles of load to grain on the tangential face (T) and the radial face (R) are usually not distinguished in typical engineering design, both the recorded crush values (Table 4) and failure modes associated with similar angles on different faces showed significant differences. These differences were dependent on temperature. The crush response of redwood reflects its cellular structure.

Table 3. Adjustments of Crush Stress Parallel to Grain for Specific Gravity, Moisture Content, and Temperature

Parameter	Adjustment	Source
Specific Gravity	Crushing strength = $14600 (SG)^{1.04}$	Forest Products Laboratory 1987
Moisture Content	For each 1% change in MC from 12% adjust crush stress by 5% of room temp. crush stress at 12% MC using the opposite sign. Valid for the range of 0% to 21% moisture content.	Gerhards 1982
Temperature	For 150°F decrease crush stress at room temp. and 12% MC by 30%. For -20°F increase crush stress at room temp. and 12% MC by 40%.	Gerhards 1982

Specific energy has been tabulated by previous investigators as a measure of the energy absorbed per pound of material being crushed. Table 5 allows comparison of values obtained by Joseph and Hill (1976) and values we obtained for room temperature conditions. If adjusted to common specific gravity and moisture content using Table 3, the values from Joseph and Hill in Table 5 are approximately 10% greater than the values obtained in our study.

Table 4. Average Crush Strength for Target Grain Angle Groups for SG=0.36, MC=14%, and Rings=12.6/in.

Target Angle Group	Ambient Crush Strength MC=14% psi	Hot Data Set Crush Strength MC=5% psi	Cold Data Set Crush Strength psi	Ratio of Hot (MC=5%) to Ambient (MC=14%) psi	Ratio of Cold to Ambient (MC=14%) psi
0°	4620	5660	6350	1.23	1.37
5° R	4290	5220	6370	1.22	1.48
5° T	4410	5200	5970	1.18	1.35
10° R	3780	4090	6530	1.08	1.73
10° T	4190	5190	5880	1.24	1.40
30° R	2940	3690	4230 (SG = 0.33)	1.26	1.44
30° T	3320	3810	4980	1.15	1.50
90°	1010	1040	1420	1.03	1.41
				Avg: 1.17	Avg: 1.46

Table 5. Specific Energy Results of Joseph and Hill and the Univ. of Wisc. Study

Crush Direction	Percent Crush	Joseph and Hill Results (1976)		Univ. of Wisconsin Results	
		Specific Energy, ft-lb/lb		Specific Energy, ft-lb/lb	
Parallel to grain	20	Avg. SG ≈ 0.33 Avg. MC ≈ 10%	6,500	Avg. SG = 0.32 Avg. MC = 13%	4,810
	40		13,640		10,000
	60		21,350		15,350
Perpendicular to grain	20		810	Avg. SG = 0.31 Avg. MC = 13%	1,060
	40		2,070		2,330
	60		4,410		4,190

Figure 4 shows the specific energy for a group of otherwise like redwood specimens with different grain angles and subject to -20° F. The effect of grain angle on specific energy follows the same trends as crush stress in Fig. 3. Because redwood subject to compression can be modeled as an elastic, perfectly-plastic material, approximations to the specific energy can be obtained by neglecting the small contribution from the elastic region and using the crush stress times the cross-sectional area, times the displacement associated with material densification. The specific energy increases nearly linearly to the onset of material densification suggesting perfectly plastic behavior.

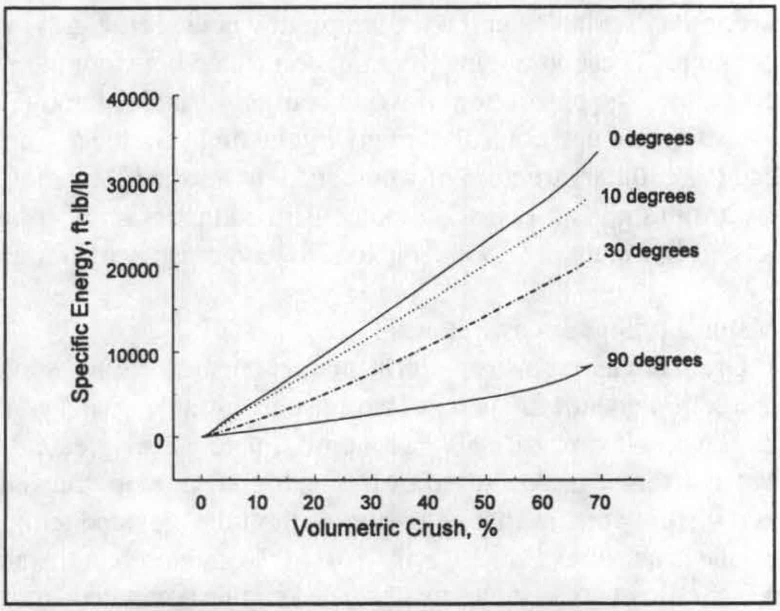

Figure 4. Specific Energy for Redwood Specimens with Different Grain Angles and Subject to -20°F.

The material densification region shown in Fig. 3 occurs as the air-space voids are removed from the crushed material. This dramatic increase in material stiffness is sometimes called material lockup. Wood cell wall material consists of cellulose and lignin and since cellulose and lignin have similar densities, solid wood material (no voids) regardless of species has a common specific gravity of approximately 1.5 (Forest Products Laboratory 1987 and Megraw 1985). The volumetric crush strain can be easily computed for theoretically complete wood densification using the specific gravity of the wood under consideration. For the average specific gravity of 0.37, complete densification would occur at a volumetric crush strain of 75%. Our data showed a strong relationship between specimen specific gravity and the crush strain associated with the onset of material densification. The material densification region shown in Fig. 3 typifies trends observed in our data. For low grain angle loading conditions, densification began abruptly at 60% volumetric crush strain. For high grain angle loading conditions, material densification began gradually at 40% volumetric crush strain but continued to increase. As indicated in Fig. 3, high grain angle situations approach the same slope of densification as low grain angle situations, but at slightly higher levels of volumetric crush. It is possible that all situations are converging toward the volumetric crush associated with complete densification. For practical purposes, one may use 80% of the volumetric crush strain at theoretically complete densification for describing material lockup. As expected, the trends associated with material densification are independent of the temperatures considered because these temperatures and moisture contents did not impact the void ratio of the material.

SUMMARY AND CONCLUSIONS

A test program was conducted to measure redwood crush behavior with grain angle and temperature as primary variables. Quasi-static strain rates were used based on earlier recommendations that strain rate has only a minor effect on measured properties. This assumption and the resulting interpretation of this data set warrants further examination.

Secondary variables in the test program were specific gravity, moisture content, and rings per inch. These variables were not controlled but were monitored during the test program. The perception of wood being a variable material is the result of a lack of measurement and control of many interacting variables. Consideration of these variables and the cellular structure of wood account for the vast majority of variability seen in this test program. Our investigation confirmed that existing adjustment factors in the wood-related literature are applicable to redwood crush behavior and can be applied directly.

Major findings are as follows:
1. Grain angle has a strong influence on crush stress and specific energy. Existing prediction equations such as Hankinson's formula do not fit the measured data well.
2. The crush stress at 150°F is approximately 20% greater than the ambient crush stress because the degrade caused by the increased temperature is more than offset by reductions in moisture content that naturally occur at the elevated temperature.
3. The crush stress at -20°F is 40 to 50% greater than the ambient crush stress.
4. Specific energy or energy absorbed can be computed from knowledge of crush stress since redwood can be modeled as elastic, perfectly plastic.
5. The onset of material densification depends on grain angle and specific gravity. Densification begins at approximately 60% volumetric crush strain for loadings parallel to grain and at approximately 40% for loadings at 90 degrees to the grain angle. Complete densification is independent of grain angle and temperature, and depends on the specimen specific gravity.

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