

PREDICTION OF FRACTURE TOUGHNESS OF CONIFERS¹

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ABSTRACT

Equations were developed to use in the prediction of the fracture toughness values of coniferous species based on the variation of specific gravity and moisture content. Equation parameters were determined for clear wood in opening mode fracture when the crack is located in a plane normal to the tangential direction and it propagates in the longitudinal direction, (K_{IcTL}). The prediction equations developed are based on test results of ten coniferous species representing wide ranges of specific gravities and moisture conditions.

Analysis of the data revealed that the relationship between fracture toughness and specific gravity is similar for all species tested and a single equation may be used for all species. However, the effect of moisture content was significantly affected by extractive content, and separate relationships are required for low and high extractive content species below the fiber saturation point.

Tensile strengths and moduli of elasticity were determined both in the L and T directions. A highly significant relationship between ultimate tangential tensile stress and fracture toughness was found, indicating that flaws present in wood are likely the controlling mechanism of failure for this system.

Keywords: Fracture toughness, elastic parameters, tensile strength, specific gravity, moisture content, prediction equations.

INTRODUCTION

Current practices in the utilization of wood in construction often lead to waste of material because of insufficient technical knowledge regarding the influence of defects on strength. Present methods of strength assignment can only account in a general statistical way for the influence of major growth characteristics of lumber, e.g., knot size, knot shape, knot location, knot-associated cross grain, global cross grain, checks, and shakes. To quantify the effects of these factors on the strength of lumber, a project "Strength Behavior of Wood—An Anisotropic, Inhomogeneous, Discontinuous Material" sponsored by the National Science Foundation (Grant No. CME-7918170) was initiated at Colorado State University. The overall objective of the project is to develop a quantitative methodology to predict the strength of wood members containing knots, cross grain, and cracks.

In addition to considering the effects of the major growth characteristics, the reliability of strength prediction can be improved by accounting for discontinuities (cracks) influencing the failure of wood. Linear elastic fracture mechanics (LEFM) theory is the basis of this approach. The application of fracture mechanics to

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wood is becoming an increasingly popular research topic. The theory has been shown to work well for brittle materials and appears to be promising for wood as well (Forintek 1979).

Current ASTM methods (1982) empirically relate strength of lumber to knot size, ignoring the effects of knot-associated cross grain and cracks that develop as a result of drying. However, tests of structural-size lumber indicate that failure often initiates at cracks located in the knot-associated cross grain. Therefore, the prediction of strength of lumber requires understanding of the mechanism of crack propagation. Of particular importance for lumber containing knots is the case when the plane of the crack is normal to the T direction and propagates in the L direction. Test samples were fabricated and tested representing this crack system.

Only limited information exists in the literature on the fracture toughness values of various wood species. Until this research, no concerted efforts were made to predict the fracture toughness values of wood as is commonly done for elastic and strength properties. The main objective of this investigation was to develop equations that can be used to predict the fracture toughness in the TL propagation system of any coniferous species if its specific gravity and moisture content are known. An additional objective of the study was to develop similar equations to predict some of the elastic parameters of wood in the LT plane.

REVIEW OF LITERATURE

The current method of visual stress grading of lumber in North America is based on the procedures outlined in ASTM D 245-81 (1982). As mentioned in the introduction, this method is based on several simplifying assumptions. While it can predict with reasonable reliability the strength distribution of a grade of lumber, it is unable to predict accurately the strength of individual pieces. To learn more about the factors affecting the elastic and strength behavior of wood containing knots and cross grain, a National Science Foundation sponsored study "Tension Behavior of Wood—An Anisotropic Inhomogeneous Material" was initiated at Colorado State University in 1976. This study produced a verified knot-associated grain angle model, termed "Flow-Grain Analogy" (Phillips et al. 1981). Further, the elastic and strength properties of knots were determined (Pugel 1980), and a finite element program for stress analysis was developed (Dabholkar et al. 1980). This research is being extended to include the effect of material discontinuities present in wood in the form of checks and shakes. The previous finite element model has been modified to allow the inclusion of checks, and preliminary studies were carried out on the tensile strength of individual pieces of lumber containing a knot, cross grain and checks (Cramer 1981). The fracture toughness study reported here is an integral part of this strength prediction process.

Fracture toughness, a fundamental material property, is necessary to predict the strength of materials containing cracks (ASTM 1981; Leicester 1974; Tada et al. 1973; Walsh 1972). For isotropic materials there are three fracture toughness values, corresponding to the three modes of crack propagations. However, for wood modeled as an orthotropic material, six different fracture toughnesses exist for each one of the three modes (Schniewind and Centeno 1973).

Since there are eighteen fracture toughnesses for each piece of wood, it is convenient to utilize a notation suggested by Schniewind and Centeno (1973).

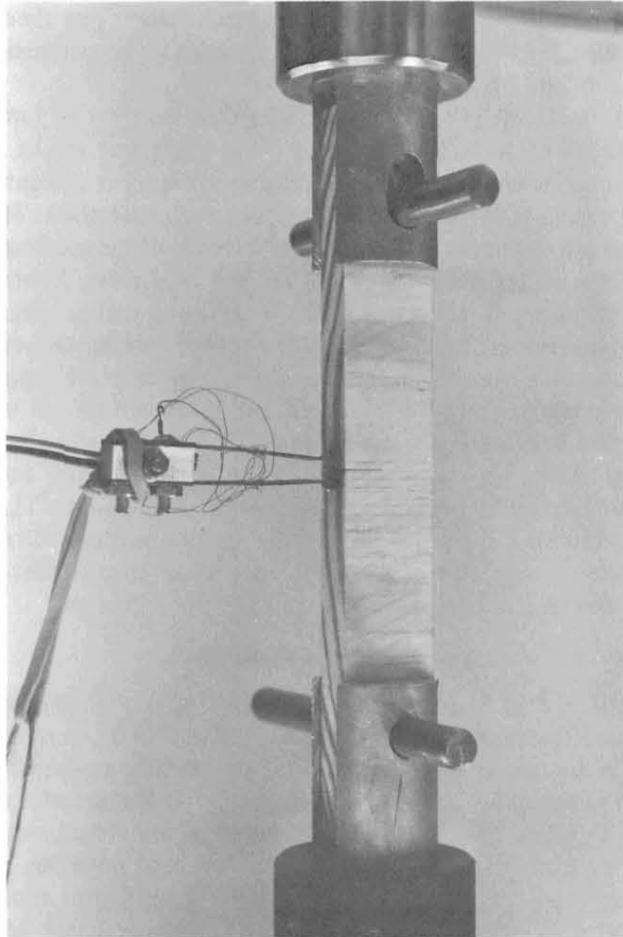


FIG. 1. Fracture specimen test set-up.

The fracture toughness involved in this study is K_{IcTL} . This is an opening mode (I) critical (c) stress intensity factor, commonly termed fracture toughness. The crack is located in a plane normal to the tangential direction (T) and propagates in the longitudinal (L) direction. Figure 1 shows the location of the crack and the direction of tensile load corresponding to the above system. The arrangement represents the fracture toughness chosen for detailed study due to its importance in the modeling of tensile strength of wood in the LT plane containing a round or oval knot.

Most of the work in the fracture behavior of wood assumes that the isotropic solution gives satisfactory results (Barrett 1976; Forintek 1979; Pellicane 1980; Porter 1964; Schniewind and Centeno 1973; Schniewind and Pozniak 1971). However, under certain conditions the assumption of isotropy could produce considerable error. The geometry of the test specimen utilized here is chosen so that the difference between the isotropic and orthotropic solutions is minimal (Walsh 1982).

A good review of the current knowledge on the fracture mechanics of wood and wood composites is contained in the "Proceedings, First International Conference on Wood Fracture" (Forintek 1979). A review of this proceedings indicates that only limited data are available on the fracture toughness of wood. Determination of fracture toughness data is a time-consuming process and a technique is badly needed by which one can predict the fracture toughness of wood without resorting to actual testing.

Walsh (1972) investigated the effects of orthotropy on the stress intensity factor utilizing a finite element technique. His findings revealed that the influence of orthotropy is highly significant for cleavage (double cantilever) specimens, but insignificant for sufficiently long prismatic specimens. Further, Schniewind and Pozniak (1971) and Barrett (1976) found that, for the TR system, length-to-width ratios of 0.67 to 2.0 had no discernible effect.

The critical K value is affected by the thickness of a fracture specimen. For metallic specimens, an empirical equation exists for computation of the minimum thickness needed for a valid evaluation of the material fracture toughness, K_{Ic} (Osgood 1971). While such an equation is not available for wood, Porter (1964) found that varying specimen thickness between $\frac{1}{8}$ and 1 inch did not affect the stress intensity factor of TL and RL white pine cleavage specimens.

Even with the limited work to date, application of fracture mechanics concepts to wood is clearly an important tool that can lead to a unified failure theory for wood. Obviously, the practical application of such a theory to the strength prediction of lumber, veneer and other wood products requires the knowledge of their fracture toughness values.

EXPERIMENTAL METHOD

Ten commercially important domestic softwood species, (Table 1) incorporating a wide range of densities, were selected for testing with a minimum sample size of thirty fracture specimens per species, including ten matched specimens for the determination of ultimate tensile stress and moduli of elasticity.

In addition to a wide specific gravity range, a wide range of moisture content was also needed so that the data would yield predictive relationships using both of these variables. To obtain the required moisture range, the specimens were maintained in green condition or air-dried to various moisture contents. Air-drying was limited to 2- to 4-h intervals to minimize seasoning defects. The specimens of each species were kept together in plastic bags for 12 to 24 h between drying periods. This conditioning allowed for equalization of moisture distribution within the specimens. The conditioned specimens were machined to final dimensions and kept in small plastic bags to retain moisture until testing.

Because of the small specimen dimensions, the E_T values were determined using cantilever beam specimens for each of the ten species studied. A minimum of eight specimens per species were tested, half of them in the green condition and the other half seasoned to intermediate moisture contents.

The fracture specimens were designed for the TL propagation system (Fig. 1). Matched necked-down specimens were used to obtain both ultimate tensile stress, σ_{uT} , and modulus of elasticity, E_T , in the tangential direction (Fig. 2). The necked-down portion was 2 inches long and 0.5 by 0.5 inch in cross section.

TABLE I. Allocation of specimens by species and test procedure.

Species	Source	S_g	M (%) range	Number of specimens		$E_{\text{longitudinal}}$	
				Mode I fracture	Necked-down	M (%) range	No. of specimens
Western redcedar	Simpson Timber Co., Shelton, WA	0.31	4.5-green	31	9	8.9-green	10
Engelmann spruce	Roosevelt Nat. Forest, CO	0.33	6.2-green	36	10	11.2-green	10
Redwood	Arcata Redwood, Arcata, CA	0.39	5.5-green	35	8	16.0-green	8
Ponderosa pine	Roosevelt Nat. Forest, CO	0.39	5.6-green	33	11	10.3-green	10
Lodgepole pine	Medicine Bow Nat. Forest, WY	0.39	6.8-green	35	11	16.2-green	8
Loblolly pine	Mississippi State Univ. MS	0.43	7.9-green	35	11	17.7-green	8
Shortleaf pine	Mississippi State Univ. MS	0.44	5.4-green	32	10	4.8-green	7
Western hemlock	Simpson Timber Co., Shelton, WA	0.49	6.0-green	35	8	10.9-green	10
Western larch	Potlatch, Corp., Lewiston, ID	0.50	8.7-green	33	10	10.7-green	10
Douglas-fir	Arcata Redwood, Arcata, CA	0.55	8.4-green	36	10	17.9-green	8
TOTALS				341	98		89

A 0.5-inch specimen thickness was adopted for consistency with previous studies (Barrett 1976; Porter 1964).

The fracture specimen was also 7 inches long but 1.0 by 0.5 inch in cross section. A crack (notch) was inserted into each fracture specimen using an 8-mil-thick razor saw in a specially fabricated jig. The shoulder of the saw provided a guide that consistently produced notch lengths of 0.4 inch. A total of 341 fracture toughness specimens were tested; of these, 98 were matched with tensile specimens at various moisture contents.

In most fracture toughness testing, a record of the load versus crack-opening displacement (COD) is made. To record COD, an extensometer or clip gage must be located at the crack. The ASTM recommended procedure for metals (1981) describes a clip gage designed to attach directly into notches at the crack mouth or to detachable knife edges located in that position. With this design concept in mind, a similar clip gage, suitable for wood specimens, was fabricated. This gage consists of two 1.6-inch-long arms made of heat-tempered bandsaw steel, each having a turned-up end with a small notch in the center. The notches accommodate two small brads, inserted into a specimen 0.30 inches apart on each side of the crack plane. Half-inch strain gages, one on the tension side and one on the compression side, were attached to each arm of the clip gage. Figure 1 illustrates a fracture specimen with the clip gage in place, ready for testing. For measure-

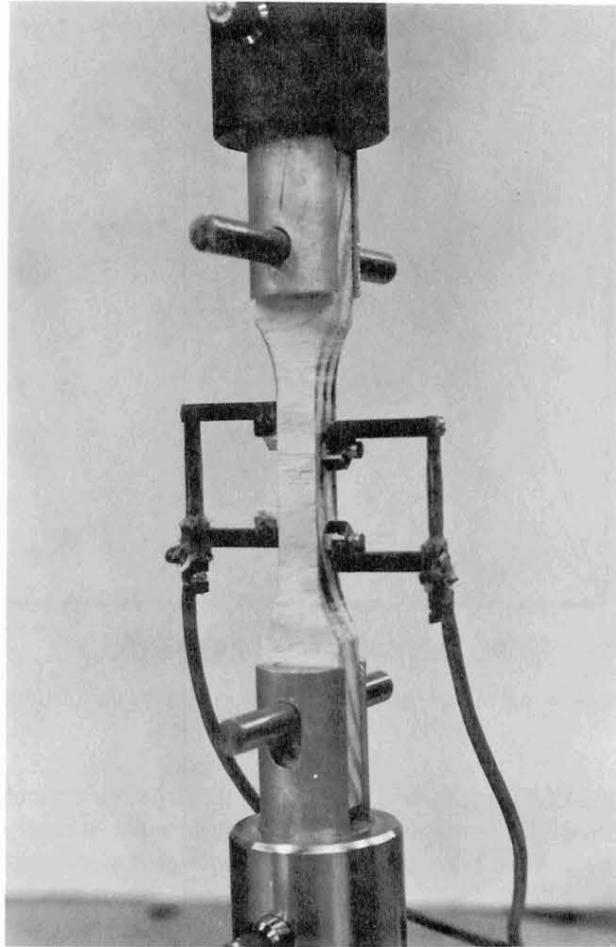


FIG. 2. Tensile test in the tangential direction.

ment of E_T , two previously constructed clip gages, which were originally designed by Schuldt (1972), were utilized as shown in Fig. 2.

The testing machine was equipped with self-aligning, tension fixtures. The cross-head speed used was 0.025 in./min, resulting in times to failure of 1.5 to 2.0 min for K_{Ic} tests and 2 to 4 min for tensile tests. Load-COD and load-deformation curves were recorded. Figure 3 exhibits the three basic types of curves obtained for the K_{Ic} specimens. The low moisture content specimen always exhibited highly brittle behavior, and the point at which crack propagation initiates is clearly delineated. The crack propagation point for the intermediate and high moisture content specimens was more difficult to determine.

Because of the variable nature of crack opening for wood, the ASTM 5% offset method that locates the point of 2% crack extension (1981), was deemed inapplicable to define crack propagation. Therefore the point at which any sudden crack growth (signified by a horizontal notch on the load-COD graph) or at which an abrupt change in crack compliance occurred (signified by an abrupt change in

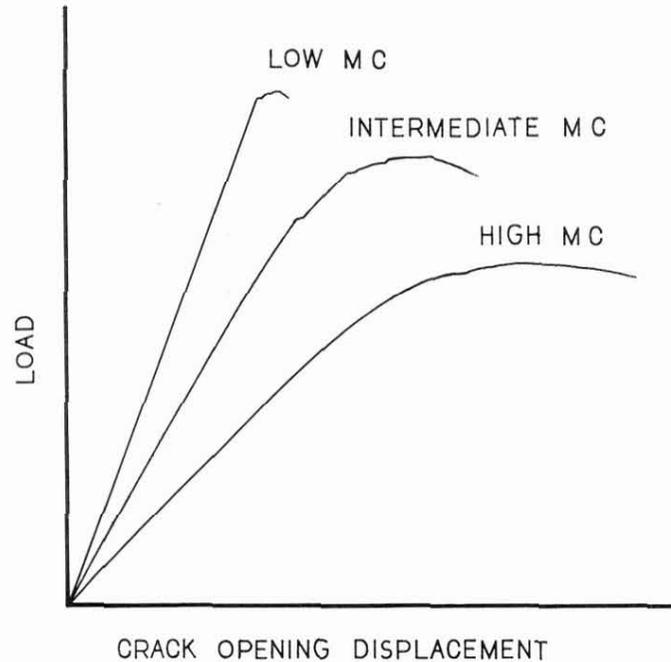


FIG. 3. Typical load versus crack opening displacement at three moisture contents.

slope on the load-COD graph) was chosen to determine the critical fracture load. This point, termed "pop-in load," was easily discernible in most cases and was considered to be a close estimator of the load at which significant crack growth was initiated.

As discussed earlier, because of the near identical results between isotropic and orthotropic solutions for the selected fracture test specimen (Walsh 1972), the isotropic solution was used for computation of the stress intensity factor, K_I . A polynomial expression derived for isotropic case (Tada et al. 1973) was used for the geometry factor as follows:

$$K_I = \sigma\sqrt{\pi a} \left[1.12 - 0.231\left(\frac{a}{b}\right) + 10.55\left(\frac{a}{b}\right)^2 - 21.72\left(\frac{a}{b}\right)^3 + 30.39\left(\frac{a}{b}\right)^4 \right] \quad (1)$$

where:

- σ = tensile stress based on total cross section,
- a = initial crack length,
- b = specimen width.

Substitution of the fracture stress values into (1) produces the fracture toughness values reported here.

Fracture toughness prediction procedure

To predict the value of the fracture toughness, relationships needed to be established with specific gravity (based on oven-dry weight and green volume (S_g)) and percent moisture content (M) below fiber saturation point (FSP). These re-

relationships were established in two steps: first, by holding the moisture content above FSP and varying the specific gravity, and second, by finding the fracture toughness–moisture content relationship below FSP for a given specific gravity.

Leicester (1974) identified a positive correlation between fracture toughness and density, and concluded that the effect is similar to those of other mechanical properties. The effect of specific gravity on mechanical properties is generally expressed as a power function (Markwardt and Wilson 1935; USFPL 1974).

$$Y = aS_g^n \quad (2)$$

where a and n are empirical constants. For the fracture toughness at green condition, this relationship is:

$$K_{Icg} = aS_g^n \quad (3)$$

A linear regression analysis of the data can be used to determine the values of a and n . This is done by first taking the logarithm of both sides of (3), resulting in

$$\log K_{Icg} = \log a + n \log S_g \quad (4)$$

The constants of a and n were obtained through linear regression analysis of seventy-nine green fracture specimens representing the ten softwood species. The regression analysis produced the following result:

$$K_{Icg} = 406.08(S_g)^{0.952} \quad (5)$$

where K_{Ic} is expressed in $\text{psi} \cdot \text{in}^{\frac{1}{2}}$. The correlation coefficient, r , for the above analysis is 0.80, while the coefficient of variation, about the regression line is 0.14. The plot of $\log K_{Icg}$ versus $\log S_g$ is shown in Fig. 4. Equation (5) can be simplified without much error by rounding off the equation parameters to

$$K_{Icg} = 400(S_g) \quad (6)$$

The error associated with this approximation ranges from 4.0% for a S_g of 0.6, to 7.5% for a S_g of 0.3. Once the fracture toughness is predicted for a given specific gravity, the effect of moisture content can be considered. It is common practice to assume a negative exponential relationship between a mechanical property, Y , and moisture content (USFPL 1974). In algebraic form:

$$Y = B(10)^{-cM} \quad (7)$$

where B and C are constants. However, this relationship does not account for specific gravity. Therefore, it is necessary to devise a dimensionless normalized moisture correction factor, α_M , which is defined as the ratio of the fracture toughness K_{IcM} at moisture content M over K_{Icg} at green condition

$$\alpha_M = K_{IcM}/K_{Icg} \quad (8)$$

Therefore, (8) can be rewritten as

$$\alpha_M = b(10)^{-cM} \quad (9)$$

where the constants b and c differ from B and C in (7) due to the normalization process of (8). Taking the logarithm of both sides of (9) results in

$$\log \alpha_M = \log b - cM \quad (10)$$

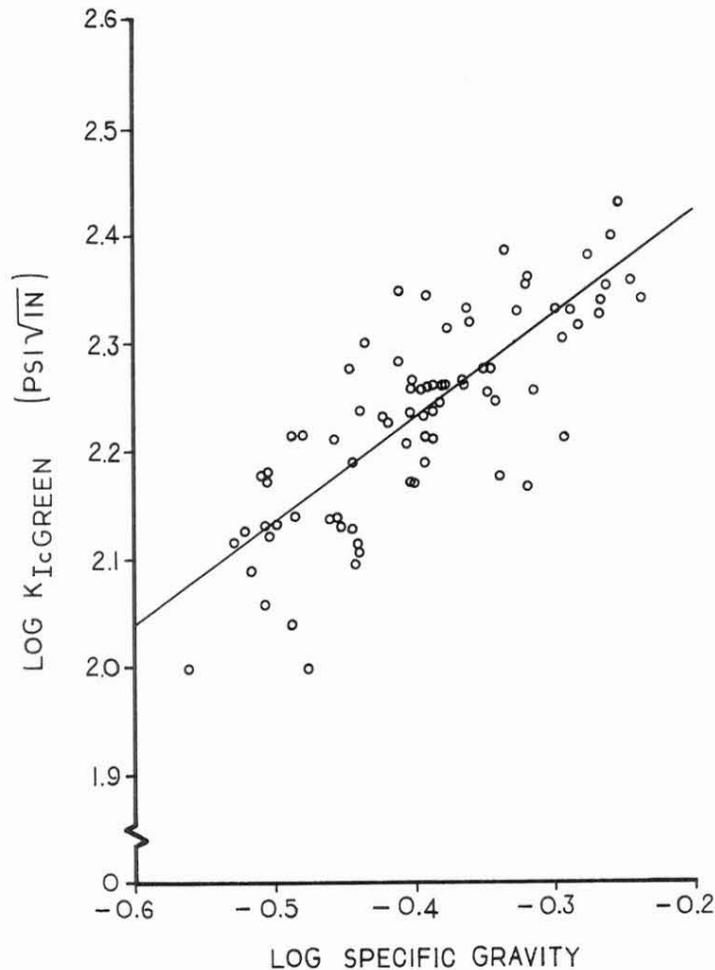


FIG. 4. Relationship between logarithm of green fracture toughness and logarithm of specific gravity.

Because (10) represents a straight line expression, plotting the log of the normalized moisture correction factor as a function of moisture content produces a linear relationship.

The regression lines between $\log \alpha_M$ and M for the ten species tested are plotted in Fig. 5. Each species is represented by thirty-one to thirty-six specimens (Table 1). The plot confirms the result of the statistical analysis that redwood and western redcedar produced insignificant regressions on moisture content; consequently, these two species were omitted from the combined regression line denoted by the dashed line in the same figure. The statistical parameters of each regression line are listed in Table 2.

The fracture toughness K_{IcM} at any specific gravity and moisture content below fiber saturation point can be computed by utilizing (3), (8) and (9), i.e.:

$$K_{IcM} = aS_g^nb(10)^{-cM} \quad (11)$$

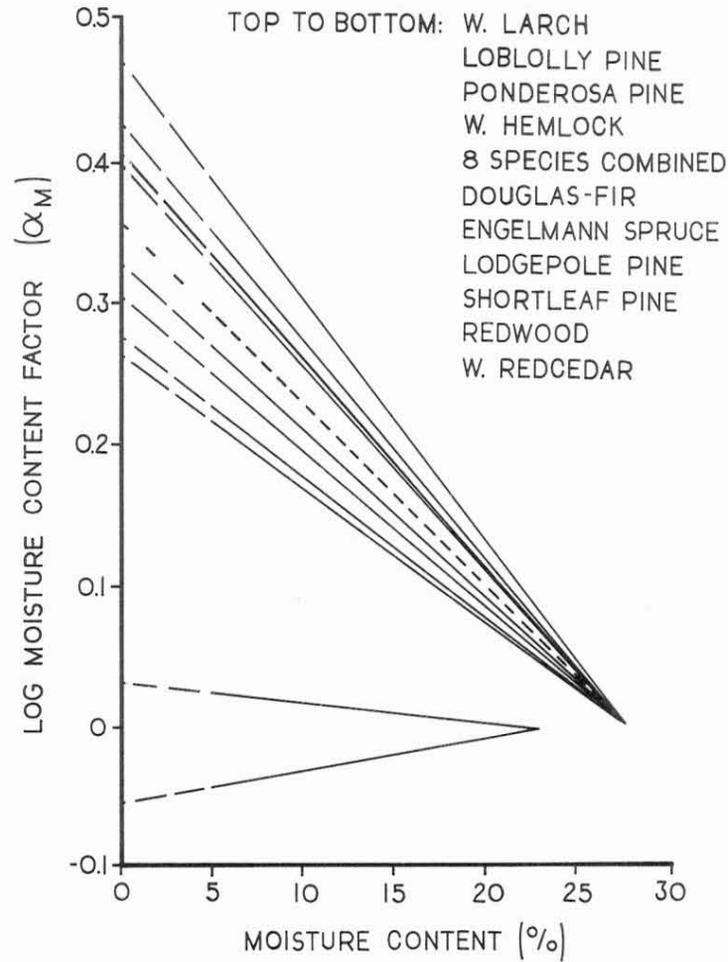


FIG. 5. Relationship between logarithm of moisture correction factor and moisture content.

TABLE 2. Statistical parameters on the effect of moisture content on fracture toughness.

Species	Parameters of Eq. (9)			CV regr.
	b	c	r	
Lodgepole pine	1.905	0.0100	-0.587	0.28
Loblolly pine	2.699	0.0154	-0.665	0.36
Shortleaf pine	1.810	0.0092	-0.720	0.18
Douglas-fir	2.099	0.0115	-0.740	0.18
Western larch	2.935	0.0167	-0.850	0.17
Engelmann spruce	2.019	0.0109	-0.869	0.12
Ponderosa pine	2.547	0.0145	-0.879	0.15
Western hemlock	2.514	0.0143	-0.831	0.19
Above species combined	2.253	0.0126	-0.743	0.22
Redwood	1.123	0.0018	-0.130	0.20
Western redcedar	0.862	-0.0023	0.161	0.21

TABLE 3. Equation constants for predicting E_L and E_T as functions of specific gravity and moisture content.

Direction	No. of specimens	Specific gravity			Moisture content			
		a	n	r	No. of specimens	b	c	r
L	45	3,583,000	1.299	0.811	89	1.295	0.00424	-0.714
T	18	114,300	0.830	0.505	98	2.282	0.01259	-0.643
T*	13	129,100	1.065	0.798	—	—	—	—

* Excluding redwood and western redcedar.

Substituting (5) gives

$$K_{IcM} = 406.08S_g^{0.952}b(10)^{-cM} \quad (\text{psi-in}^{\frac{1}{2}}) \quad (12)$$

and can be approximated by using (6) as

$$K_{IcM} = 400S_g b(10)^{-cM} \quad (13)$$

By taking the values of b and c from Table 2 for the species tested or the combined slope for a species of low extractive content, the fracture toughness value in question can be predicted for any specific gravity and moisture content below FSP. For high extractive content species, no moisture correction is needed and (6) may be used directly.

Prediction of modulus of elasticity

Previously, Bodig and Goodman (1972) determined the constants of (2) for predicting the various elastic parameters of wood with specific gravity as the variable. However, these constants were derived only for 12% moisture content. To expand the range of prediction, the effect of moisture content was studied here.

For the two-dimensional modeling of the tensile behavior of wood containing a knot, E_L and E_T are needed. These two moduli can be computed similarly to (11) with the constants tabulated in Table 3. Note that the E_T -specific gravity relationship is greatly improved if the two high-extractive species, i.e. redwood and western redcedar, are excluded.

Ultimate tensile strength vs. fracture toughness relationship

Pellicane (1980) found no significant relationship between ultimate tensile strength and fracture toughness of 104 lodgepole pine specimens taken from a single piece of lumber. However, when wide ranges of specific gravity and moisture content are involved, it seems logical to expect a species with a higher fracture resistance also to be stronger in tension.

The data generated from the ninety-eight matched specimens bear out this expectation. Figure 6 shows the σ_{uT} vs. K_{IcM} plot for all ten species combined. The regression equation obtained from these data is

$$\sigma_{uT} = 72.6 + 1.31K_{IcM} \quad (14)$$

The plot shows a strong linear relationship between TL fracture toughness and tensile strength, σ_{uT} , at all moisture contents. The correlation resulted in an r

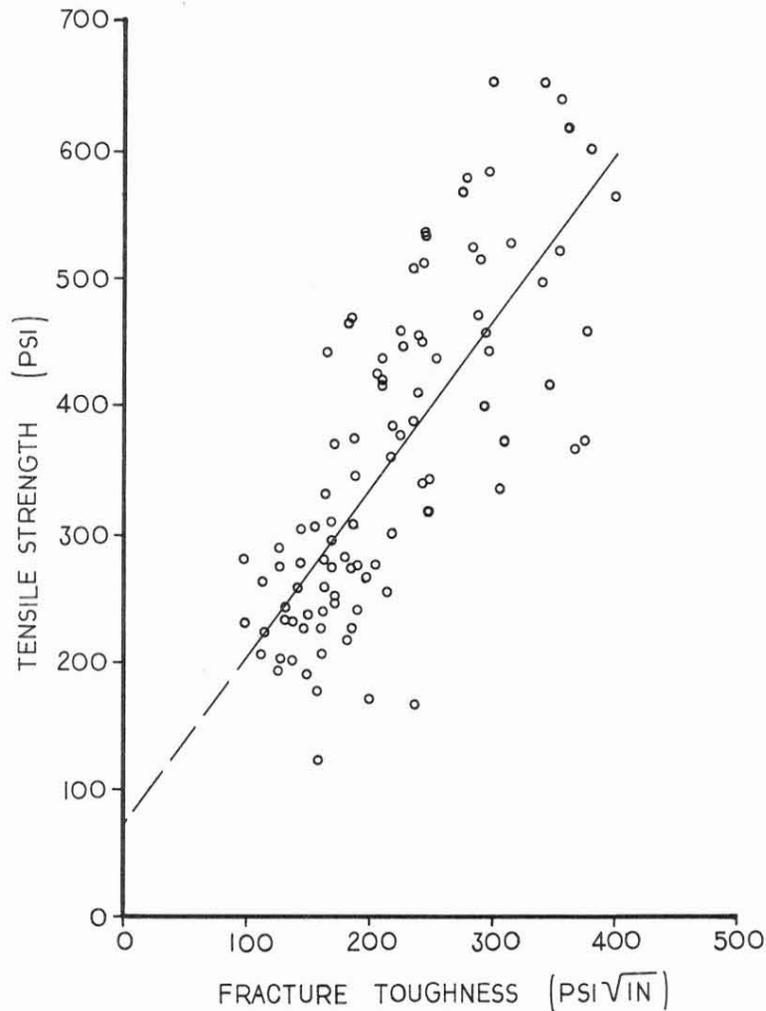


FIG. 6. Relationship between tangential tensile strength and fracture toughness.

value of 0.756 and a coefficient of variation about the regression line of 0.237. Thus, the tensile strength of wood in the tangential direction at any specific gravity and moisture content can be predicted by first determining the fracture toughness value using (13) and substituting the result into (14).

DISCUSSION

Research (Pellicane 1980) has shown that perpendicular-to-grain stresses control the tensile strength of lumber over a large range of angles of load to grain, suggesting that the crack system studied in the current work may be one of the most critical factors governing the strength of lumber. However, before meaningful data could be collected for wood, a decision had to be made on specimen configuration and load level at which the fracture toughness is evaluated. The specimen size and crack width selected were chosen to produce a minimum

difference between orthotropic and isotropic analyses (Walsh 1972) and in the range where the length-to-width ratio variation had no significant effect on the fracture toughness value (Barrett 1976; Porter 1964). The pop-in load, determined by the crack opening displacement, proved to be the most reliable value for the fracture toughness computation.

The K_{Ic} values obtained by the pop-in load method are similar to those of previous studies (Forintek 1979; Pellicane 1980; Pugel 1980). Also, the trends of K_{Ic} with respect to moisture content and specific gravity agree with the relationships found for most other mechanical properties of wood, i.e., a positive correlation with S_g and a negative correlation with M up to FSP (Bodig and Goodman 1972; Leicester 1974; Markwardt and Wilson 1935; Palka 1973; USFPL 1974). It is reasoned that a high density specimen provides more resistance to crack propagation than a low density specimen due to the higher concentration of wood substance.

The fracture toughness-moisture content relationship for all but two species was strongly negative. The lack of significant relationships for redwood and western redcedar has also been noted for tension perpendicular-to-grain strength. In fact, both Markwardt and Wilson (1935) and the *Wood Handbook* (1974) report slightly higher perpendicular-to-grain strength values at green than at 12% moisture content for these two species. It can be speculated that this phenomenon is probably due to the development of a severe moisture gradient along the specimen cross section caused by blockage of moisture movement pathways by extractives. In turn, severe moisture gradient produces higher drying stresses causing development of cracks in the specimens. These cracks then result in lower tensile strength and fracture toughness perpendicular to grain. Thus, it is not surprising that high extractive content species do not follow the same relationship as species with low extractive content.

The similar effect of moisture on fracture toughness and tensile strength perpendicular to grain, σ_{uT} , coupled with the strong regression of the two for all species, suggests that K_{Ic} and σ_{uT} are somewhat analogous. Considering this premise, and the fact that perpendicular-to-grain strength values normally respond erratically with changes in moisture content (USFPL 1974), the r values of the fracture toughness-moisture content regressions (Table 2) can be considered extremely good.

The K_{Ic} prediction procedure requires that softwoods be divided into two groups: those with low, and those with high extractive contents. The low-extractive species are represented by the combined regression line of eight species, while no moisture effect should be considered for high-extractive species. Because of the wide variety of softwoods studied, other softwoods are expected to behave similarly to the two groups tested.

The maximum error associated with use of the combined regression line on moisture content in Fig. 5, occurs with western larch. This error ranges from 24% at 6% moisture content to zero at fiber saturation point. The error increases with decreasing moisture content since the normalized K_{Ic} is based on the green predicted value. Even for the most extreme test case, the maximum error is not excessive. However, it is possible that some species, not included in the tests, may produce a slightly higher deviation. The regression analyses produced highly

significant relationships for K_{Ic} prediction, considering the inherent variability of wood.

The prediction procedure is illustrated by the following example. If the fracture toughness of green eastern hemlock with a specific gravity of 0.39 is desired, the computation using (5) would result in 166 psi·in^{1/2}. If the fracture toughness value is needed at 12% M then (12) would produce a predicted K_{Ic} of 266 psi·in^{1/2}.

The relatively strong regression between ultimate tensile strength, σ_{uT} and fracture toughness, K_{IcTL} , supports the validity of fracture mechanics for wood. In other words, tensile strength is most likely controlled by flaws (cracks) either inherent or induced in the material. The association between these two properties is intuitively understandable and was shown to be theoretically feasible by Pellicane (1980), who obtained the best agreement between experimental and simulated strength distributions under the assumption that K_{Ic} and σ_u are positively correlated. In the current research, a wide variety of conditions was incorporated. Moisture content ranged from air-dry (about 6%) to green and specific gravity from 0.30 to 0.58.

SUMMARY AND CONCLUSIONS

This research was undertaken primarily for the purpose of establishing prediction relationships for mode I TL fracture toughness of softwood species. Fracture toughness was calculated using an empirical equation developed under the assumption of isotropy. A procedure has been established to predict the value of fracture toughness of clear wood, which in turn is needed to predict the strength of wood. The prediction relationships are based on two of the most important variables: moisture content and specific gravity. Specific gravity adjustment can be performed with no distinction between species for green fracture toughness. The moisture content effect suggests that softwoods be separated into two groups according to level of extractive content. The low-extractive species demonstrated significant negative correlation with moisture, while high-extractive species need not be adjusted for moisture condition when predicting mode I fracture toughness in the TL system. *Fracture toughness value at room temperature may now be predicted for any softwood with the knowledge of only moisture content and specific gravity.*

Prediction equations developed in this work for moduli of elasticity in the tangential and longitudinal directions may also be used for any softwood species at any moisture content.

A definite positive relationship between tangential tensile strength and fracture toughness was established for the combined data of ten species. The existence of such a relationship supports the applicability of fracture mechanics to wood and the contention that cracks control the tangential tensile strength of wood.

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