Wood Sci. Technol. 28: 147–157 (1994)

Wood Science
and Technology

Factors affecting mode I fracture energy of plantation-grown red pine *

I. Smith and **Y. H. Chui**, Fredericton, New Brunswick, Canada

Summary. Mode I fracture energy of premature plantation-grown red pine is discussed, for crack growth in the longitudinal direction. It is demonstrated that fracture energy is influenced by moisture content at test and the direction that stress is applied in the radial-tangential plane. Secondary influences of moisture conditioning and density on fracture energy were observed, with the severity related to the moisture content of the material at test. Discrepancies with findings in the literature are identified and discussed. It is likely that results of this study apply to other conifer species with low extractive contents.

Introduction

Beginning with pioneering work in the 1960's, it has become accepted that fracture mechanics can replace empiricism for a range of timber engineering problems (Valentin et al 1991). Design code provisions based on fracture mechanics concepts have already found their way into practice. At the moment, this is restricted to control of cleavage type failures at corners of notches in beams (SAA 1982), and control of shear induced growth of centre line end splits in lumber (CSA 1989). Early work concentrated on linear elastic fracture mechanics (LEFM) methods (FCC 1979). LEFM methods can be expected to yield an accurate prediction of the load level at which a crack in a structural component will grow, if the fracture process zone is small compared to the length of the crack. Boström (1992) has shown that there is non-linear material behaviour in the fracture process zone when fibers are parted by tensile stress normal to their axes or shear stress parallel to their axes (modes I and II, Fig. 1). He also demonstrated that assumption of a LEFM behaviour can lead to erroneous results, for example, in tests to characterise the mode I fracture toughness, K_{Ic}, using an ASTM compact tension specimen (ASTM 1981). Boström's work provides a potential explanation for specimen size related influences on fracture toughness observations reported in the literature, and beam size related errors in predictions of failure loads for end notched timber beams.

Recently, emphasis has shifted to energy methods where total energy release rate is calculated, rather than separated into different fracture modes as in LEFM.

* *The work was undertaken with financial support from the Natural Sciences and Engineering Research Council of Canada under operating grants OGP 0004417 and OGP 0109473*

Neglecting any failure mode and direction of crack growth dependencies in fracture energy, Gustafsson (1988) demonstrated that simple design expressions can be obtained by balancing the change in a system's strain energy with energy required to form a fracture surface. Boström (1992) combined fracture energy observations with a "Fictitious Crack Model" to accurately predict behaviour of ASTM compact tension specimens, and to model formation of drying cracks in lumber. Generally, energy methods show great promise for situations where the fracture process zone is not small compared with the length of a crack. This opens the door to accurate prediction of fracture behaviour in notched small dimension timbers, in mechanical connections made with fastenings such as nails, bolts, shear plates or split-rings, and to reliable interpretation of results from "standardised" fracture property tests.

There is not yet general agreement concerning how fracture energy of wood should be estimated for the various failure modes illustrated in Fig. 1. In this paper mode I fracture energy for complete failure is denoted G_{IfNL}. The subscript NL signifies stress is applied normal to the longitudinal (grain) direction and crack growth is in the longitudinal direction. Mode I is studied because this has several important applications, and because it is the only mode for which some agreement has been reached on a test method. Fracture energy observations discussed below were obtained following the draft ISO method proposed by Larsen and Gustafsson (1989). It should be noted that G_{IfNL} observations differ from G_{Ic} values reported in the literature. The parameter G_{Ic21} is the mode I critical fracture energy for stress in the 2-direction and crack growth in the 1-direction. Critical fracture energy G_{Ic21} is proportional to the square of the critical stress intensity factor K_{Ic21}. This presumes perfect brittle-elastic material behaviour (Bodig and Jayne 1982).

Larsen and Gustafsson (1990) summarise mode I fracture energy data pooled by twelve institutes, as part of a collaborative evaluation of the draft ISO fracture energy test. For conifer species, pooled data showed a strong dependence of G_{IfNL} on density, over a density range 350 to 800 kg/m^3. No influence on G_{IfNL} was found from the direction in which stress is applied within the radial-tangential (R-T) plane. Most of the results reported by Larsen and Gustafsson are for moisture contents at test in the range 10 to 15 percent. Those authors concluded that "There is not enough data to indicate whether the fracture energy is dependent on the moisture content". Rug et al. (1990) conducted a series of tests that included an evalution of sets of European redwood specimens manufactured from mechanically stress graded lumber belonging to strength class C7 of the draft stan-

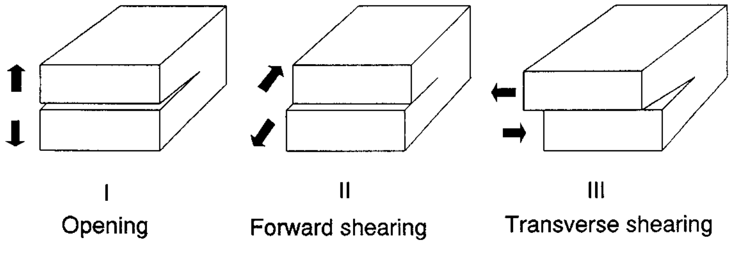

Fig. 1. Primary fracture modes

dard EUROCODE 5. Their tests conformed to the draft ISO method for estimating fracture energy. After 'cutting and gluing', sets of specimens were conditioned to nominal moisture contents of 12, 18 and 24 percent. It was concluded that there was a small decrease in the mean fracture energy up to a moisture content at test of 18 percent. There was a slight but continual reduction in fracture energy at the 5 percentile level of exclusion with increase in moisture content at test, 12 to 24 percent. Overall, Rug et al did not find a strong influence from moisture content on G_{IfNL}. Reliable insights into the influence of moisture conditioning on fracture behaviour of wood depend on knowing what the moisture history was from the time the tree was felled to the time of test. There is no record of the overall moisture conditioning history of material tested by Rug et al, so the study cannot yield reliable information on how moisture conditioning influences fracture energy estimated using the draft ISO method.

According to the literature, there are clear dependencies shown by K_{IcNL} on moisture content at test and the stressing direction in the R-T plane (e.g. see Valentin et al 1991). Thus it seems that both moisture content and 'stressing direction' should influence G_{IfNl} significantly, even though there is no clear indication of this in the literature. Concerning the influence of moisture content, it is essential to recognise the possible influence of moisture conditioning, as distinct from moisture content at test. Overall, it seems that "... there is still a lot of experimental and theoretical work left to do, especially regarding the evaluation of the experiments, because of the orthotropy, and the effect of moisture conditioning on the fracture properties" (Valentin et al 1991).

Related to the above, a study was undertaken to elucidate factors that affect mode I fracture energy of red pine (*Pinus resinosa* Ait.). Red pine was studied as part of a larger programme of work at the University of New Brunswick on physical and mechanical properties of fast grown conifers. Primary attention was focused on the influences of moisture conditioning, and moisture content at test on G_{IfNL}. Secondary attention was focused on the direction of stressing in the R-T plane, density and growth ring width. No attention was directed toward effects of the test method or specimen size.

Methods

Material was sampled in green condition from flat sawn boards from three premature red pines grown in a plantation in southwest New Brunswick, Canada. A total of five 25 × 150 mm rough sawn boards were used (three from one tree, and one from each of the other two). The boards were planed to a 20 mm thickness prior to cutting of specimens. Cutting patterns avoided defects such as knots, allowing production of 500 mm long sticks of clear wood, Fig. 2, and producing nine sticks per board. The sticks were sorted into groups such that each group contained one from each of the three length positions in every board. Within-board group matching was diagonally across the 3 × 3 grid defining length and width positions. This sampling strategy provided three matched sets with fifteen sticks per set. A set of sticks subsequently provided fracture energy specimens representing two or three different combinations of moisture conditioning and moisture centent at test.

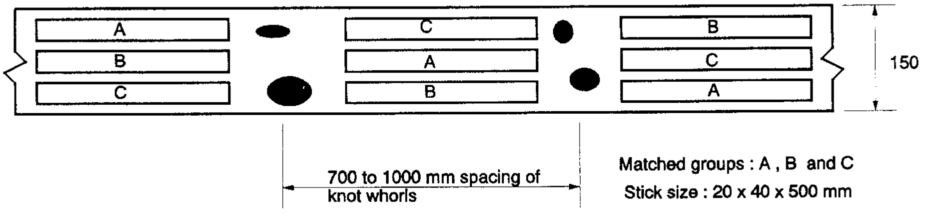

Fig. 2. Schematic of within-board cutting of sticks of clear wood

The programme of tests was designed to provide fracture energy data for material that was very carefully conditioned to avoid, as far as possible, drying defects. Specimens in green condition were included as a control group. Other specimens were tested at nominal moisture contents of 24, 18, 12, 10 and 7 percent. All material to be tested at 24 percent or a lower nominal moisture content was conditioned together, by incrementally reducing relative humidity of the surrounding air. A 24 percent condition was reached in about six weeks. Material to be tested at 18 percent or a lower moisture content was further conditioned, and so on. The specimens tested at 7 percent moisture content had been conditioned over a period of 30 weeks when tested.

Tests for estimating fracture energy, G_{IfNL}, followed the draft ISO method proposed by Larsen and Gustafsson (1989) but with minor variations. Figure 3 illustrates the general arrangement of a test specimen. Both end supports had bearings that allowed horizontal freedom in the direction of span and rotational freedom about the two horizontal axes. Out-of-plane rotation of the specimen was not allowed at the steel prism attached to the loading head. These details allowed unconstrained relative rotations of cross-sectional planes in a specimen, and avoided introduction of axial force in a specimen at "large" displacements. In all other respects the test arrangement used matched exactly requirements of the draft ISO method. Technically the arrangement used and the draft ISO arrangement are equivalent, but that used by the authors is believed simpler to implement.

Using flat-sawn boards, the nominal orientation of fracture observations was the TL system. However, there was substantial deviation from this owing to growth ring curvature within boards. Availability of a range of stressing directions in the radial-tangential (R-T) plane provided valuable subsidiary information, as will be discussed later. All tests were conducted in environmental conditions of 20 °C and 65 percent relative humidity. The 3 mm wide 'saw cut' used as the starter notch, Fig. 3, was made immediately prior to testing. Specimens were not exposed to ambient room conditions for more than about five minutes, including the time for testing. Actual times to specimen failure (collapse) ranged from 1 to 3 minutes, which compares with a range 1 to 2 minutes specified in the draft ISO standard for a 40 mm deep specimen.

Part way through the study, it was decided to add a subsidiary programme of tests. This secondary series was designed to give an insight into whether choice of a moisture conditioning regime can influence estimates of G_{IfNL}. A set of tests were conducted on material that was very carefully resaturated, following careful drying to 10 percent moisture content as described before. Resaturation was achiev-

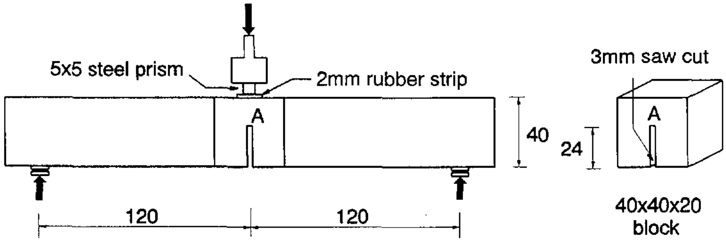

Fig. 3. Test arrangement for fracture energy

ed by first placing material in a conditioning chamber and gradually increasing the relative humidity, up to 85 percent, over several weeks. Finally, the material was placed under water for several more weeks. This whole resaturation process lasted about three months. The set is designated series G-10-G in subsequent discussion. Another set of tests were conducted on material that was dried and resaturated as just described, then left on the laboratory bench for about three months, achieving a final equilibrium moisture content of about five percent. The set is designated series G-10-G-5 in subsequent discussion.

Subsidiary tests were done to determine density (D) and moisture content (M) of each fracture energy specimen, using one half of a broken fracture energy specimen for each test. Measurements were taken at the time of testing for ring width (RW) and orientation of the starter cut within the R-T plane (θ). If θ is zero, stress is in the radial direction. If θ is 90°, stress is in the tangential direction. In all cases crack growth is in the longitudinal direction.

Results and discussion

Tables 1 and 2, and Fig. 4 and 5 summarise the results. Good matching of material in the various groups of specimens is indicated by the means and coefficients of variation for variables D, RW and θ. This suggests that reliable deductions can

Table 1. Summary of test results: drying from green

	Moisture condition at test					
Property	Green	24 Percent	18 Percent	12 Percent	10 Percent	7 Percent
$G_{IfNL}(J/m^2)$	455 (19.6)[1]	509 (25.0)	565 (21.1)	435 (22.2)	403 (18.1)	345 (18.9)
D[2](kg/m^3)	319 (8.3)	325 (9.5)	318 (9.0)	323 (8.8)	322 (8.6)	322 (7.9)
RW(mm)	3.92 (25.6)	3.77 (21.5)	3.61 (14.6)	3.97 (22.6)	3.79 (25.4)	3.85 (23.1)
θ(deg.)	61.7 (44.9)	60.7 (41.2)	57.0 (43.2)	58.9 (43.5)	57.7 (45.5)	58.3 (46.2)
M[3](%)	>30 (N/A)	23.9 (4.0)	17.8 (5.4)	11.8 (3.5)	10.0 (4.4)	6.7 (6.0)
Number of replicates	15	14	15	19	15	15

Notes:
[1]) Values given are means, with coefficients of variation (percent) in parentheses
[2]) Densities are based on oven dry weight and green volume
[3]) M signifies moisture content at the time of testing

Table 2. Summary of test results: moisture cycled

	Moisture regime	
Property	G-10-G	G-10-G-5
G_{IfNL}(J/m^2)	428 (29.1)[1]	276 (26.5)
D[2](kg/m^3)	338 (9.7)	330 (9.0)
RW(mm)	3.62 (17.5)	3.65 (17.6)
θ(deg.)	56.3 (46.2)	59.0 (47.3)
M[3](%)	>30 (N/A)	4.9 (6.4)
Number of replicates	15	10

Notes: [1]) Values given are means, with coefficients of variation (percent) in parentheses
[2]) Densities are based on oven dry weight and green volume
[3]) M signifies moisture content at the time of testing

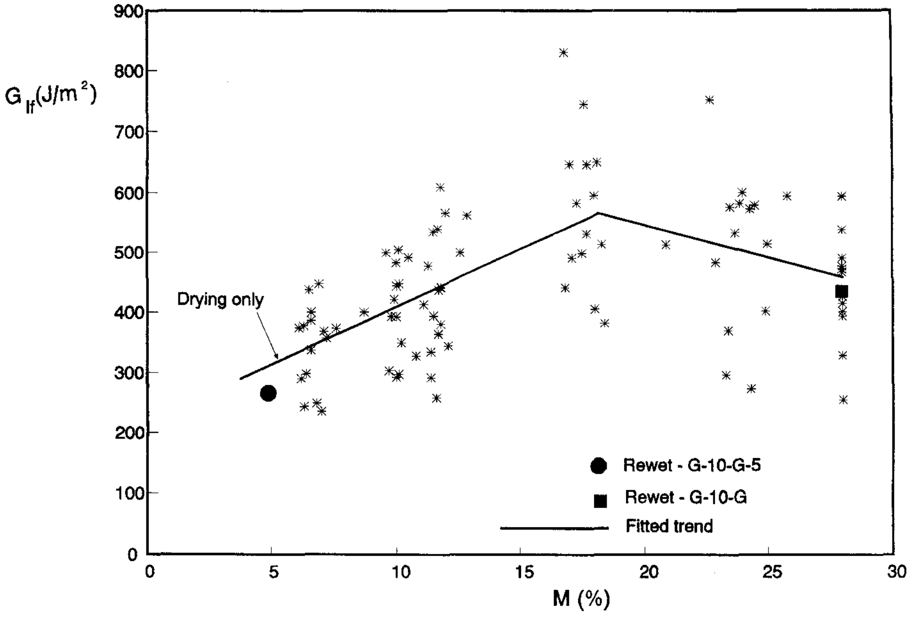

Fig. 4. Fracture energy vs moisture content (mean values only for series G-10-G and G-10-G-5)

be made regarding influences of moisture conditioning and moisture content at test. The G_{IfNL} values were not calculated from the expression proposed in the draft ISO (Larsen and Gustafsson 1989). Instead, the expression for a similar test method for mortar and concrete was used, because it allows a correction for the influence of specimen overhangs at the ends (RILEM 50-FMC 1985). The test arrangement proposed by Larsen and Gustafsson requires a steel ball-bearing and a small steel prism situated beneath the loading head of the test machine. Masses

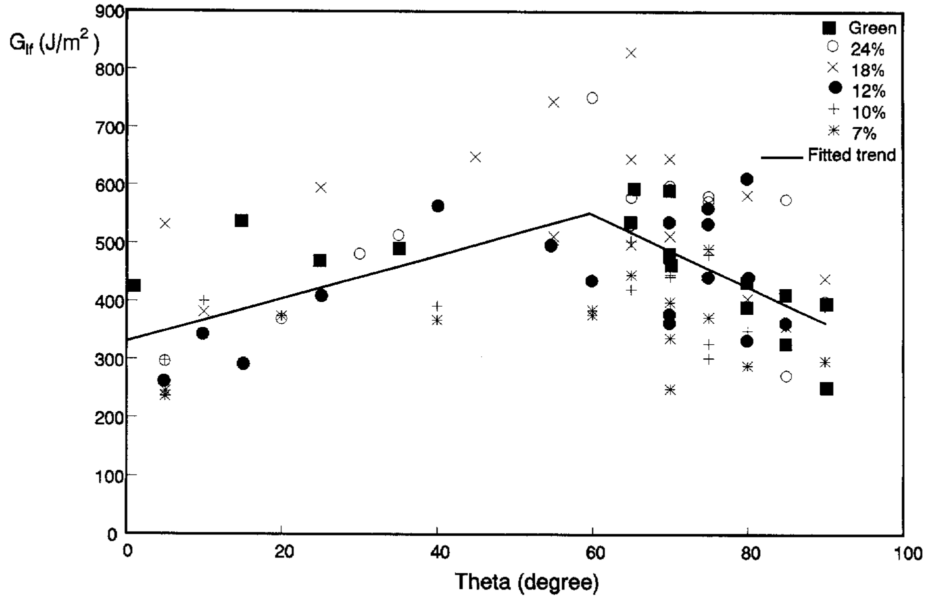

Fig. 5. Fracture energy vs orientation of the fracture plane (series G-10-G and G-10-G-5 excluded)

of these elements should strictly be taken into account if they are not supported by the test machine, i.e. if influences of their masses are not discounted in the force recorded by the machine. A correction can be made to the work done by the midpoint force, to account for contributions from the masses of loading arrangement parts resting directly on the specimen (RILEM 50-FMC 1985). In the tests reported here the only mass resting on the specimen was the 2 mm rubber strip shown in Fig. 3, and which made a negligible contribution to estimates of G_{IfNL}. Had no correction been made to account for the influence of the specimen overhangs, fracture energies summarised in Tables 1 and 2 would have been in the order of 1 to 2 percent higher than shown. Corrections that should be applied if a ball-bearing and a steel prism rest on the specimen will increase estimates of fracture energy. Thus, fracture energy results reported by Larsen and Gustafsson (1990) and Rug et al (1990) will contain counteracting errors associated with neglect of the contribution of the overhangs and neglect of 'supported' masses when determining the total work done at failure. A reanalysis of results given by Rug et al suggests that strict adherence to the test arrangement and the method for analysis of results laid down in the draft ISO (Larsen and Gustafsson 1989) will typically result in overestimation of fracture energy by 1 to 2 percent, compared with estimates following procedures adopted by the authors. Thus errors introduced during estimation of fracture energy will reflect both the test arrangement and analysis of results employed, but their magnitudes tend to be small.

One data point was excluded from the statistical analyses. This represents a 24 percent moisture content specimen that contained a small resin pocket offset about 5 mm from the fracture plane. For that specimen G_{IfNL} was 1 102 J/m^2 and the time to failure was 4.68 minutes. This was by far the highest fracture energy observed in any series.

The sensitivity of G_{IfNL} to the moisture content of the wood at test is illustrated in Fig. 4. It was assumed for the purposes of the figure that the fiber saturation point corresponds to a moisture content of 28 percent. This parallels the assumption made by Petterson and Bodig (1983) for conifers with a low extractive content. The plotted data suggests that the trend reverses at about 18 percent moisture content. Two trend lines are fitted to the data. The line with a positive slope ($R = 0.635$) is a regression line through data points corresponding to 7 percent to 18 percent moisture content groups. The line with a negative slope ($R = 0.387$) was obtained by fitting to data for groups with moisture contents equal to or greater than 18 percent.

Since fiber saturation points can vary between 25 to 30 percent moisture content (Desch and Dinwoodie 1981), additional regression analyses were conducted to assess the sensitivity of the peak G_{IfNL} location to the assumed fiber saturation point. It was found that the location of peak G_{IfNL} is not sensitive if the fiber saturation point is assumed to be anywhere in the range 25 to 30 percent. Thus 18 percent appears to be a reliable estimate of the moisture content at test associated with the peak fracture energy.

For moisture contents at test greater than 18 percent, the data displays a relative sensitivity in mean G_{IfNL} similar to the sensitivity in G_{IcTL} that can be deduced from Petterson and Bodig (1983) for conifers with a low extractive content. Petterson and Bodig's study was related to K_{IcTL}. The authors have deduced equivalent G_{IcTL} values based on LEFM concepts (Valentin et al 1991) and material compliance information (Bodig and Jayne 1982). For moisture contents at test less than 18 percent there is a radical departure of the trend in Figure 4 from that which would be predicted from Petterson and Bodig's work, and assuming a brittle-elastic behaviour. Those researchers observed a continuous increase in K_{IcNL} with any reduction of moisture content from the fiber saturation point down to about six percent. The reason why different moisture sensitivities are observed for K_{IcNL} (G_{IcNL}) and G_{IfNL}, is believed to lie in the aforementioned sensitivity of small timber elements to non-linear material response in the fracture process zone. It seems reasonable to suppose that the degree of non-linearity (softening behaviour), and the extent of the fracture process zone, will depend upon the moisture content at test.

The mean results from series G-10-G and G-10-G-5 are plotted on Fig. 4. This enables a comparison with the trend relationship from the primary programme of tests. To evaluate the effects of moisture cycling, statistical testing was performed on the mean G_{IfNL} values for the green and G-10-G specimens. A *t* test failed to prove that there are significant differences between the mean fracture energies of the green and G-10-G specimens. However, if the difference is small, any differences in mean values may have been masked by the large variances of the data sets. Comparison of Tables 1 and 2 shows that variability in fracture energy between replicates increases due to moisture cycling. When data was analyzed on a within board basis, it was found that statistically three of the five boards had significantly higher within board mean fracture energies for the green condition than for the G-10-G condition. In one board, the mean G_{IfNL} values for green and G-10-G conditions were almost equal. It appears that some boards were more prone to damage than others. Between board differences in moisture sensitivity may manifest themselves as a 'quality' related phenomenon in commercially dried lumber products. However, that is speculation that cannot yet be substantiated.

The study indicates that a degree of damage can occur even with very careful drying conditioning over severval months. Relatively severe drying practices, e.g. commercial kiln drying, could produce damage that increases the variability in fracture energy by significant amounts. This raises serious concern about using results from tests on material whose moisture conditioning is unknown. It seems that the only moisture condition in which a true observation of fracture energy can be made reliably is the green condition.

Examination of data for each moisture content group reveals that a maximum G_{IfNL} value is observed when θ is equal to about 60°. It was found that the θ value at which maximum G_{IfNL} occurs does not vary appreciably between the different moisture content groups. Thus all data from the primary programme of tests are combined and presented in Fig. 5. Two regression lines are plotted to represent what was judged to be a bi-linear tendency in the data trend. The line with a positive slope relates to θ values less than 60°, whereas the line with a negative slope represents specimens with θ values greater than 60°. The regression coefficients for the two lines are 0.666 and 0.486 respectively. Based on this analysis, a maximum G_{IfNL} value is obtained when stress is applied at an angle of about 30° to the tangential plane. The trend fitted in Fig. 5 shows mean G_{IfTL} to be around 10 percent higher than mean G_{IfRL}. This is qualitatively similar to findings of Johnson (1973) who studied fracture toughness of Douglas fir and Western red cedar. However, as discussed by Valentin et al (1991), the literature is not consistent concerning sequencing of fracture properties for RL and TL systems. The reasons are unclear but seem to be related to the species, type of specimen and rate of crack growth.

A strong inverse dependence of density on the ring width was found ($R = 0.71$, $SE = 19.63$ kg/m^3). Because of the inverse relationship between these two parameters, only the relationship between G_{IfNL} and density will be discussed. Table 3 summarizes the results of correlation analyses between fracture energy and density for each moisture content at test, for tests in the primary programme. It is found that there is no relationship between the two variables for tests in the green condition. Statistical testing revealed that the slope of the regression line is not significantly different from zero. As the moisture content at test is reduced the

Table 3. Summary of correlation analyses showing dependence of G_{IfNL} on D

Moisture Condition	Correlation Coefficient	Standard Error (J/m^2)
Green	0.01	90.75
24 Percent	0.42	124.6
18 Percent	0.58	104.5
12 Percent	0.66	76.2
10 Percent	0.64	60.1
7 Percent	0.60	56.0

dependence of G_{IfNL} on density increases. The reason for this is unknown. Kretschmann et al (1990) observed similar dependencies based on correlations between fracture toughness, density and moisture content at test, for southern pines. Density related trends discussed here should not be confused with those found when the density range is artificially expanded by pooling data from tests on different species.

Comparing, in a global sense, with fracture energy values reported by Larsen and Gustafsson (1990), it appears that the values given here are relatively high. Using density as a predicting variable, mean G_{IfNL} values in Table 1 are in the order of 200 J/m^2 higher than expected from regressions given by Larsen and Gustafsson. A specimen size effect reported by those authors would compound the discrepancy. There is drying damage (cracks) in commercial lumber type products due to development of uneven shrinkage and uneven moisture content distribution. This is most accentuated during fairly rapid and high temperature kiln drying (Zhou and Smith 1991). It is suspected that drying related damage in commercial lumber materials used in tests reported by Larsen and Gustafsson led to an underestimation of the "real" fracture energy. However, there is no hard evidence to support or disprove this suspicion. Allowance for existence of drying damage will be necessary in design, but should not be dealt with in any unintended and uncontrolled fashion through observation of apparent G_{IfNL} values that include influences of drying degrade.

The results and discussion presented here illustrate a dependence of mode I fracture energy of red pine on physical (and probably also anatomical) features of test materials, moisture conditioning, and moisture content at test. Above all, the findings illustrate a need to clearly control and record parameters associated with test observations on fracture energy, whatever the species considered.

Conclusions

The following conclusions apply to clear wood from plantation-grown red pine:

1. Reduction in moisture content at test from the fiber saturation point to 18 percent results in an increase in mode I energy for complete separation of fracture surfaces, when crack growth is in the longitudinal direction. Below 18 percent moisture content, any reduction in moisture content at test results in a reduction in fracture energy.

3. If test material is not conditioned carefully to moisture contents below the fiber saturation point, damage will occur in some pieces. This may not lead to statistically significant reductions in mean estimates of G_{IfNL}, but the variance can increase by a significant amount.

3. Mode I fracture energy for crack growth in the longitudinal direction depends upon the direction in which stress is applied in the R-T plane.

4. Within species correlation of G_{IfNL} values with density depends upon the moisture content at test. Lowest correlations are obtained for moisture contents close to the fiber saturation point.

Most of these conclusions may apply to other conifer species and other tree growth environments. Further work is required to determine mechanisms underlying relationships discussed here.

References

American Society for Testing and Materials. 1981: Standard test method for plane strain fracture toughness of metallic materials. ASTM, Philadelphia, ASTM 339–381

Bodig, J. and Jayne, B. A. 1982: Mechanics of wood and wood composites. Van Nostrand Reinhold Company, New York, NY

Boström, L. 1992: Method for determination of the softening behaviour of wood and the applicability of a nonlinear fracture mechanics model. Report TVBM-1012 (Doctoral thesis), Lund Institute of Technology, Lund, Sweden

Canadian Standards Association. 1989: Engineering design in wood (limit states design). CAN/CSA 086.1-M-89, CSA, Rexdale

Desch, C. H. and Dinwoodie, J. M. 1981: Timber: Its structure, properties and utilisation. 6th Edition. The MacMillan Press Ltd:, London

Forintek Canada Corp. 1979: Proceedings of the first international conference on wood fracture, FCC, Vancouver, Canada

Gustafsson, P. J. 1988: A study of the strength of notched beams. Paper No. 21-10-1. Proceedings of the meeting of International Council for Building Research Studies and Documentation Working Commission W18A – Timber Structures. University of Karlsruhe, Karlsruhe, Germany

Johnson, J. A. 1973: Crack initiation in wood plates. Wood Science 6: 151–158

Kretschmann, D. E., Green, D. W. and Nelson, W. J. 1990: The effect of moisture content on mode I fracture toughness in southern pine. Proceedings of the International Union of Forestry Research Organizations/S5.02 – Timber Engineering Meeting, Technical University of Denmark, Horsholm, Denmark

Larsen, H. J. and Gustafsson, P. J. 1989: Draft standard: Determination of fracture energy of wood for tension perpendicular to the grain. (Unpublished Report), Lund Institute of Technology, Lund, Sweden

Larsen, H. J. and Gustafsson, P. J. 1990: The fracture energy of wood in tension perpendicular to the grain – Results of a joint testing project. Paper No. 23-19-2. Proceedings of the Meeting of International Council for Building Research Studies and Documentation Working Commission W18A – Timber Structures, University of Karlsruhe, Karlsruhe, Germany

Petterson, R. W. and Bodig, J. 1983: Prediction of fracture toughness of conifers. Wood and Fiber Science 15: 302–316

Rilem 50-FMC Committee Fracture Mechanics of Concrete. 1985: Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. Materials and Structures 18: 285–290

Rug, W., Badstube, M. and Schöne, W. 1990: Determination of the fracture energy of wood in tension perpendicular to the grain. Paper No. 23-19-1. Proceedings of the Meeting of International Council for Building Research Studies and Documentation Working Commission W18A – Timber Structures. University of Karlsruhe, Karlsruhe, Germany

Standards Association of Australia. 1982: Australian timber engineering code. AS 1720-1975. SAA, Sydney, New South Wales

Valentin, G. H., Boström, L., Gustafsson, P. J., Ranta-Maunus, A. and Gowda, S. 1991: Application of fracture mechanics to timber structures RILEM state-of-the-art report. Research Notes 1262, Technical Research Centre of Finland, Espoo, Finland

Zhou, H. and Smith, I. 1991: Influence of drying treatments on bending properties of plantation-grown white spruce. Forest Products Journal 41: 8–14

(Received August 18, 1992)

I. Smith, Ph.D., P.Eng., FIWSc.
Y. H. Chui, Ph.D., AIWSc.
Wood Science and Technology Centre
University of New Brunswick
Hugh John Flemming Forestry Centre
Fredericton, New Brunswick
Canada E3B 6H6