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Thickness and moisture content effect in the fracture toughness of Scots Pine

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Fracture toughness tests were performed on specially prepared specimens taken from a single tree. These were kiln dried, machined to various thicknesses and then sets of them conditioned to various moisture contents. It was found that about half the specimens were rejected because of warping and splitting for thicknesses greater than 10 mm, but below this the rejection rate decreased. Fracture toughness values showed thickness variations in the kiln dried state, but the toughness decreased and became constant when the moisture content was changed. An explanation is proposed in terms of residual stresses induced by the drying which increases the toughness and constraint stresses which cause a decrease. A characteristic length of the annual ring spacing seems appropriate in defining the various transitions.

1. Introduction

It is now well established that linear elastic fracture mechanics can be used to describe the fracture of wood parallel to the grain direction [1–3], but because wood is a natural product, substantial variability would be expected. Several studies (e.g. [2]) have examined the variation of the fracture toughness, K_{IC}, within a set of samples and have concluded that, although there is substantial scatter, K_{IC} is geometry independent and, therefore, of value in defining material properties. Developments in fracture mechanics concepts have reached the stage where design criteria using fracture mechanics have been introduced to timber design codes [4]. Information is available on the effect of thickness on fracture toughness [5] but the important parameter, moisture content, has been neglected.

Wood is cylindrically anisotropic (see Fig. 1) and there is a difference between toughness values in the two principal natural cleavage systems, TR and TL. The convention used here for defining crack growth is that the first symbol defines the normal to the plane of propagation and the second the direction of crack growth within that plane.

This paper uses single edge notch specimens prepared to give fractures in the TL system, as shown in Fig. 1, to examine the variation of toughness in Scots Pine with two practically important parameters, i.e. thickness and moisture content. In an attempt to isolate the two effects, it was decided to reduce variability to a practical minimum by cutting all the samples from the same tree and from a similar location within the trunk, and to prepare all the specimens using the same procedure.

2. Fracture mechanics concepts

In general, fracture cannot be predicted by simple calculations based on either gross or local stresses.

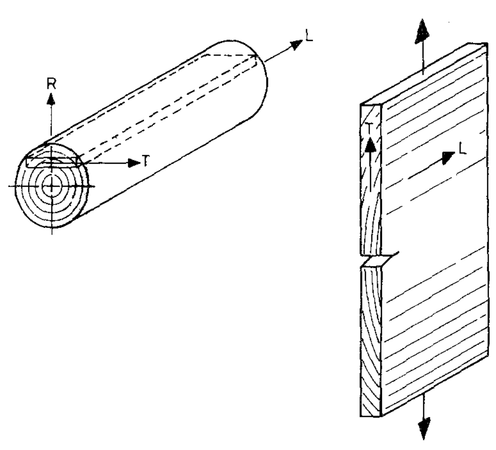

Figure 1 Principal directions and specimen orientation.

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Some materials, although normally ductile when tested in simple tension, fail in a brittle manner if tested after notching (inducing a flaw or crack). Fracture mechanics is thus based on the strength of a flawed member which, in turn, is represented by a notched specimen. When a piece of wood containing a notch or flaw (check) is stressed in tension perpendicular to grain direction, the notch surfaces move apart. This type of crack surface displacement is classified as the opening mode or Mode I. (The other modes of fracture, II and III, are defined as forward shear and transverse shear, respectively.)

The notch, or flaw, will have an elastic stress pattern associated with it and stress function solutions for these stresses, in terms of the applied stress, are available for various specimen geometries. These show that there is one parameter, K_1, the stress intensity factor, which relates the elastic stress field near the crack tip to the loading and geometry of the system. Any fracture criterion should thus be related to K_1 or to the applied stress, σ, but since σ is not constant on either gross or net area, it is postulated that K be constant and equal to K_{IC} at fracture. K_{IC} is a measure of the "fracture toughness" and is a material constant having the value:

$$K_{IC} = \sigma\sqrt{(\pi a)} \tag{1}$$

for an infinite plate containing a central crack of length $2a$.

For a single edge notch specimen subjected to a stress σ, the fracture toughness has been shown [6] by boundary collocation methods to be:

$$K_{IC} = \sigma Y \sqrt{a}, \tag{2}$$

where σ is the applied gross stress, a the crack length and Y the finite width correction factor:

$$Y = 1.99 - 0.41\left(\frac{a}{W}\right) + 18.7\left(\frac{a}{W}\right)^2 - 38.48\left(\frac{a}{W}\right)^3 + 58.8\left(\frac{a}{W}\right)^4, \tag{3}$$

where W is the specimen width.

3. Specimen preparation

A Scots Pine (*Pinus sylvestris*) was purchased from the Forestry Commission. The tree, aged 65 years, of approximate diameter 0.5 m and height 30 m, was cut down from the centre of the King's Forest, Thetford, Norfolk. The first 6 m was quite uniform and was cross-cut into 2 m lengths and then rip sawn into 380 mm x 70 mm planks, as shown in Fig. 2. The planks were then kiln-dried to a moisture content of approximately 12% and the specimens then machined from them. The specimens were prepared in the following sizes: thicknesses 3, 6 and 12 mm ($\frac{1}{8}$, $\frac{1}{4}$ and $\frac{1}{2}$ in.) with a width of 50 mm and a length of 150 mm; and thicknesses 25 and 50 mm (1 and 2 in.) with a width of 50 mm and a length of 250 mm.

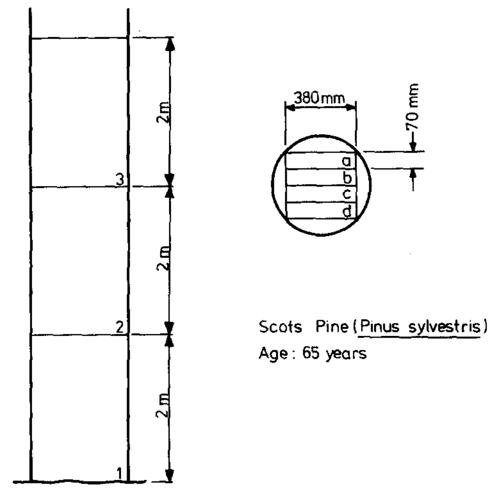

Figure 2 Cutting dimensions.

In all, some 400 specimens were prepared, and most were taken from positions a and d (see Fig. 2) in all three pieces. This is preferable to achieve consistency and, in fact, the planks from the b and c positions (which contain heart wood) showed considerable splitting and warping, and only small percentages could be used. The specimens were randomly divided into five groups covering the thickness range and then each set was conditioned as follows:

Set 1: placed in a dry air oven at 105° C to reduce the moisture content to zero;

Set 2: placed in a humidity room to achieve a moisture of 7%;

Set 3: unchanged at the kiln-dried condition, nominally at 12% moisture content but, in fact, 11.2%;

Set 4: as in Set 2, but for a 14% moisture content:

Set 5: as in Set 2, but for a 20% moisture content.

These values of moisture content were chosen since there is published strength data on moisture contents within this range [7]. In green timber, water is contained within the cell cavities and cell walls, and drying to the fibre saturation point (approximately 27%) removes the cell cavity water. Below this value, water is removed from the cell walls, resulting in shrinking and significant property changes. It was expected that strength would increase with decreasing moisture content below 27% [7].

The most significant feature of the sample preparation was the occurrence of splits and of warping. The drying process results in differential shrinking due to different tangential and radial shrinking gradients, and this sets up residual stresses within the structure of the wood. The distribution of these stresses is governed by the details of the grain structure which induces a random element in addition to the inherent variability of properties. In some cases, very high tensile stresses will result in spontaneous fracture (splits or shakes) and in others there will be distortion to correct for unbalanced stresses (warping). It should also be noted that machining will also influence the residual stresses since the surfaces have no stresses normal to them so that the residual stresses become less intense in the thinner specimens. This will be discussed later, but it is interesting to consider the percentages of specimens rejected prior to testing because of distortion or splitting, as shown in Table I.

The high rejection rate, as indicated in Table I, is partly due to the limitations imposed by the tensile test method. In tension testing, the specimens should be flat and not curved, otherwise bending stresses are imposed on the specimen when clamping it in the testing machine. For the 3, 6 and 12 mm thick specimens (length 150 mm), a radius of curvature of > 1.1 m was found to be acceptable. For the 25 and 50 mm thick specimens (length 250 mm), the value was > 2.5 m. All specimens that had radii of curvature less than these values were rejected.

Firstly, around half of all specimens were rejected, indicating a high residual stress level, and secondly, the thinner specimens show a substantial decrease in rejection rate in accordance with the residual stress argument.

TABLE I

Nominal thickness, H (mm)	3	6	12	25	50
Percentage rejection (R)	23	48	57	31* (57)	58

*Some bent specimens were shortened and used here because of a lack of material. The number in brackets is the rejection rate using the normal criteria.

The rejection rates (Table I) show that there is a transition from a constant rejection rate of around 57% to decreasing values for thicknesses less than 10 mm. Extrapolating this decrease gives a zero rejection rate for a thickness of about 2.2 mm. Because of the small number of points used, no great precision would be expected for these figures, but they do indicate a stress free thickness of about 2 mm and a transition to constant residual stress at about 10 mm.

4. Fracture toughness testing

The sharpness of the initial notch is important in fracture toughness testing and a preliminary test series was carried out with notches prepared in various ways. These used a single point cutter with an included angle of 10° and a tip radius of less than 10 μm, a razor blade (tip radius < 5 μm), a 60° cutter with a tip radius of 80 μm, and a fret saw with a tip radius of 300 μm. Table II shows the K_{IC} values, together with the standard deviation for each set of specimens, using these notching methods. The single point cutter and the razor blade give the same result and it was decided, therefore, to notch all the specimens with a single point cutter prior to conditioning, as the notch length can be controlled more accurately than with razor notching.

The specimens, having a range of crack lengths from 5 to 15 mm at each condition, were loaded via metal clamps and pin joints in an Instron testing machine at 0.5 cm min^{-1} with a temperature of 20° C and 60% relative humidity. The data obtained for each particular set of specimens of

TABLE II Effect of notching on K_{IC}. Scots Pine, 6 mm; moisture content, 11.2%; number of specimens tested for each notch type, 5

Notch	K_{IC} (MN m$^{-3/2}$)	Standard deviation (s)
Single point cutter (Tip radius < 10 μm)	0.42	0.017
Razor blade (Tip radius < 5 μm)	0.42	0.017
60° cutter (Tip radius = 80 μm)	0.46	0.031
Fret saw (Tip radius = 300 μm)	0.47	0.011

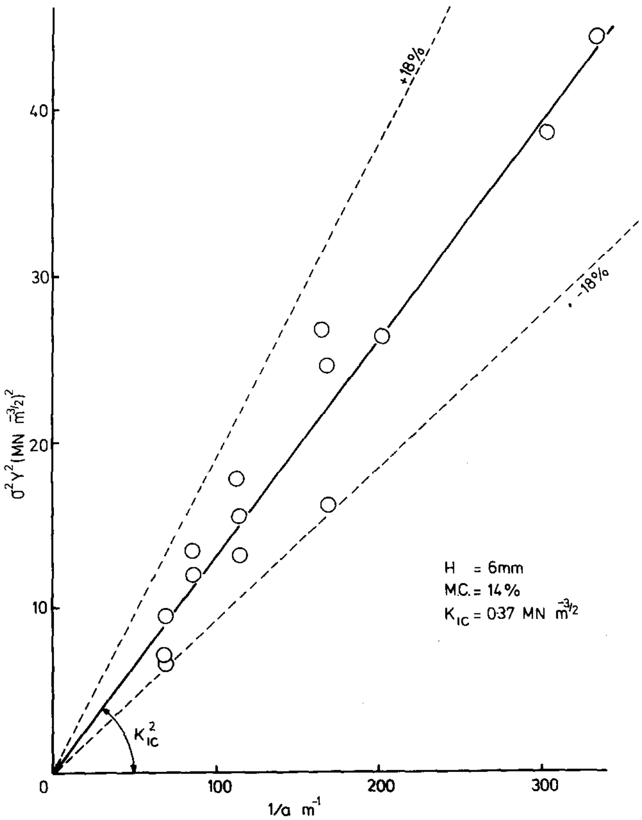

Figure 3 Typical K_c determination data.

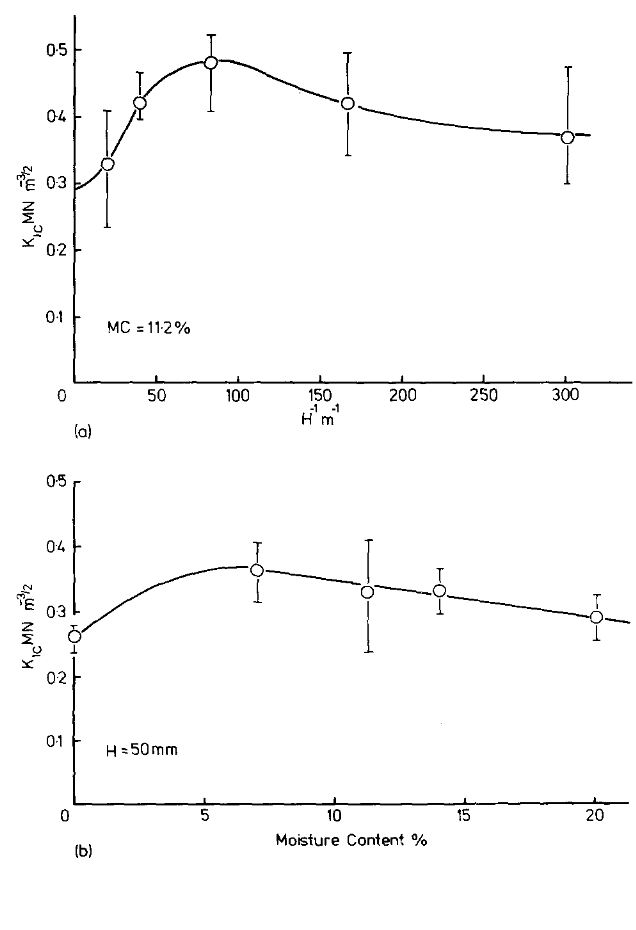

Figure 4 Typical K_{IC} data as (a) a function of inverse thickness and (b) moisture content.

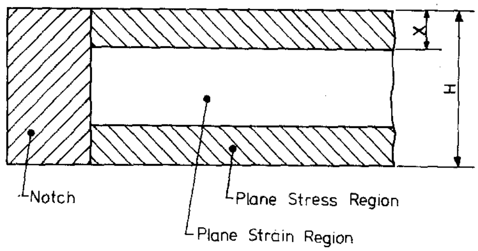

Figure 5 Stress state in specimen.

different thickness and moisture contents were curve-fitted to give the best straight line through the data points. A typical set of data is shown in Fig. 3 plotted as $\sigma^2 Y^2$ versus a^{-1}, indicating linearity and showing that K_{IC} is independent of crack length as required. In general, a range of ± 18% was recorded for all the data. The mean K_{IC} values, together with the standard deviations, are given for all sets of specimens in Table III.

Fig. 4 shows typical values of K_{IC} from Table III plotted against the inverse thickness and moisture content, respectively.

5. Discussion

There are some noticeable features of the data shown in Table III. In Set 3 (moisture content = 11.2%), there is a variation with thickness with a maximum at about 12 mm. The 3 mm thick specimens show very little variation between the sets with a value of around 0.37. Both the 0% and 20% moisture content sets show very little variation with thickness, except for a decrease for the 50 mm specimens, and again they average at around 0.37. The 14% set is rather similar to the 0% and 20% sets, but that at 7% does show some variation with thickness, although less than the 11.2% set. The effect of moisture content on K_{IC} shows generally an increase in fracture toughness for all thicknesses as the moisture content decreases from 20% to a maximum at around 10% and then the K_{IC} values tend to decrease. This effect has also been noted by Barrett [8].

A consistent explanation of these effects can be deduced in terms of the stress state in the specimens and, in particular, the residual stresses. As with the rejection rate data, the 3 mm results would suggest only slight residual stress effects since the free surfaces render the specimens stress-free, and thus the differences from the various moisture contents, which could arise from residual stresses, are eliminated. The 50 mm results are always low, indicating a decrease due to the higher constraint in this case. In addition, the changes in moisture content from the kiln-dried value (Set 3) indicate a general decrease and removal of thickness variations (except for that at 50 mm), suggesting that moisture content changes reduce residual stress effects.

A useful model for describing plane stress–plane strain effects has been used in other materials (e.g. [9, 10]) and has some utility here. Fig. 5 shows a cross-section of a specimen in which zones of width X near the surface are rendered stress free while the central region is maintained in a state of plane strain. If the K_{IC} values are K_{c1} in plane strain and K_{c2} in plane stress, then the average value recorded, K_c', may be computed from:

$$HK_c' = 2XK_{c2} + (H - 2X)K_{c1},$$

i.e.

$$K_c' = K_{c1} + \frac{2X}{H}(K_{c2} - K_{c1}). \qquad (4)$$

In general, $K_{c1} < K_{c2}$ because of the higher constraint so that a graph of K_c' versus inverse thickness should be linear with a positive slope and an intercept of K_{c1} at $H^{-1} = 0$. The extent of the plane stress region is given by:

$$X = \frac{1}{2\pi}\frac{K_{c2}^2}{\sigma_c^2}, \qquad (5)$$

where σ_c is the yield stress or that stress which results in gross deformation. The plane strain condition can only be maintained completely when there is sufficient material to provide the constraint and, in general, it only occurs for:

$$H > \text{about } 4X$$

although, from Equation 4, $K_c' = K_{c2}$ when $H < 2X$.

In applying this model to wood, it seems reasonable to propose that for $H < 2X$, i.e. plane stress, neither the constraint stresses nor the residual stress will be maintained, so the basic plane stress value, K_{c2}, will be achieved. For $H > 2X$, the plane strain condition will result in a decline in K_c' but, in addition, there will be an effect due to the residual stresses. Since the drying process *increases* strength, it is reasonable to suppose that the residual stresses will increase K_c' providing no warping and consequential cracking occurs.

Fig. 6 shows the data from Table III plotted

TABLE III

Set number	Moisture content (%)	$H = 3$ mm			$H = 6$ mm			$H = 12$ mm			$H = 25$ mm			$H = 50$ mm		
		n	K_{IC} ($MN\,m^{-3/2}$)	s	n	K_{IC} ($MN\,m^{-3/2}$)	s	n	K_{IC} ($MN\,m^{-3/2}$)	s	n	K_{IC} ($MN\,m^{-3/2}$)	s	n	K_{IC} ($MN\,m^{-3/2}$)	s
1	0	11	0.37	0.045	8	0.34	0.029	5	0.37	0.057	8	0.34	0.044	3	0.26	0.017
2	7	11	0.42	0.044	18	0.42	0.051	10	0.45	0.035	6	0.38	0.05	9	0.36	0.034
3	11.2	9	0.37	0.054	18	0.42	0.052	6	0.48	0.039	4	0.42	0.029	8	0.33	0.058
4	14	8	0.38	0.024	14	0.37	0.035	14	0.33	0.033	6	0.30	0.017	8	0.33	0.025
5	20	17	0.37	0.037	18	0.36	0.031	14	0.38	0.03	4	0.38	0.055	8	0.29	0.044

n = number of specimens, s = standard deviation.

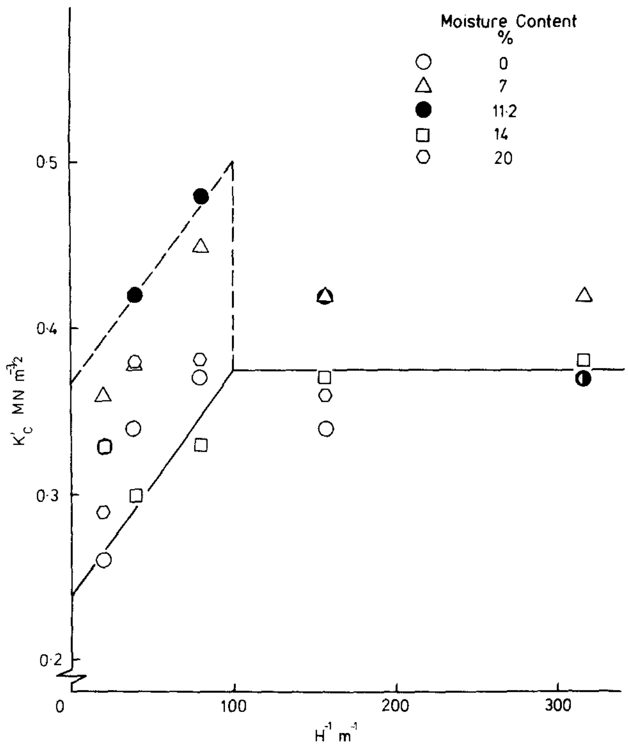

Figure 6 Fracture toughness as a function of inverse thickness.

against inverse thickness and the full line is a reasonable lower bound which could be interpreted as free from the residual stress effects and may be described in terms of Equation 4. This gives:

$$K_{c1} = 0.240\,\text{MN}\,\text{m}^{-3/2}$$

and

$$K_{c2} = 0.375\,\text{MN}\,\text{m}^{-3/2}$$

with $X \simeq 5$ mm. The transition thickness to plane stress conditions appears to be well defined at $H = 2X$ here and also agrees with the rejection rate transition shown in Table I. For $H > 10$ mm, the results of the various moisture contents lie above this line and indicate an upper bound effect of a residual stress additional toughness $K_R = 0.13$ MN $\text{m}^{-3/2}$ which operates in the original data and the 7% set but decrease for other values. For $H <$ 10 mm, the additional effect declines rapidly; again, in accordance with the rejection rate data.

It is difficult to relate this transition thickness to a damage zone since the implied stress, σ_c, is low. For $K_c = 0.375\,\text{MN}\,\text{m}^{-3/2}$ and $X = 5$ mm, we have $\sigma_c = 2.1\,\text{MN}\,\text{m}^{-2}$ which is about the same as the gross stress for the notched specimens and would imply "damage" in most tests. Unnotched specimens from Set 3 and $H = 6$ mm gave a fracture stress of $4.8\,\text{MN}\,\text{m}^{-2}$ which, coupled with $K_c = 0.375\,\text{MN}\,\text{m}^{-3/2}$, gives a zone size of 1 mm or an inherent flaw size of 2 mm. As noted by Schniewind and Pozniak [2], this is rather large.

The most reasonable interpretation of these numbers is that in inhomogeneous materials, such as wood, the governing size factor is not the plastic zone but an inhomogeneity dimension of the structure. In this case, there is a significant difference in stiffness across the annual growth rings and the average spacing is approximately 2.5 mm. It would appear that the plane stress region is approximately two zones in extent. This concept is confirmed by the rejection rate data which has no applied stress and is thus difficult to explain in terms of damaged zones. The transition to decreasing residual stress is at 10 mm and the implied zero residual stress case is for $H = 2.2$ mm, approximately one ring. It should also be noted that the computed inherent flaw size is also equal to the same dimension.

As a final point, it should be noted that the average crack size used was 7.5 mm, so that the residual stress toughness, K_R, implies a residual stress value of $0.9\,\text{MN}\,\text{m}^{-2}$. In addition, the scatter range of 36% of the average value of $K_{c2} = 0.375\,\text{MN}\,\text{m}^{-3/2}$ is $0.13\,\text{MN}\,\text{m}^{-3/2}$ which is the same as K_R, suggesting that the scatter is largely due to residual stresses.

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References

1. A. P. SCHNIEWIND and P. E. LYON, *Wood Sci. Tech.* 7 (1973) 45.
2. A. P. SCHNIEWIND and R. A. POZNIAK *Eng. Fract. Mech.* **2** (1971) 223.
3. J. A. JOHNSON, *Wood Sci.* **6(2)** (1972) 151.
4. Standards Association of Australia, A8 CA65 (1972).
5. J. D. BARRETT, *Eng. Fract. Mech.* 8 (1976) 711.
6. H. F. BROWN and J. E. SRAWLEY, ASTM STP 410 (1966).
7. J. M. DINWOODIE, *J. Microscopy* **(104)1** (1975) 3.
8. J. D. BARRETT, private communication.
9. M. PARVIN and J. G. WILLIAMS, *Int. J. Fracture* **11** (1975) 963.
10. J. I. BLUHM, *Proc. ASTM* **61** (1961) 1324.

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