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THE FRACTURE OF WOOD IN RELATION TO ITS STRUCTURE

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Summary. The work of fracture of wood has been measured and the experimental results have been discussed in relation to a model based on various morphological aspects of wood structure. The asymmetrical helical structure of the S_2 wall layers appears to be relevant to the fracture behaviour of wood in tension.

INTRODUCTION

Biological structures of higher plants and animals seem to be particularly successful in avoiding catastrophic failures in their load bearing components such as bone or wood. This success is probably due to sophisticated design and also to the mechanical properties of the materials themselves. In wood, the combination of stiffness, strength, toughness and lightness (Dinwoodie, 1975) is of primary importance to the living plant and to the engineer.

The relationship between stiffness, strength and structure of wood has received a great deal of attention in the past and in recent years very promising developments have taken place, although our knowledge is far from being complete (Cowdrey & Preston, 1966; Mark, 1967; Gibson, 1970; NATO, 1975). On the other hand, the fracture behaviour of wood has been somewhat neglected particularly in the context of the modern approach to fracture. Whilst work has been done in the areas of compression failure and cleavage of wood along the grain (Dinwoodie, 1968, 1974, 1975; Atack *et al.*, 1961; Debaise *et al.*, 1966; Schniewind & Pozniack, 1971), very little systematic work has been published on the tensile failure of wood across the grain. This is perhaps due to the fact that the compressive strength along the grain is about one half of the tensile strength and therefore, in structural applications, timber is more likely to fail in compression than in tension. The situation is probably different in living trees which, when they break, do so because of tensile failures. In trees, the periphery of the trunk is in tension and the inside in compression. An advantage of this pretensioning is that it may prevent the development of local compression failures should loading, that would otherwise be excessive, occur. Yet a disadvantage of this pretensioning of the stem periphery is that the tensile stresses may lead to a reduction of critical crack length (equation 3) beyond which crack growth could lead to catastrophic failures if the work of fracture was not high enough. Furthermore, if compression creases are already developed, they can act as initial cracks leading to tensile failures if the loading pattern changes from compression to tension.

The high anisotropy of wood is a consequence of the structure of the cells and of their overall orientation. This anisotropy becomes apparent when the mechanical properties of wood are measured in different directions. Broadly speaking, the longitudinal modulus is about twenty times greater than transverse moduli (radial and tangential) and the longitudinal tensile strength about forty times the tensile strength in the transverse directions. The fracture of wood also depends on the particular direction of crack propagation (it is much easier to split wood along the grain than to break it across it).

This paper is concerned mainly with the fracture behaviour of wood in tension and an attempt has been made to correlate the experimental results with the structural features of wood.

THEORY

The purpose of modern fracture mechanics is to establish failure criteria for materials under stress and to measure their resistance to the propagation of cracks. This last property, the toughness of the material, is perhaps of greater value than the concept of tensile strength for a useful description of fracture.

The first formulation of a failure criterion based on energetic consideration is due to A. A. Griffith (1920). If a semi-infinite plate of material loaded in tension contains a crack of length a, the necessary condition for unstable crack propagation can be expressed as:

$$\frac{\partial}{\partial a}\left(\frac{\pi\sigma^2 a^2}{E}\right) \geqq \frac{\partial}{\partial a}(4a\,\gamma_s) \tag{1}$$

where:

a = crack length
σ = applied tensile stress
E = Young's modulus
γ_s = free surface energy of the material.

Equation (1) expresses the fact that in a brittle solid which behaves elastically up to failure, a crack will become unstable if the strain energy release rate with respect to an infinitesimal extension of crack length is greater than the corresponding increase in surface energy due to the creation of new surfaces (Liebowitz, 1968). From equation (1) it is possible to derive the following failure criterion:

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{\frac{1}{2}} \tag{2}$$

which establishes a relationship between fracture stress (σ_c), crack length and free surface energy. Equation (2) has been verified experimentally for brittle solids like glasses for which the theoretical free surface energies and the measured 'effective' surface energies are of the same order of magnitude ($\gamma_s \simeq 1 - 5\,J/m^2$). For such solids, the critical crack lengths, even under relatively low stresses, turn out to be of the order of a few μm only. This is due to the fact that, because of the very nature of such substances, only a small proportion of the strain energy released during crack propagation can be absorbed as free surface energy. Non-brittle materials, however, are capable of absorbing energy in other ways, as plastic work or frictional work for example. To take account of this, equation (2) has been modified by introducing a new term, γ_F, the work of fracture, which should include all the energy absorbed by mechanisms other than the creation of the crack faces. This modified failure criterion can be formulated as:

$$\sigma_c = \left(\frac{2E(\gamma_s + \gamma_F)}{\pi a}\right)^{\frac{1}{2}} \tag{3}$$

For tough engineering solids, γ_F is many orders of magnitude greater than γ_s; ($\gamma_F \simeq 10^3 - 10^5\,J/m^2$) so that:

$$(\gamma_s + \gamma_F) \simeq \gamma_F \tag{4}$$

and the work of fracture can be used as a measure of toughness.

The development of fracture mechanics (Liebowitz, 1968) has introduced two other parameters which are used for fracture toughness measurements, the strain energy release rate G and the stress intensity factor at the tip of a crack, K. G, K and γ_F are related by the following equations (ASTM, 1965):

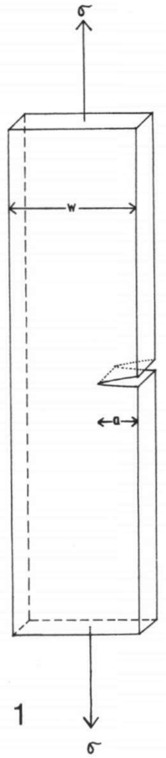
$$G_{IC} = 2\gamma_F \tag{5i}$$

$$G_{IC} = K^2{}_{IC} \cdot \emptyset \tag{5ii}$$

$$K_{IC} = \sigma_c(\pi a)^{\frac{1}{2}} f(a/w) \tag{5iii}$$

where G_{IC} and K_{IC} are the critical values of G and K corresponding to the onset of crack propagation for the opening mode (Mode I), illustrated in Figure 1. Under plane strain conditions:

$$\emptyset = \frac{1 - \nu^2}{E} \tag{6}$$



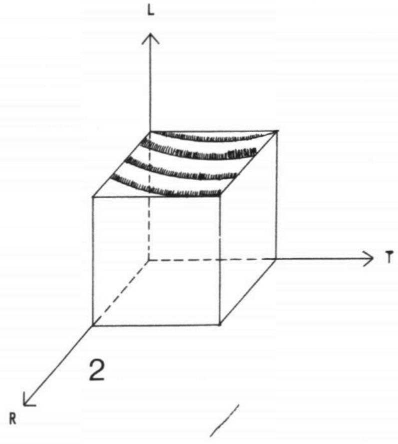


Fig. 1. Opening mode (Mode I) of crack propagation for a single-edged-notched specimen.

Fig. 2. Reference system for crack propagation in wood.

if the material is isotropic and

$$\emptyset = \left[\frac{A_{11}A_{22}}{2}\right]^{\frac{1}{2}} \left[\left(\frac{A_{22}}{A_{11}}\right)^{\frac{1}{2}} + \frac{2A_{12} + A_{66}}{2A_{11}}\right]^{\frac{1}{2}} \tag{7}$$

(Sih *et al.*, 1965) for the orthotropic case[1], where ν is the Poisson's ratio and A_{ij}'s are the elastic compliances.

The term $f(a/w)$ in equation (5iii) is a correction factor which depends on the ratio of crack length to width, introduced in order to take into account the finite width of real specimens. K_{IC} and G_{IC} can be measured independently as described in the experimental section.

[1] A material is said to be orthotropic if it possesses three planes of elastic symmetry mutually perpendicular.

CRACK PROPAGATION IN WOOD

Wood is an orthotropic material in which the three planes of elastic symmetry are normal to the longitudinal, radial and tangential directions respectively. It follows that in wood there are six principal systems of crack propagation systems which can be defined as: LT, LR, TL, TR, RL, RT. The first letter refers to the direction normal to the crack plane and the second to the direction of crack propagation (Fig. 2).
Values of γ_F for the different systems are reported in Table 1.

TABLE 1. Work of fracture of wood for different crack propagation systems (values obtained at room temperature)

Species	system of crack propagation	γ_F $\times 10^{-2}$ J/m^2	condition	reference
Canadian deal	LT, LR	20.0	air dry	a
Teak	LT, LR	60.0	air dry	a
Teak	LT, LR	160.0	air dry	b
Douglas fir	TL	0.19	air dry	c
Douglas fir	TR	1.15	air dry	c
Black spruce	RT	1.8	green	d
Black spruce	TR	1.0	green	d
White pine	TR, RT	1.6	air dry	e
Pitch pine	LR	92.0	air dry	f
Mahogany	TL	1.5	air dry	g

a : Tattersall & Tappin, 1966
b : Chapell & Morley, 1976
c : Schniewind & Pozniack, 1971
d : Atack et al., 1961
e : Debaise et al., 1966
f : Gordon & Jeronimidis, 1974
g : Williams & Birch, 1975

It is interesting to note that the work of fracture for cracks propagating across the grain is about 100 times greater than for those propagating in the grain direction.

EXPERIMENTAL

γ_F, G_{IC} and K_{IC} have been measured independently using three different experimental techniques which have been outlined very briefly. For fuller details reference should be made to the relevant publications.

Measurement of γ_F by quasistatic fracture bending tests (Tattersall & Tappin, 1966)

The specimens, cut and machined in the form of beams of square cross section, are simply supported at two ends and loaded centrally. To ensure that no crushing takes place at the loading points, the span length of the beam should be much greater than the depth. It was found that a span length of 120 mm for a cross section of 10 × 10 mm

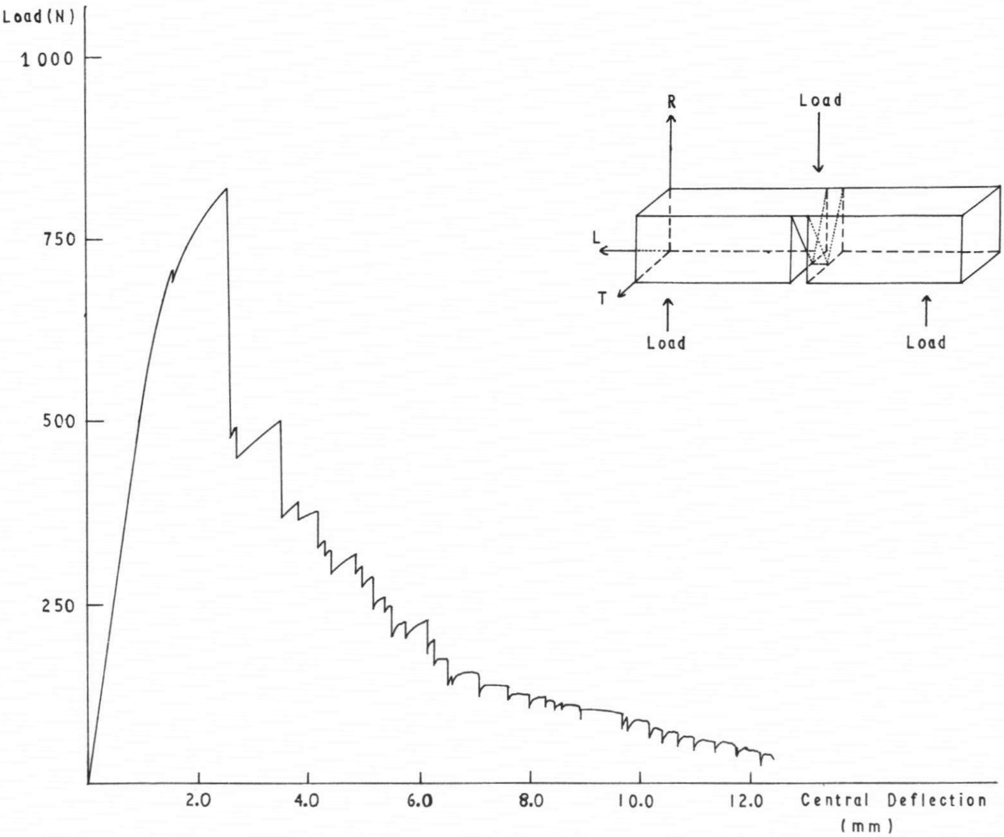


Fig. 3. The load-deflection curve obtained from a work of fracture measurement of wood in three point bending. The diagram in the top right illustrates the testing geometry.

fulfilled this condition. An 'inverted roof' notch (Fig. 3, insert) or a straight edge notch is cut in the centre of the beam on the face opposite the one which is loaded at midspan. The specimen is then loaded to failure and the load-deflection curve is recorded (Fig. 3). The total work done in fracturing the specimen is proportional to the area under the curve and the work of fracture γ_F is obtained as:–

$$\gamma_F = \frac{\text{Total work consumed during fracture}}{2 \times \text{Nominal cross sectional area}^2 \text{ of specimen}}$$

Following this technique, the work of fracture of sitka spruce and teak has been measured under a range of different conditions. It was found that the notch geometry

[2] By nominal cross sectional area is intended the gross fracture area irrespective of irregularities and excluding the cut away portions.

TABLE 2. The work of fracture of Sitka spruce and teak obtained from slow bending tests and impact tests. LR crack propagation system. Each value represents the average for 10 specimens. The standard deviations are reported in brackets.

species	conditions		γ_F (slow bending) $\times 10^{-2}$ J/m^2		γ_F (impact) $\times 10^{-2}$ J/m^2	
	temp. °C	approximate moisture cont. %				
Sitka spruce	20°	12	160	(42)	170	(51)
" "	100°	1	-	-	80	(22)
" "	-100°	12	-	-	270	(48)
" "	-195°	12	320	(51)	-	-
" "	-195°	1	132	(31)	-	-
" "	-195°	72	134	(60)	-	-
Teak	20°	12	90	(16)	100	(17)
"	100°	1	-	-	110	(25)
"	-100°	12	-	-	160	(47)

did not have a significant effect on the values obtained. The results, referring to the LR system of crack propagation, are summarised in Table 2. In the last column the results obtained in some impact tests have been reported, for comparative purposes.

Measurement of G_{IC} by the compliance calibration method (Irwin, 1960; Strawley *et al.*, 1964).

Specimens of sitka spruce are cut in the shape of thin strips 150 × 10 × 0.5 mm with the grain direction as parallel as possible to the long dimension, the plane of the strip being the longitudinal tangential plane. Twenty-four such strips were used and in each one an edge notch of given length was cut. Notch lengths varied from 1 to 5 mm. Each strip was then loaded in tension (Fig. 1) and the breaking load recorded. All tests were carried out at ambient conditions (20°C and 12% moisture content approximately).

G_{IC} is found using the expression:

$$G_{IC} = \frac{P^2}{2b}\left(\frac{\partial C}{\partial a}\right)_{a\,=\,a^*} \tag{8}$$

where P is the breaking load of the notched strip, and b its thickness. $\partial C/\partial a$ is the rate of change of compliance (extension / load) for the given crack length (a^*) and has to be evaluated experimentally using a compliance calibration curve.

For this purpose six strips of sitka spruce were used, the strips having the same dimensions as those used for the fracture tests. The compliance C of each specimen was measured as a function of crack length (a) for crack lengths increasing from 0 to

5 mm. The compliance calibration curve was obtained by fitting a 2nd degree polynomial to the results. $\partial C/\partial a$ could then be evaluated graphically or numerically for any given crack length.

For this system of crack propagation (LT) the average value of G_{IC} was found to be $1.8 \times 10^4 J/m^2$. The work of fracture, γ_F, was computed from equation (5iii) given a mean value of $0.9 \times 10^4 J/m^2$ with a standard deviation of $0.2 \times 10^4 J/m^2$.

Measurement of K_{IC}

For this purpose, forty strips of sitka spruce $60 \times 10 \times 0.5$ mm containing edge cracks (Fig. 1) were loaded up to failure. All tests were carried out at ambient conditions. For each specimen K_{IC} was computed from the values of the fracture stress and notch length using equation (5i) with the appropriate correction factor (ASTM, 1965). The average value of K_{IC} (LT system of crack propagation) was found to be $7.0 \times 10^6\ Nm^{-3/2}$ with a standard deviation of $1.2 \times 10^6\ Nm^{-3/2}$. This corresponds to a mean work of fracture, γ_F, of $0.65 \times 10^4\ J/m^2$. (Equations (5ii) and (5iii) where $\emptyset = 0.26 \times 10^{-9}\ m^2\ N^{-1}$).

The values of γ_F calculated from the experimental determination of G_{IC} and K_{IC} respectively are in good agreement although they are lower than the work of fracture measured in bending. This is not entirely surprising because G_{IC} and K_{IC} are critical values corresponding to the onset of unstable crack propagation, whereas the bending tests results are a measure of the total energy absorbed during controlled propagation of cracks across the specimens.

DISCUSSION AND CONCLUSIONS

The experiments described in the present paper indicate that the work of fracture of wood, for failure in tension across the grain, is of the order of $10^4\ J/m^2$. This figure is at least three orders of magnitude higher than the free surface energy of cellulose (Gordon & Jeronimidis, 1974). This means that during the fracture process, energy must be dissipated irreversibly in regions relatively remote from the crack tip. A similar situation occurs in ductile metals ($\gamma_F \simeq 10^5 J/m^2$) and most polymers ($\gamma_F \simeq 10^3 - 10^4 J/m^2$) where the high work of fracture can be accounted for in terms of plastic work in a relatively large volume of material on both sides of the final crack (Andrews, 1968; Gordon, 1974; Liebowitz, 1968). Fibre composite materials have also very high works of fracture (10^3–$10^4\ J/m^2$) which are mainly due to the frictional work dissipated in pulling out fibres from the matrix (Kelly, 1966).

A certain number of observations suggests that either these energy absorbing mechanisms are not available to wood or that they are not very important. The molecular and supermolecular structure of the crystalline regions of cellulose seems to rule out the possibility of highly mobile dislocation processes similar to those occurring in ductile metals and which are responsible for their plastic behaviour. In polymers, plastic deformation is related to the presence of long molecular chains and to their relative freedom of movement at certain temperatures. However, as the temperature is decreased, the thermal motion is reduced and polymers exhibit brittle behaviour during fracture (Andrews, 1968).

The results obtained for wood do not show the order of magnitude changes which would be expected if wood behaved like other polymers. The small changes observed will not affect the critical crack length (equation 3) to a great extent. In particular, the work of fracture measured at temperatures as low as about – 200° C is not very different from that at room temperature. The composite nature of wood suggests that its fracture behaviour may be similar to that of artificial fibre reinforced composites. Although fibre pull out has been proposed as an energy absorbing mechanism in wood (Tattersall & Tappin, in 1966), microscopical observation of the fracture surfaces does not support this possibility, at least, if it is assumed that the cells represent the 'fibres' in the composite sense.

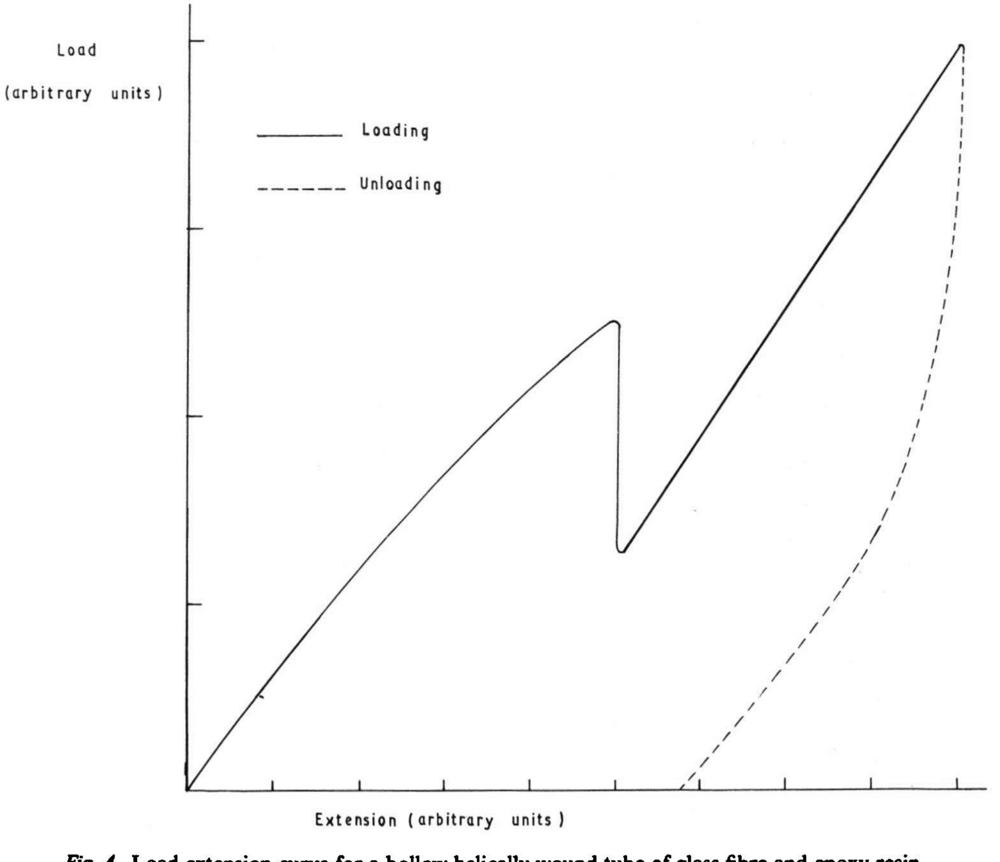


Fig. 4. Load-extension curve for a hollow helically wound tube of glass fibre and epoxy resin.

In view of all this, an attempt has been made (Gordon & Jeronimidis, 1974) to correlate the high work of fracture of wood with the structural features of the plant cell walls, the behaviour of single cells under load and the stress distribution at the tip of a crack in an inhomogenous material.

It has been shown that single wood tracheids subject to an axial load can fail in a very characteristic way by buckling in tension (Page *et al.*, 1971; Hardacker & Brezinski, 1973). The buckling process allows the cell to reach breaking strains of 18% or more, far in excess of the breaking strain of bulk wood in tension (usually of about 1%). This deformation mechanism depends upon the structure of the plant cell wall and more precisely upon the helical arrangement of the cellulose microfibrils in the S_2 wall layer, which is the major load-bearing component.

From a structural point of view, it is certainly rather curious that the S_2 wall layers should have a well-defined and constant helix sense. The result of this is that if a single tracheid is loaded in tension and its ends are prevented from rotating, the tubular cells will tend to collapse inwards decreasing the diameter of the S_2 wall layer. This is very similar to the extension of an internal helical metallic spring beyond its elastic limit. The load-extension curve of such a system is illustrated in Fig. 4. The structure of the S_2 wall has been simulated by a hollow tube made of helically wound glass fibres embedded in an amorphous matrix. The buckling point is clearly defined and this type of deformation is very similar to that of ductile metals.

The important point is that the postbuckling deformation is non-elastic which means that work has been absorbed irreversibly during the process. From the area under the load-extension curve of a buckled tracheid (Hardacker & Brezinski, 1973; Page *et al.*, 1971) it is possible to evaluate the work done. The maximum work of fracture obtainable from the buckling mechanism can be found dividing the total work absorbed during the deformation by the cross sectional area of the tracheid. From data presented by Gordon & Jeronimidis (1974), for an average tracheid diameter of 30 μm, the maximum work of fracture is about 10^5 J/m^2. It is interesting to note that Mark *et al.* (1971) find that the energy absorbed in allowing single tracheids to untwist under a dead load is of the order of 2.0×10^{-4} Joules/tracheid which converted into work of fracture yields a figure of 3×10^5 J/m^2. This probably means that, irrespective of the loading pattern, the energy absorbing processes occurring in the S_2 wall layer are the same. These processes involve failure between the microfibrils before the ultimate fracture of the microfibrils themselves takes place. This is illustrated in Plate 1A (tensile failure of sitka spruce) which shows the post-buckling aspect of a tracheid and in particular the typical spiralling cracks which follow the helical pattern of the S_2.

In order to relate the tensile behaviour of single cells to the fracture of bundles of fibres, as in wood, it is necessary to have some mechanism which, during the propagation of cracks, would separate the fibres and allow them to deform independently. The study of the stress distribution at the tip of a crack (Cook & Gordon, 1964) in a material loaded in tension, shows that apart from the tensile stress normal to the crack plane there is a transverse tensile component of stress in the direction of the extending crack.

The maximum value of this component occurs at a certain distance from the crack tip itself. If the material has a composite nature and if the adhesive strength between fibres and matrix does not exceed 20% of the axial strength, the transverse stress component will induce failure at the fibre-matrix interface before the crack itself has reached it. This debonding process is very common in wood and is illustrated in Plate 1B. The splintery fracture surfaces of tensile failures in wood cells are the result of this mechanism which can also provide a means of separating cells from each other.

The experimental values of γ_F are one order of magnitude lower than the theoretical

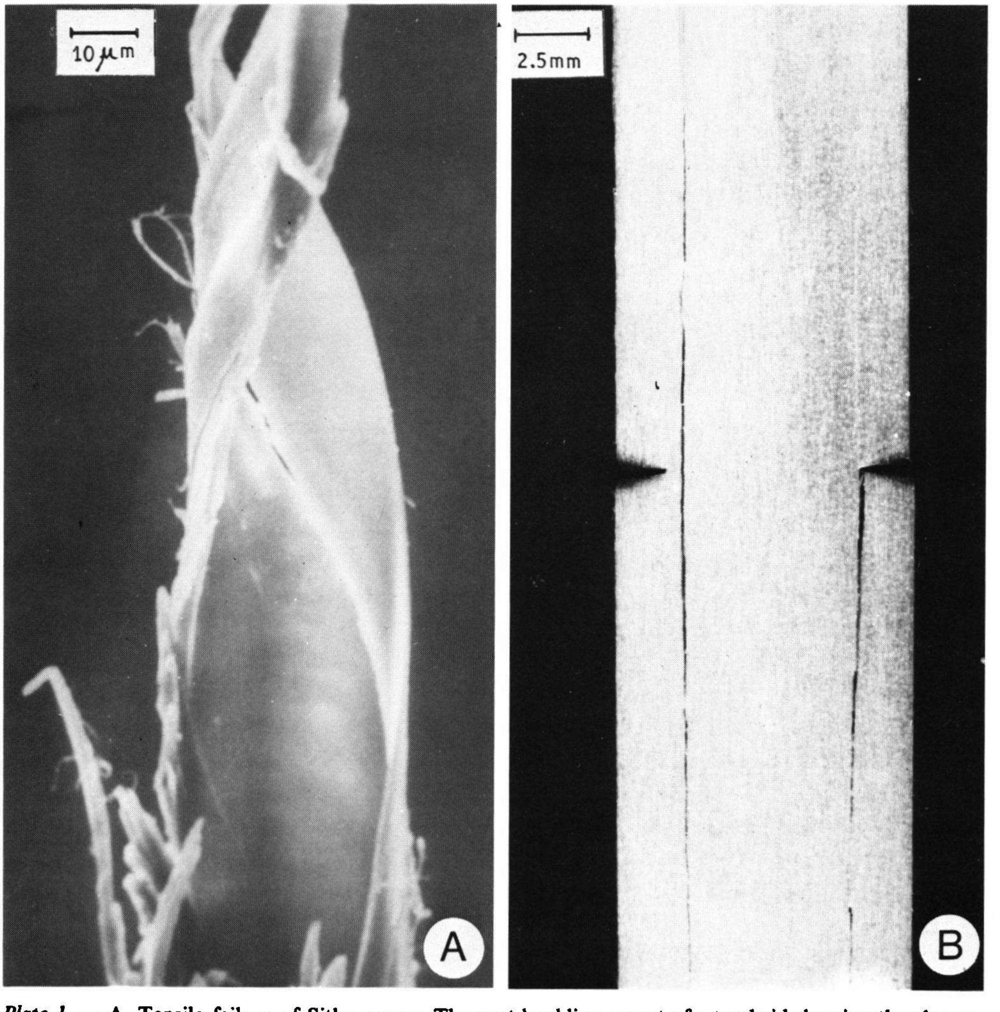


Plate 1. — A. Tensile failure of Sitka spruce. The post-buckling aspect of a tracheid showing the characteristic spiralling cracks (SEM photograph).—B. Cook & Gordon mechanism at the tip of a crack. Sitka spruce strip loaded in tension.

figure based on the model which has been described. This discrepancy is not unexpected considering that the predicted value of γ_F is an upper limit based on the tensile buckling of all the cells across the crack plane.

The proposed model is consistent with the microscopical observation of damaged wood cells. The spiralling cracks illustrated in Plate 1A have been observed before (Wardrop, 1951) and are a consequence of the buckling behaviour. The observed separation of the S_1 and S_2 wall layers after failure (Mark, 1967) can be accounted for in terms of the inwards buckling of the S_2 wall layer with respect to the S_1 wall in which the microfibrillar orientation leads to a symmetrical elastic behaviour. This last effect has also been observed in models of the wood cell where both S_1 and S_2 layers were simulated (Gordon & Jeronimidis, unpublished results).

It is interesting to speculate that the asymmetric helical structure of the S_2 wall layer in wood cells is the basis of a rather sophisticated way of absorbing irreversibly great amounts of energy thereby preventing catastrophic failures. Complex mechanisms to provide high work of fracture seem to be widespread in Nature, although it is only recently that they have begun to be studied and applied to artificial materials.

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REFERENCES

Andrews, E. H. 1968. Fracture in polymers.

Atack, D., W. D. May, E. L. Morris, & R. N. Sproule. 1961. The energy of tensile and cleavage fracture of black spruce. Tappi 44: 555–567.

A.S.T.M. 1965. Fracture toughness testing and its applications. STP 381. Philadelphia.

Chapell, M. J. & M. J. Morley. 1976. The fracture toughness of conventional materials and composite systems containing non-fracturing reinforcing elements. J. Mat. Sci. 11: 57–70.

Cook, J. & J. E. Gordon. 1964. A mechanism for the control of cracks in brittle systems. Proc. R. Soc. A 282: 508–520.

Cowdrey, D. R. & R. D. Preston. 1966. Elasticity and microfibrillar angle in the wood of Sitka spruce. Proc. R. Soc. B 1966: 245.

Debaise, G. R., A. W. Porter, & R. E. Pentoney. 1966. Morphology and mechanics of wood fracture. Mat. Res. Stand. 6: 493–499.

Dinwoodie, J. M. 1968. Failure in timber. Part 1. Microscopic changes in cell wall structure associated with compression failure. J. Inst. Wood. Sci. 21: 37.

Dinwoodie, J. M. 1974. Failure in wood. Part 2. The angle of shear through the cell wall during longitudinal compression stressing. Wood Sci. Technol. 8: 56.

Dinwoodie, J. M. 1975. Timber. A review of the structure-mechanical property relationship. J. Microsc. 104: 3–32.

Gibson, E. J. 1970. Some aspects of the relation between the structure of wood and its properties. Timberlab. Papers No. 12.

GORDON, J. E. 1974. The new science of strong materials, ed. 4. Pelican.

GORDON, J. E. & G. JERONIMIDIS. 1974. Work of fracture of natural cellulose. Nature 252: 116.

GRIFFITH, A. A. 1920. The phenomenon of rupture and flow in solids. Trans. R. Soc. London. A 221: 163–198.

HARDACKER, K. W. & J. P. BREZINSKI. 1973. The individual fiber properties of commercial pulps. Tappi 56: 154–157.

IRWIN, G. R. 1960. Fracture mechanics.

KELLY, A. 1966. Strong solids.

LIEBOWITZ, H. (ed.) 1968. Fracture—an advanced treatise.

MARK, R. E. 1967. Cell wall mechanics of tracheids.

MARK, R. E., J. L. THORPE, & A. J. ANGELLO. 1971. Twisting energy of holocellulose fibers. J. Polymer Sci. C 36: 177–195.

N.A.T.O. 1975. The properties of wood in relation to its structure. N.A.T.O. Science Committee Conference. Working Papers. Les Arcs, France.

PAGE, D. H., F. EL-HOSSEINY, & K. WINKLER. 1971. Behaviour of single wood fibres under axial tensile strain. Nature 229: 252–253.

SCHNIEWIND, A. P. & R. A. POZNIAK. 1971. On the fracture toughness of Douglas fir wood. Engin. Fract. Mech. 2: 223–233.

SIH, G. C., P. C. PARIS, & G. R. IRWIN. 1965. On cracks in rectilinearly anisotropic bodies. Int. J. Fract. Mech. 1: 189.

STRAWLEY, J. E., M. H. JONES, & B. GROSS. 1964. Experimental determination of the dependence of crack extension force on crack length for a single-edge-notched tension specimen. N.A.S.A., TN-D 2396.

TATTERSALL, H. G. & G. TAPPIN. 1966. The work of fracture and its measurement in metals, ceramics and other materials. J. Mater. Sci. 1: 296–301.

WARDROP, A. B. 1951. Cell wall organization and the properties of the xylem. I. Cell wall organization and the variation of breaking load in tension of the xylem in conifer stems. Aust. J. scient. Res. B 4: 391–414.

WILLIAMS, J. G. & M. W. BIRCH. 1975. Mixed mode of fracture in anisotropic media. N.A.T.O. Science Committee Conference. Working papers. Les Arcs, France.