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Investigation of wood fracture toughness using mode II fracture (shearing)

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The test results of fracture toughness for three wood species, such as pine, alder and birch are presented. Examination of fracture toughness is carried out using mode II fracture (shearing). Values of the stress intensity factor, K_{IIc}, are determined for the three main anatomic directions of wood. Microstructural tests of particular wood species, performed on specimens along the three main anatomic directions of wood, are discussed. Qualitative relationships are found to exist between the microstructure of wood and the obtained values of the stress intensity factor, K_{IIc}.

1. Introduction

A variety of building materials used for engineering construction have numerous drawbacks such as inaesthetic appearance, liberation of various substances detrimental to health during a prolonged utilization period, or lack of resistance to the erosive influence of the environment, which causes degradation of materials and of complete constructions.

Wood and its composites are relatively widely used for such building construction elements that have not only to satisfy strength conditions, but to meet aesthetic, environmental and other requirements as well.

Such applications of wood, and particularly its composites (such as plywoods or glued wood), in high reliability constructions require precise determinations of their strength parameters to be made. This has resulted in the implementation of fracture mechanics methods into the examination of wood. The parameters defined in fracture mechanics, such as the stress intensity factor, K, and the fracture energy, G, characterize a state of stress at the tip of a defect at the moment of its non-controllable growth.

Wood may undergo failure during utilization due to fracture occurring, in particular, along its natural cleavage planes.

In recent years some research works have considered the problem of wood strength in terms of fracture mechanics. In the works of References [1–5] the results of testing different wood species and their composites with the use of fracture modes I and II are presented.

The tests reported in the above works have proved the suitability of fracture mechanics for evaluation of wood fracture toughness and its composites. The results obtained show a high "sensitivity" of the fracture mechanics quantities, e.g. the stress intensity factors, K_{Ic} and K_{IIc}, and the fracture energy, G_{Ic} and G_{IIc}, depending on the particular wood species, its humidity, the mode in which it is loaded, and also on the direction of sampling in the specimens during testing, i.e. the location of primary cracks in relation to the anatomic directions of wood.

2. Experimental procedure

Examination of the fracture toughness of wood was carried out on specimens made of the following three wood species: pine, alder and birch.

The following investigations were carried out

1. tests of the stress intensity factor, K_{IIc} (mode II, shearing;
2. microscopic tests using a scanning electron microscope.

In addition to fracture toughness testing, tensile and compression testings along the fibres, and tests of bending strength were performed (Table I). In the tests every ten specimens of each wood species were used.

In the fracture toughness testing cube, specimens of 100 mm edge dimension were used, with two 50 mm long primary notches. The notches were cut out by milling.

The specimens for fracture toughness testing were taken from a single balk along the three main anatomic

TABLE I The strength of wood

Wood species	Compressive strength (MPa)	Tensile strength (MPa)	Flexural strength (MPa)
Pine	47.3 ± 1.0 [6.0][a]	87.0 ± 5.9 [12.8]	80.7 ± 8.3 [27.1]
Alder	40.5 ± 0.4 [2.4]	72.3 ± 4.9 [18.1]	86.3 ± 3.5 [10.9]
Birch	53.6 ± 1.2 [6.1]	65.5 ± 2.6 [10.7]	77.2 ± 6.6 [22.5]

[a] Values in square brackets denote coefficients of variation (%).

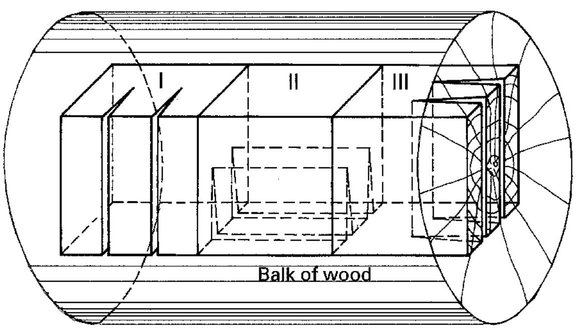


Figure 1 Mode of taking the specimens for the examinations.

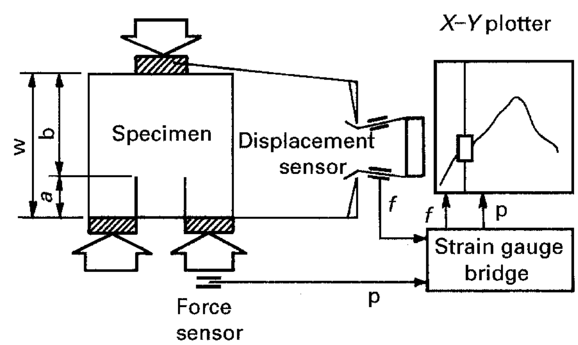


Figure 2 Diagram of test stand.

directions of the wood (Fig. 1). In each testing series seven specimens were tested. The graphs of load–displacement relationships were plotted using an x–y recorder.

The specimens used for the tests had the following moisture content and density values

	Moisture content (wt%)	Density ($MG\,m^{-3}$)
Pine	10.0 ± 1	0.55
Alder	11.5 ± 1	0.53
Birch	12.0 ± 1	0.65

2.1. Fracture toughness tests

Fracture toughness tests were performed according to mode II cracking (shearing) on the stand presented in Fig. 2. The load was measured against the crack displacement with a strain gauge and registered on an x–y plotter.

The stress intensity factor, K_{IIc}, was determined using the formula derived by Dixon and Strannigan [6], in which the stress intensity factor, K_{IIc}, depends on a critical value of the force, P_Q

$$K_{IIc} = \frac{5.11 P_Q}{2BW} (\pi a)^{1/2}$$

where P_Q is the force initiating cracking (growth); B is the thickness under the crack, W is the height; and a is the length of the crack.

Table II contains values for the stress intensity factor, K_{IIc}, for each batch of specimens.

A load–crack displacement curve was obtained for each specimen. Some specimen curves are shown in Fig. 3.

In Fig. 4 the stress intensity factor, K_{IIc}, is plotted against wood species and type of sample.

The obtained stress intensity factor values, K_{IIc}, show considerable variation in relation to both the wood species and specimen type (I, II and III).

For type I specimens the obtained values of K_{IIc} were decidedly the greatest. Type I specimens made of pine wood had K_{IIc} values five times greater than those of type II specimens, and about two times greater than the K_{IIc} values of type III specimens. In the tests of alder wood, type I specimens had K_{IIc} values seven times greater than the values of type II specimens, and about two times greater than those of type III specimens. In the tests of birch wood, type I specimens had K_{IIc} values five times greater than the values of type II specimens, and about two times greater than those of type III specimens.

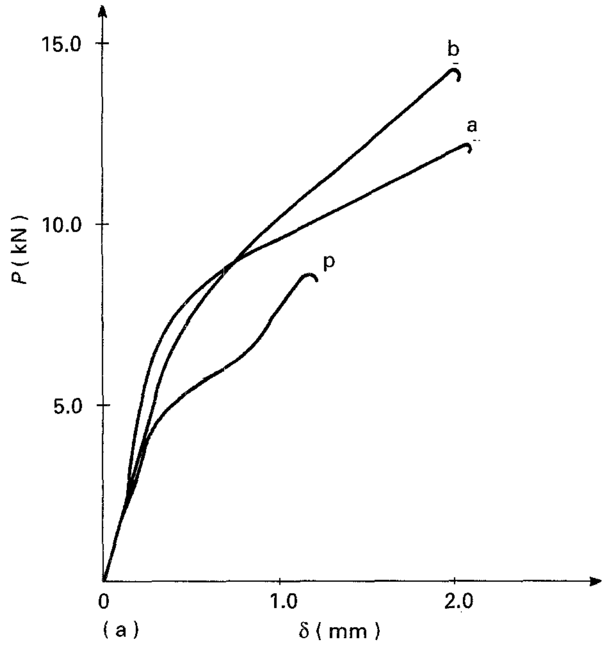
The failure curves obtained in the fracture toughness tests show different behavioural tendencies of particular wood species and type of specimen (I, II and III).

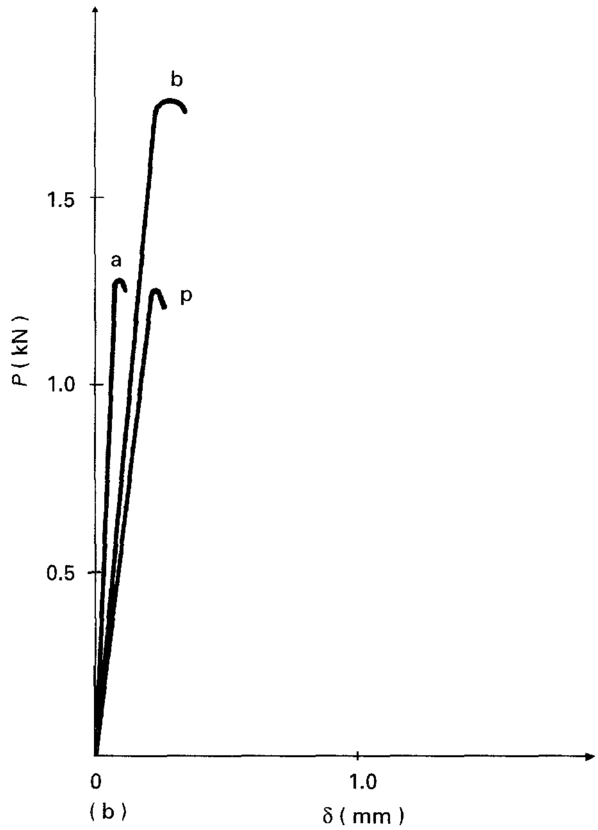
In the tests of type I specimens the existence of considerable plasic deformations has been found in all three wood species. The character of the failure process and the obtained values of destructive forces were determined by mutual relations between particular

TABLE II Stress intensity factor, K_{IIc}, for sample types I, II and III

	Pine			Birch			Alder		
	I	II	III	I	II	III	I	II	III
K_{IIc}	0.851	0.196	0.543	1.212	0.211	0.528	1.478	0.317	0.717
($MN\,m^{-3/2}$)	0.830	0.166	0.513	1.212	0.181	0.513	1.337	0.302	0.702
	0.790	0.151	0.471	1.175	0.166	0.393	1.316	0.272	0.702
	0.770	0.136	0.460	1.154	0.136	0.377	1.276	0.272	0.687
	0.729	0.121	0.374	1.012	0.136	0.332	1.276	0.257	0.672
	0.729	–	0.340	1.012	0.106	–	–	0.242	–
	0.783[a]	0.154[a]	0.450[a]	1.130[a]	0.156[a]	0.429[a]	1.337[a]	0.277[a]	0.696[a]
	0.049[a]	0.026[a]	0.073[a]	0.079[a]	0.034[a]	0.076[a]	0.067[a]	0.025[a]	0.015[a]
	[6.6][b]	[16.9]	[16.2]	[7.0]	[22.0]	[17.7]	[5.0]	[9.0]	[2.2]

[a] Values are for $K_{II} \pm \delta$.
[b] Values in square brackets denote coefficients of variation.





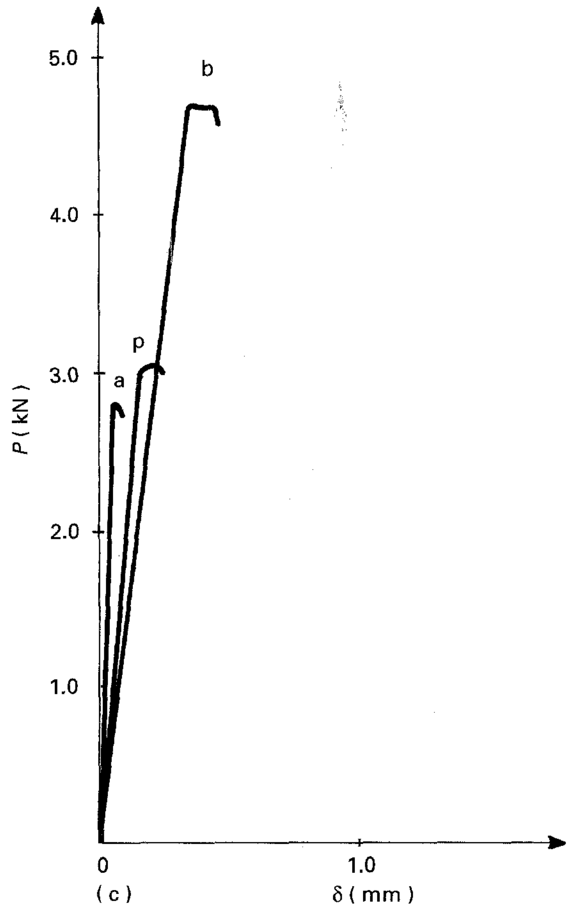


Figure 3 Examples of load–displacement for alder (a), birch (b) and pine (p) curves obtained from the fracture toughness tests : (a) type I, (b) type II, and (c) type III.

components of the wood structure and the "ordering" level of the structure.

The variation of the values and proportions of the stress intensity factor, K_{IIc}, of particular wood species was caused by differences in the structure.

2.2. Microstructural examination

Microstructural examination was carried out on samples taken along the three main anatomic directions of particular wood species, with the use of a scanning electron microscope. An area of about 400 mm^2 was observed for each specimen. The specimens for microstructural examination were sprinkled with graphite powder. The magnification used was from 50 to 1000 times.

The microstructural examination showed structural differentiation among the wood species tested and also an evident structural differentiation along the three main directions of the anatomic structure of wood.

The best structural "ordering" in all directions was shown by pine wood (Figs 5–7). On the fractures, distinctly formed fibres were visible, with specific "tube-like" cross-sections, situated along the III direction, i.e. the direction of growth of the tree, in the form of a reticular structure (Fig. 7). In the pine wood structure, relatively less structural disorder was found with increasing regularity of the structure.

The most chaotic structure was found in the case of alder wood (Figs 8–10), which had the closest "packing" of particular elements of the structure. Numerous diversified structural elements were seen, which created disturbances in the structure.

The character of the structure close to that of alder wood, while having fewer structural disorders, is shown by birch wood (Figs 11–13). In the micrographs, fibres can be seen which are developed in the direction of growth (Fig. 13) and have defined "tube-like" cross-sections (Fig. 12), with numerous structural disorders lateral in relation to the direction of the fibres.

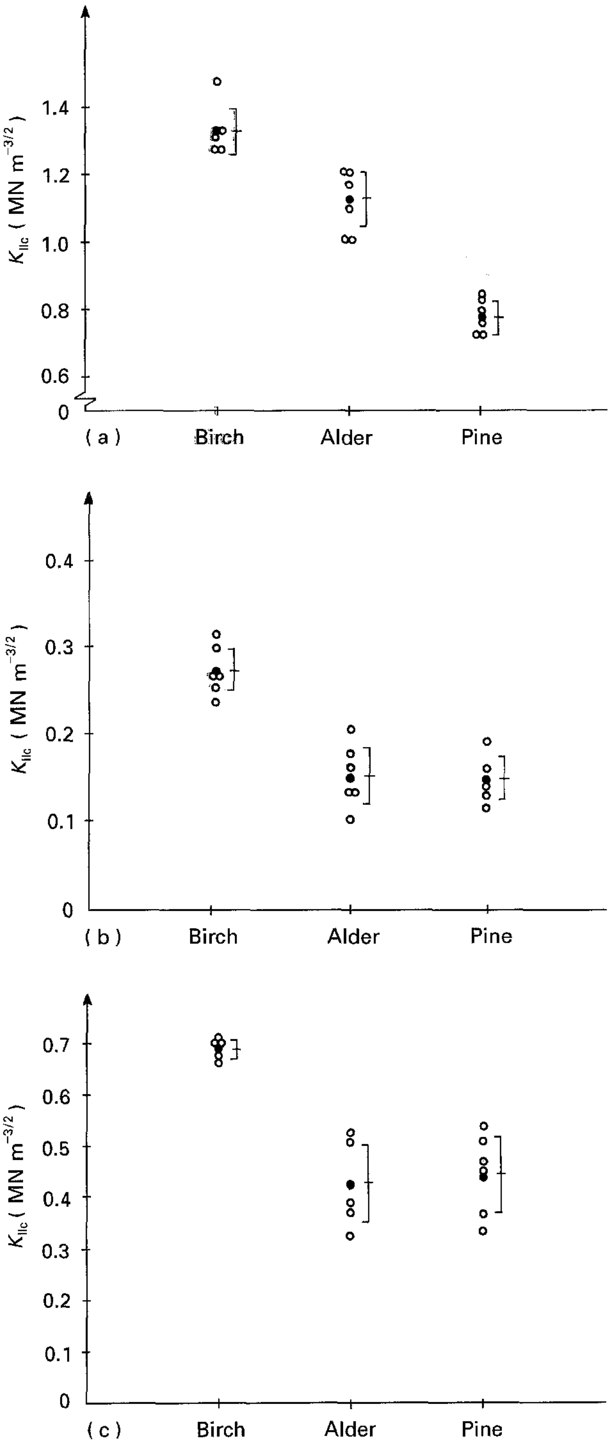


Figure 4 Stress intensity factor, K_{IIc}, for specimens: (a) type I, (b) type II, and (c) type III.

3. Results and discussion

The examination of fracture toughness carried out using mode II fracture, shearing, and the microstructural tests have shown the occurrence of qualitative relationships between the obtained values of the stress intensity factor, K_{IIc}, and the microstructure of particular wood species.

Significantly higher values of K_{IIc} have been found for two species of hardwood (alder and birch) in relation to those of softwood (pine). This is mainly true for type I specimens, for which K_{IIc} values for alder (1.130 $MN\,m^{-3/2}$) and birch (1.337 $MN\,m^{-3/2}$) clearly exceed the value of K_{IIc} obtained in the studies of pine (0.783 $MN\,m^{-3/2}$).

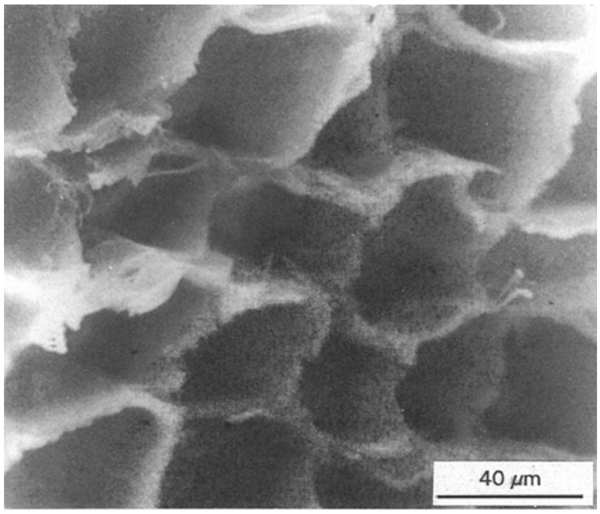


Figure 5 Microstructure of pine wood, fracture type I, showing a visibly ordered lateral fracture of the clearly formed "tubular" fibres of pine wood of relatively large cross-sectional dimension.

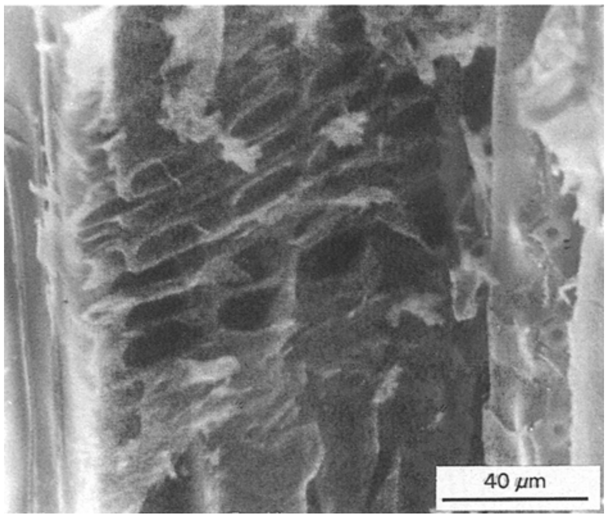


Figure 6 Microstructure of pine wood, fracture type II, showing the visible fibrous structure of pine wood, with laterally situated elements of structure connecting the fibres.

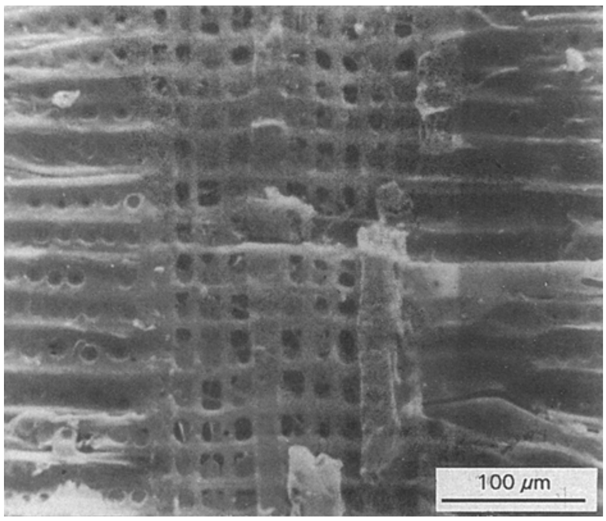


Figure 7 Microstructure of pine wood, fracture type III, showing the visible irregular, reticulated surface of the pine wood fracture, which forms a natural cleavage plane.

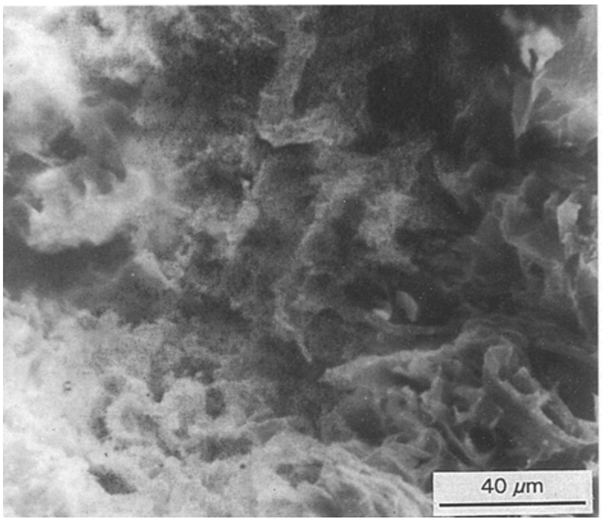


Figure 8 Microstructure of alder wood, fracture type I, showing a visibly lateral fracture of the chaotic fibre structure of alder wood of small cross-section, with mutually intersecting structural elements.

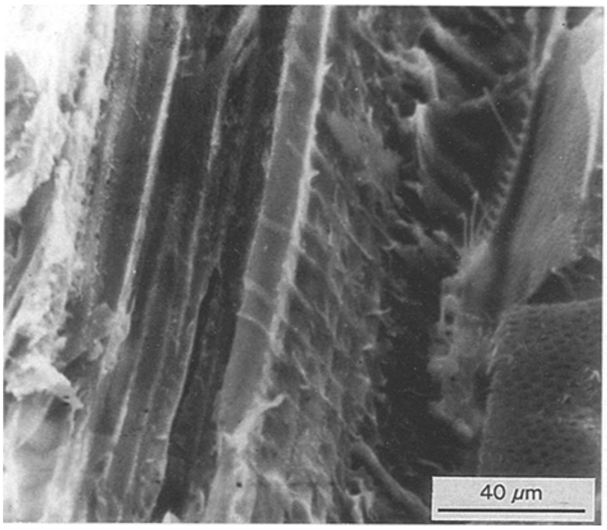


Figure 9 Microstructure of alder wood, fracture type II, showing the visible fibrous structure of alder wood, with numerous lateral microfibres that connect the main fibres.

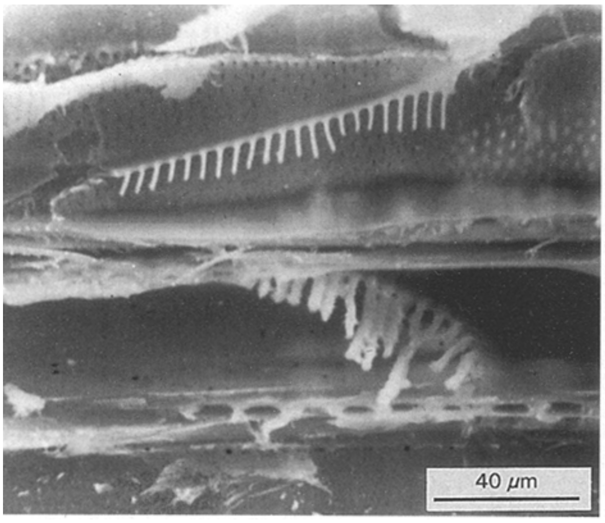


Figure 10 Microstructure of alder wood, fracture type III, showing the visible, fairly regular, fibrous structure of alder wood, with a few structural elements situated in different directions.

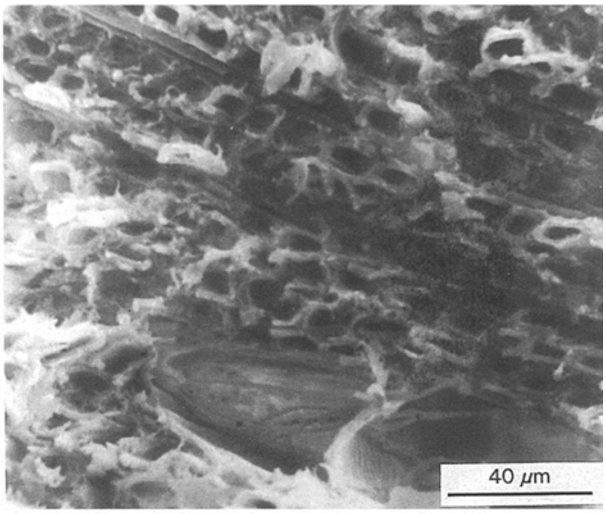


Figure 11 Microstructure of birch wood, fracture type I, showing a lateral fracture of the complicated structure of birch wood, with visible "tubular" cross-sections of fibres of small dimension and elements connecting the fibre layers.

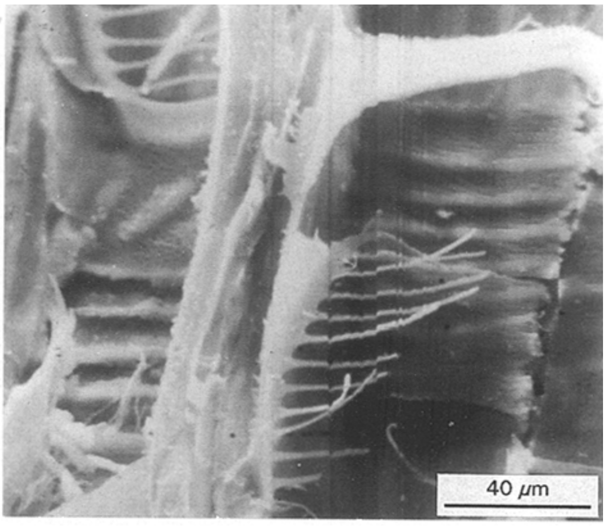


Figure 12 Microstructure of birch wood, fracture type II, showing the visible irregular structural fibres of birch wood, with numerous lateral microfibres that connect the main fibres.

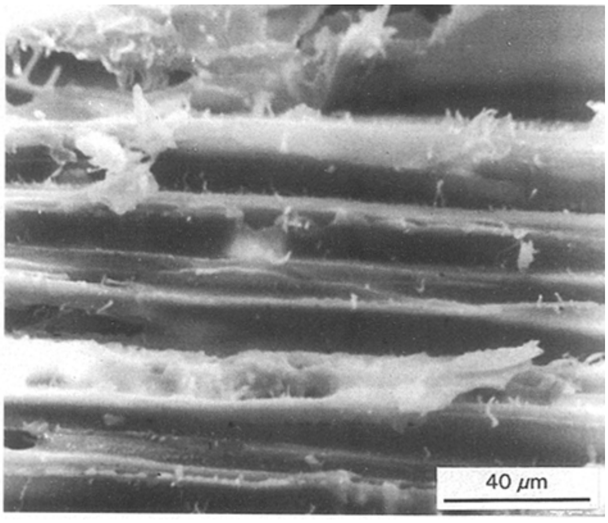


Figure 13 Microstructure of birch wood, fracture type III, showing the clearly visible fibrous structure of birch wood, with a large content of main fibres.

Such behaviour of particular wood species under breaking load is related to their density and to the observed structure of specimen fractures.

The coherent structure of pine wood is the best ordered of all, with clearly formed cleavage planes along directions II and III (Figs 6 and 7). The pine wood fracture across the fibres (direction I) is regular and tubular, without any additional structural elements.

The fractures of alder wood, and particularly those of birch wood, have a compact and very complex structure (Figs 8 and 11). The structure of these fractures is complicated and shows a wide variety of forms that connect the particular elements of the main fibres. This is directly related to the differences existing between the microstructure of hardwood and softwood. Hardwood is composed of four cell types, while softwood is only composed of two fairly loosely bound cell types in the structure. Figs 8 and 11 illustrate the more complicated and rugged failure surfaces of alder and birch wood, while the fracture surface of pine wood (Fig. 5) is regular and significantly less complicated.

The greatest stress intensity factor values in the examination of II and III type specimens, are associated with birch wood, and are approximately 50% greater than the values obtained in the examination of pine and alder wood.

Microscopical analysis of the fractures of these specimens has shown that birch wood has the most complex microstructure of all the three wood species. The mutually perpendicular elements of the birch wood structure (Figs 12 and 13) cause the energy necessary for failure to be greater than that for the other wood species.

In Fig. 7 a flat grid of mutually perpendicular fibres is seen, which indicates easier shearing of pine wood along the natural cleavage plane, i.e. along direction III. Such arrangement of the fibre plane promotes crack propagation at a relatively small force which in this case is, however, comparable with the force necessary for the failure of alder wood. The relatively high (as compared to alder wood) fracture toughness of pine wood along directions II and III can be explained by some similarity of the microstructure of these wood species (Figs 6, 9 and 7, 10) and similarity of density.

The evidently most complex microstructure along directions II and III (a great number of highly developed elements that are lateral to the fibres, Figs 12 and 13) is shown by birch wood, for which the obtained values of K_{IIc} are the greatest, being, respectively $0.277 \text{ MN m}^{-3/2}$ for direction II, and $0.696 \text{ MN m}^{-3/2}$ for direction III.

The fracture toughness results obtained have shown that the use of fracture mechanics-based research methods in conjunction with microstructure studies in relation to wood is justified. Significant variation of the K_{IIc} values for particular wood species indicates that wood is sensitive to this kind of examination.

References

1. S. M. CRAMER and A. D. PUGEL, *Int. J. Fracture* **35** (1987) 163.
2. K. WRIGHT and M. FONSELIUS, in "Proceedings, First International RILEM Congress", Vol. 2 (Chapman & Hall, London, 1987) pp. 764–771.
3. A. VAUTRIN and B. HARRIS, *J. Mater. Sci.* **22** (1987) 3707.
4. G. PROKOPSKI, *ibid.* **28** (1993) 5995.
5. P. TRIBOULOT, "Report de D.E.A.", Universite de Metz (1978/79).
6. J. R. DIXON and J.S. STRANNIGAN, *J. Strain Analysis* **7** (1972) 125.

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