The application of fracture mechanics to the testing of wood

G. PROKOPSKI
Technical University of Częstochowa, 42-200 Częstochowa, Armii Krajowej 27, Poland

The problem of a mode I fracture toughness of wood is considered. After a short discussion of relevant literature the test results concerning mode I fracture on three types of wood and the obtained values of stress intensity factor, K_{Ic}, are discussed. The compressive and tensile strength of the wood fibres and flexural strength are also presented. A considerable variation of the stress intensity factor, K_{Ic}, has been found to depend on the wood species and the direction of taking specimens for tests. The character of a failure process and the obtained values of the stress intensity factor, K_{Ic}, were determined by interrelations of cohesion forces existing between particular components of the wood structure, and by anisotropy of the wood. Both the compressive and tensile strength tests performed along the fibres and the bending strength tests crosswise to the fibres have not confirmed the tendencies observed in the fracture toughness tests. The investigations performed show the usefulness of fracture mechanics for evaluation of the strength properties of wood. It is concluded that materials science must consider wood as a valuable and rewarding material upon which to focus research efforts.

1. Introduction

The assessment of the strength properties of wood has been carried out so far with the use of traditional strength parameters, such as tensile strength, compression strength and bending strength. A relatively large number of studies have been concerned with rheological and fatigue testing of wood.

Results published so far on the strength studies pertaining to wood have very seldom included results of fracture toughness tests, in spite of the fact that the wood may fail due to cracking in the process of load accretion. Fracture mechanics has already been used for a broad range of construction materials, such as metals, cement-based materials, both unreinforced and reinforced with various fibres, as well as ceramic materials. Although in studies carried out using the concepts of fracture mechanics, some satisfactory results have been obtained that correctly characterize the failure process, there are many problems left unresolved (e.g. the effects of the dimensions and the shape of a sample or the length of the primary crack either present or cut in the samples).

The fracture toughness may be evaluated from the value of the stress intensity factor, K_{Ic} (determined during a tensile test), which characterizes the stress field at the crack tip at the initiation of failure

$$K_{Ic} = \sigma(\pi a)^{1/2} \tag{1}$$

where σ is the stress in the region of the slit, and a is the length of the slit.

The increase of stress around the crack may be the result of external effects (loading of the construction), or structural stress resulting from the specific structure of the material. The increase of the stress above the critical value results in the sudden development of the crack that may lead to the failure of the component.

In addition to the characterization of fracture toughness with the use of the stress intensity factor, K_{Ic}, studies of the critical crack opening displacement (COD) can also be applied, which ensures obtaining correct results in the case of considerable plastic deformation

$$\delta = \frac{\pi\sigma^2 a}{E\sigma_{pl}} \tag{2}$$

where δ is the crack tip displacement, σ the stress in the sample, a the length of the crack, E the modulus of elasticity, and σ_{pl} the stress equal to the yield point.

In the investigation of notched samples tested in bending of wood, large plastic deformation has been found to occur [1]. The useful application of δ in characterizing the state of stress and deformation at the crack tip is confirmed by studies using the method of finite elements and with the use of the J integral. The J integral was proposed by Rice [2] as a criterion of failure of materials in which a non-linear relationship between deformation and stress exists. The essential property of the J integral is that, in non-linearly elastic materials, the critical J_c may be interpreted as the energy required for the propagation of the crack, G_c (where G is the fracture energy).

The correct assessment of the fracture toughness of a material may be achieved by the use of test samples of specific dimensions. The correspondence of the stress state in the sample and in the component is conditioned by the minimal thickness, B, of the sample

$$B \geq 2.5\left(\frac{K_{Ic}}{\sigma_{pl}}\right)^2 \tag{3}$$

In the case of wood, fulfilment of this condition is not difficult.

So far only few studies of the fracture toughness of wood and wood composites (plywood) have been carried out. Cramer and Pugel [3] have reported results of tests performed according to mode II fracture (shearing) on pine and fir samples. The calculation of the stress intensity factor, K_{IIc}, has also been carried out using the method of finite elements. A relationship between K_{IIc} and the relative humidity and density of a particular wood species has been found. Wright and Fonselius [4] presented results which were obtained by testing about 1200 wood samples loaded according to modes I and II. The tests were performed on pine and spruce samples, as well as on veneered spruce samples. The investigations showed the different behaviour of the samples in the process of loading depending on the wood species and the fracture model used.

Acoustic emission investigations during the tensile tests of fir, oak and beech samples were carried out by Vautrin and Harris [5]. They stated the usefulness of the acoustic emission method in the determination of a critical stress level, particularly in those cases when the initiation of the crack occurred "deep inside" the material. Extensive studies of the fracture toughness of three sorts of wood, (beech, pine and a kind of tropical wood, *Entandrophragma utile*) were carried out by Triboulot [1]. The tests were performed using mode I fracture (tension at bending) on beam samples of dimensions of 20 mm × 70 mm × 250 mm, with one primary crack of variable length (from 20–50 mm). The samples were tested along the three main anatomical directions of the wood. The stress intensity factor, K_{Ic}, and the fracture energy, G_{Ic}, were determined. Both the wood species and the sample type (the place of sampling), as well as the length of the primary crack were found to have an influence on the results obtained in the tests.

In all the afore-mentioned studies, a great variation of the results was observed depending on the sort of wood, its relative humidity and the modulus of elasticity.

During its utilization, wood is loaded most often with forces that cause bending. The testing of the fracture toughness of wood using fracture mode I (tensile at bending) is the representative mode used in wooden constructions, therefore mode I fracture is appropriate for the evaluation of the fracture toughness of wood.

The parameters of fracture mechanics make it a modern tool in materials testing. The application of fracture mechanics concepts in the determination of the fracture toughness of wood should generate useful results.

2. Scope of the investigation

In this study the values of the stress intensity factor, K_{Ic}, have been determined for the following three species of wood: common oak, alder and birch. In addition, determination of the fracture toughness according to mode I fracture (tensile at bending), compressive and tensile tests along the fibres, and bending tests (Table I) were also performed. In these tests, six samples from each wood species were used, which were taken from the same log.

TABLE I The strength of wood after tests

Wood species	Compressive strength (MPa)	Tension strength (MPa)	Flexural strength (MPa)
Common oak	67.0 ± 2.9	81.2 ± 17.3	98.9 ± 7.7
Coefficient of variation (%)	4.3	21.3	11.1
Alder	59.3 ± 5.2	55.6 ± 12.5	87.4 ± 5.5
Coefficient of variation (%)	8.8	22.6	6.3
Birch	66.7 ± 3.6	83.2 ± 11.4	121.5 ± 14.0
Coefficient of variation (%)	5.4	13.6	11.5

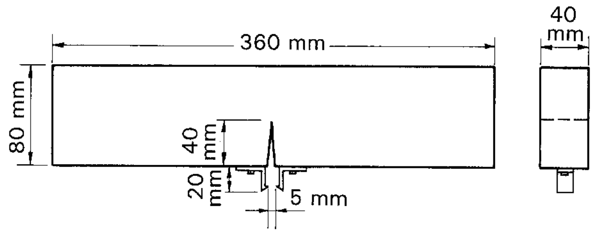


Figure 1 The sample geometry used for fracture toughness tests.

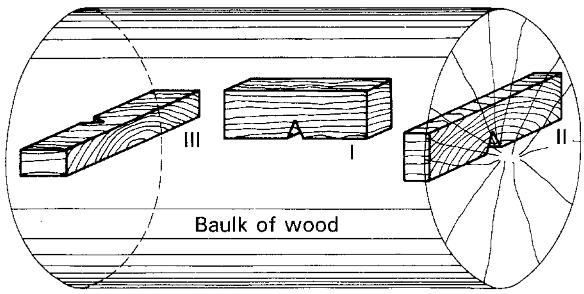


Figure 2 The types of investigated samples.

The fracture toughness tests were carried out using notched samples of dimensions 40 mm × 80 mm × 360 mm, which were bent with one force (Fig. 1). The notches in the samples were cut by milling. Special steel catches were fixed to the samples for installing a notch opening gauge.

The samples for fracture toughness testing were taken in each case from the same log and along the three main anatomical directions of the wood (Fig. 2). In each series, seven samples were tested.

Load–displacement graphs were recorded with the use of an X–Y plotter. The wood species samples tested had the following moisture contents: oak 12% ± 1%; birch 10.5% ± 1%, alder 10% ± 1%.

3. Fracture toughness tests

The fracture toughness tests were performed using the test apparatus illustrated in Fig. 3. During the tests, a

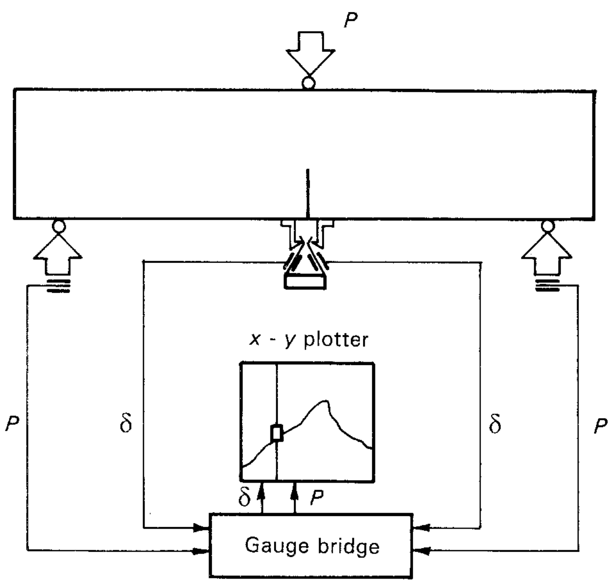
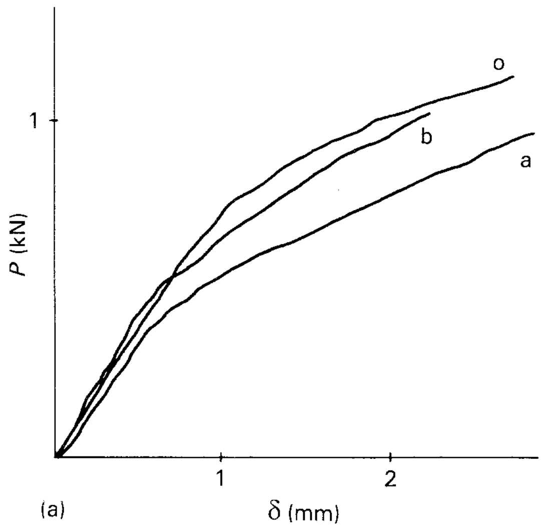
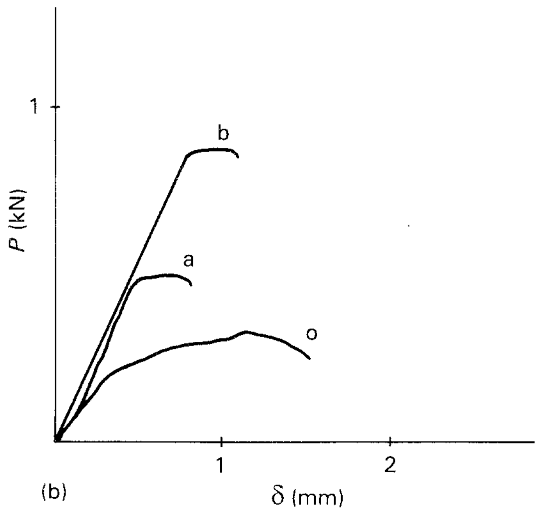


Figure 3 Diagram of test stand.

graph of the dependence of the loading force on the primary crack opening was obtained for each sample. Examples of failure curves obtained in the tests of the different wood orientations (I, II and III) are shown in Fig. 4.





The choice of the force, P_Q, used for the determination of the stress intensity factor was based on the ASTM standard [6]. The value of the force, P_Q, was obtained through the intersection of the failure curves with the straight line inclined by 5% less than the tangents to the failure graphs drawn from the origin of the coordinates. In order to find P_Q, the tangents, s, to the linear part of the graph was drawn (Fig. 5) to the intersection with the straight line, b, parallel to that drawn from the coordinate point equal to 100 mm and parallel to the abscissae, to obtain the point A. From point A, a vertical section AB of length 5 mm was drawn. From the origin of the coordinates the straight line s_1 was drawn crossing the point B up to its intersection with the failure graph, to give point C. Point C determines the value of the critical force, P_Q (Fig. 5).

The stress intensity factor K_{Ic} was determined from

$$K_{Ic} = \frac{P_Q}{BW^{1/2}} Y\left(\frac{a}{W}\right) \tag{4}$$

where P_Q is the critical force, a the length of the primary crack, B the sample thickness, W the sample height, $Y(a/W)$ a function of deformability of a bent sample, determined according to Brown and Srawley [7].

The results of the calculations of the stress intensity factor, K_{Ic}, are presented in Table II. The graphic illustration of the results obtained is shown in Fig. 6.

4. Discussion

The obtained values of stress intensity factors, K_{Ic}, have shown a considerable variation in relation to both the wood species and the specimen types (I, II and III). For type I specimens the obtained values of K_{Ic} were decidedly the greatest. Type I specimens made of oak wood had values of K_{Ic} forty times greater than those of type II specimens, and about 17 times greater than the K_{Ic} values of type III specimens. In the tests of alder wood, type I specimens had the

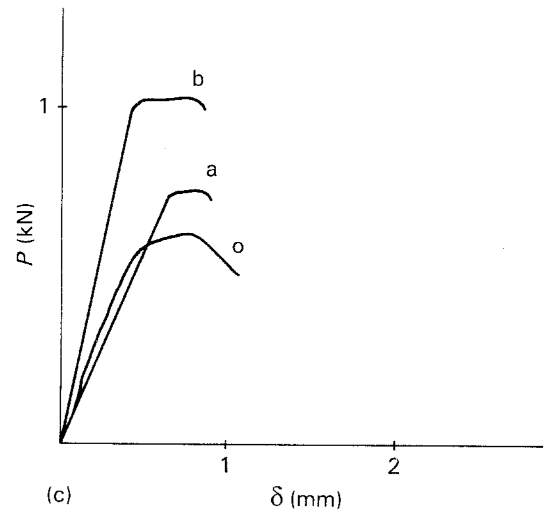


Figure 4 Typical load – deflection relations, (a) for samples of type I, (b) for samples of type II, (c) for samples of type III. o, oak; a, alder; b, birch.

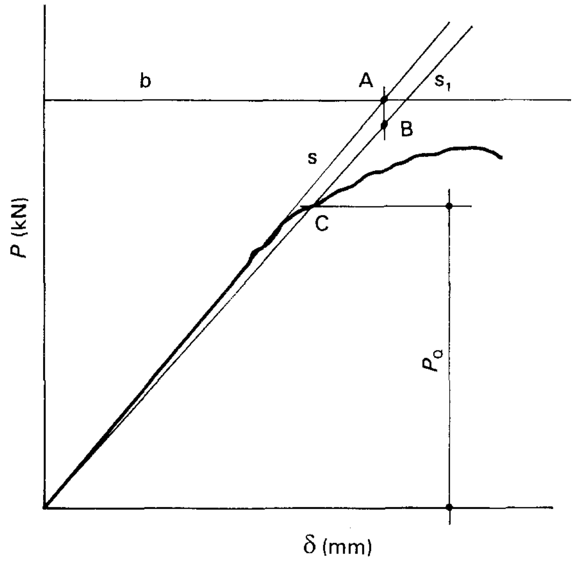
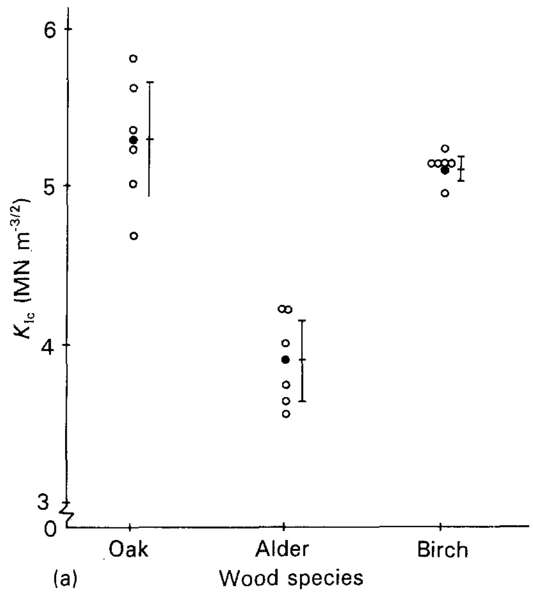


Figure 5 The method of P_Q determination.

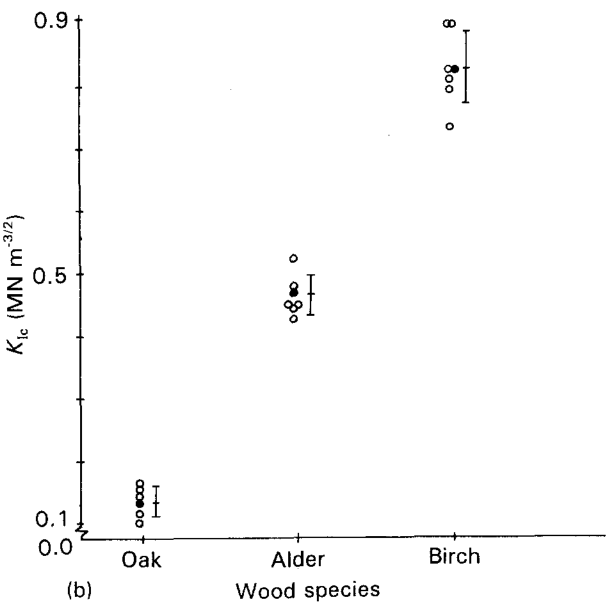


values of K_{Ic} eight times greater than the values of type II specimens, and about nine times greater than those of type III specimens. The values of K_{Ic} obtained in the tests of birch wood were relatively the least diversified. Type I specimens had the values of K_{Ic} about six times greater than the values of type II specimens, and about five times greater than those of type III specimens.

The failure curves (Fig. 4) obtained in the fracture toughness tests show different tendencies of the behaviour of particular wood species and the types of specimens tested (I, II and III). In the tests of type I specimens, the existence of considerable plastic deformation has been found in all three wood species. In the tests of types II and III specimens, the plastic deformations were shown only by oak wood. Such a behaviour of particular wood species under an increasing load, results from differences in their anatomical structure.

Characteristics of a failure process and the obtained values of destructive forces were determined by mutual relations between particular components of a wood structure on the "ordering" level of the structure. The variation of the values and proportions of the stress intensity factors, K_{Ic}, of particular wood species was caused by differences in the structure. The best "ordering" (the greatest systematics) of the structure in every direction (I, II and III) was shown by oak wood. This resulted in obtaining the relatively least values of K_{Ic} in the tests of types II and III specimens, in spite of the greatest fracture toughness of type I specimens of oak wood. This was due to the facilitation of the propagation of a crack along structurally well-formed cleavage directions of oak wood.

Alder and birch wood had worse "ordering" of the structure than oak wood. This caused a considerably lower variation of the values of K_{Ic} obtained in the tests of these wood species (specimens of types I, II and III) and relatively high (compared with oak wood) values of K_{Ic} obtained in testing the specimens of types II and III.



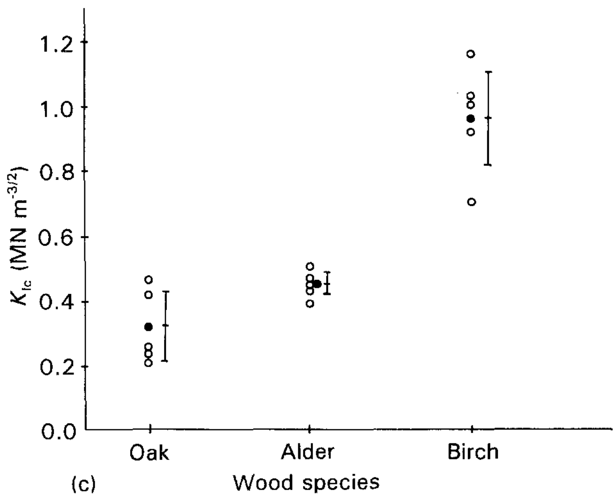


Figure 6 Stress intensity factor, K_{Ic}, (a) for samples of type I, (b) for samples of type II, (c) for samples of type III. (○) Test value, (●) mean value.

TABLE II Stress intensity factor, K_{Ic}, for type I, II and III samples

	Common oak			Alder			Birch		
I	I	II	III	I	II	III	I	II	III
K_{Ic} ($MNm^{-3/2}$)	5.81	0.16	0.47	4.22	0.52	0.50	5.25	0.89	1.12
	5.63	0.15	0.42	4.22	0.48	0.46	5.16	0.89	1.03
	5.34	0.14	0.25	4.03	0.45	0.45	5.16	0.82	1.00
	5.25	0.12	0.24	3.75	0.45	0.43	5.16	0.82	0.92
	5.06	0.10	0.21	3.66	0.44	0.39	5.16	0.80	0.70
	4.69	–	–	3.56	0.43	–	4.97	0.73	–
$K_{Ic} \pm \delta$	5.30	0.13	0.32	3.91	0.46	0.45	5.14	0.82	0.96
	0.37	0.02	0.11	0.26	0.03	0.03	0.08	0.05	0.14
Coefficient of variation (%)	6.9	16.0	33.1	6.7	6.8	7.6	1.6	6.7	14.7

5. Conclusions

The investigations performed have shown the usefulness of the fracture mechanics principles for the estimation of the fracture toughness of wood.

During utilization under load, wood undergoes failure due to cracking, therefore the proposed method of testing may be used for the evaluation of the appropriateness of particular wood species for use under specific conditions.

The values of the compressive and tensile strength along the fibres, as well as those of the bending strength obtained in the investigations, have not showed any relationship with the stress intensity factor, K_{Ic}, determined in the fracture toughness tests. This proves fracture toughness testing to be more useful for the evaluation of the mechanical properties of wood.

The introduction of fracture mechanics methods is proposed for testing wood. It will make possible a more reliable assessment of the strength properties of wood and will enable its rational use in utilized constructions.

It is advisable to extend the investigations to other sorts of wood and to include different states of sample loading to that presented in this paper.

Considering the observed cracking of wood under the influence of drying, this phenomenon should also be considered in further investigations using the fracture mechanics methods.

References

1. P. TRIBOULOT, "Mécanique de la rupture appliquée au matériau Bois", Report de D.E.A., Université de Metz (1978/79) p. 85.
2. J. R. RICE, *J. Appl. Mech.* **35** (1968) 379.
3. S. M. CRAMER and A. D. PUGEL, *Int. J. Fract.* **35** (1987) 163.
4. K. WRIGHT and M. FONSELIUS, in "Proceedings of the First International RILEM Congress", Wersal, France, 1987, Vol. 2, (Chapman and Hall, London, New York, 1987) p. 764.
5. A. VAUTRIN and B. HARRIS, *J. Mater. Sci.* **22** (1987) 3707.
6. ASTM Designation: E 399–83, "Standard test method for plane-strain fracture toughness of metallic materials" (American Society for Testing and Materials, Philadelphia, PA). p. 680.
7. W. F. BROWN Jr and J. E. SRAWLEY, "Plane strain crack toughness testing of high strength metallic materials", ASTM STP 410 (American Society for Testing and Materials, Philadelphia, PA, 1967).

Received 2 January 1992
and accepted 28 April 1993