THE FRACTURE TOUGHNESS OF WOOD UNDER IMPACT LOADING

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ABSTRACT

The instrumented impact test of a three-point-bend specimen of eastern red spruce was conducted. The dynamic fracture initiation toughness, K_{Id} was evaluated with the dynamic finite element analysis from the experimental impact load-time history. The fracture toughness for impact loading was 74 percent of its value under static loading condition, for the TL system of crack propagation.

KEYWORDS

Wood fracture; dynamic fracture initiation toughness; dynamic fracture; impact loading; dynamic finite element analysis.

INTRODUCTION

The science of fracture mechanics has already asserted a profound influence on failure-control procedures for engineering structures. It has the basic tenet that fracture takes place by flaw or crack extension; and it is natural to assume, in most cases, that the crack or flaw already exists, or could exist in service. The analysis of failure, then, involves the determination of the size of flaw or crack and the resistance of the material to the crack extension which is commonly expressed in terms of the fracture toughness, K_{IC}. Failure in wood is usually associated with the pre-existing imperfections (e.g. checks, shakes, etc.) or defects introduced by unfavorable circumstances of manufacture and/or environmental conditions, yet these irregularities are not accounted for when the strength of the wood is measured. The parameters of fracture mechanics are, therefore, more realistic measures of strength than those currently in use for wood. They also provide a basis for understanding failure mechanisms in wood structures. This motivation has generated the interest of many investigators to study the fracture of wood using the concepts of fracture mechanics (Barrett, 1980). These studies have shown that fracture mechanics theory, originally developed to predict the onset of crack growth in metals, can be extended to predict failures in wood by rapid crack extension.

However, previous investigations have been concerned only with the fracture failure of wood under static loading condition. The resistance to impact or shock loading is the strength property to be taken into account for timber where such loading is a normal occurrence, e.g. members of building structures, athletic and gymnasium equipment, tool handles, ladders, scaffold boards, etc. The resistance to impact load is conventionally assessed in metals as well as in wood in terms of "traditional toughness" with a single-blow impact test. Recommended test procedures to obtain traditional toughness are the Charpy-V test (A.S.T.M., 1972) and Drop Weight Tear Test (A.S.T.M., 1971) for metallic materials; and Drop weight impact bending test and Forest Products Laboratory pendulum toughness test for wood (A.S.T.M., 1978b). In all these impact tests, the traditional toughness of the material is assessed from the absorbed energy (or its measured parameter, the drop height of impact tup) of the specimen for the total failure or without sustaining any damage. This traditional toughness is, however, a qualitative index of the specimen and does not represent a quantitative measure to evaluate the resistance against fracture failure of structural members subjected to impact load.

To overcome this shortcoming of the traditional impact tests, a modified technique, commonly referred to as "Instrumented Impact Testing" has been employed for metallic materials (A.S.T.M., 1974). This procedure provides a quantitative measure of the resistance of material to impact or shock load in terms of the fundamental material property, dynamic fracture initiation toughness, K_{Id}. The objective of the present investigation was to utilize this methodology to measure the dynamic fracture initiation toughness, K_{Id} of a locally available wood. This is also the first step towards the development of a design procedure for wooden structural members, based on the concepts of fracture mechanics, subjected to impact or shock loading.

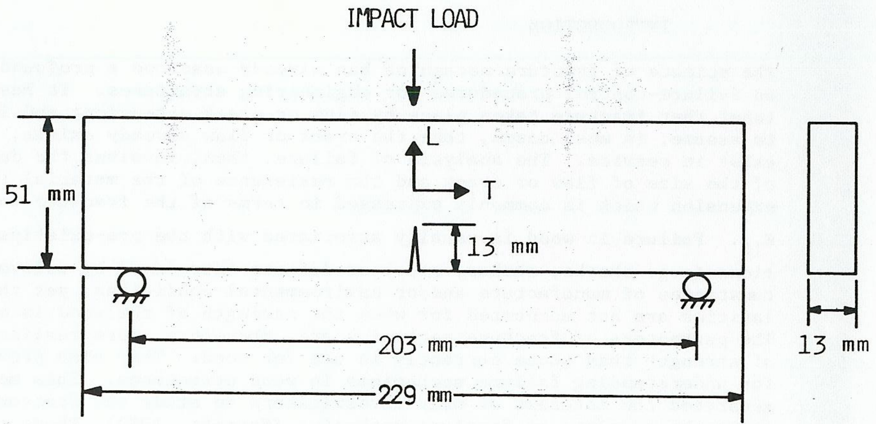

Fig. 1. Three-point-bend specimen.

EXPERIMENTAL PROCEDURE

The experimental program consisted of instrumented drop-weight impact tests of three-point bend specimens. The specimen configuration is shown in Fig. 1. Eighteen specimens were machined from nine flat-sawn boards of eastern red spruce (Picea rubens Sarg) which were purchased locally in the kiln-dried condition and were further conditioned in a humidity room at 20°C and 65 percent relative humidity (A.S.T.M., 1978b), resulting in a nominal equilibrium moisture content of 12 percent. Two specimens were machined from each board at the same location. This arrangement provided one specimen for impact test and one for static fracture test from each board. A crack of 13 mm was cut with a very fine razor blade. The crack was collinear with the grain direction which resulted in the TL system of crack propagation, where "T" (transverse) indicates the direction normal to the crack surface and "L" (longitudinal) the direction of crack propagation.

The impact testing machine involved a free-falling weight with an instrumented striker tup and a rigidly supported anvil that provided an arrangement of impact loading of a three-point-loaded beam. The drop weight was 3.6 kg, the drop distance of the striker tup was 305 mm, and the impact velocity was about 2.45 m/sec. The sliding friction between the drop weight and guide rails was minimized by two ball bushings installed in the drop weight housing. A four-arm strain gage bridge was mounted on the striker tup, thus permitting the recording of the load-time history during the impact. The strain-gage-bridge output versus applied-load relation was obtained by the static calibration of the tup. A crack wire of about 1.6 mm wide made of silver conductive paint was put in front of the crack to determine the time of crack initiation during impact test. A typical impact load-time oscillogram is shown in Fig. 2, along with the signal from the crack wire. The sudden drop in the crack wire signal shows the breaking of the crack wire caused by crack propagation. The details of the experimental procedure can be obtained in the previous work (Mall, Kobayashi and Urabe, 1978). The experimental impact-load versus time relations of the nine specimens, up to the time of crack initiation, are shown in Fig. 3. These relations were input in the dynamic finite element analysis to evaluate the dynamic fracture initiation toughness, K_{Id}.

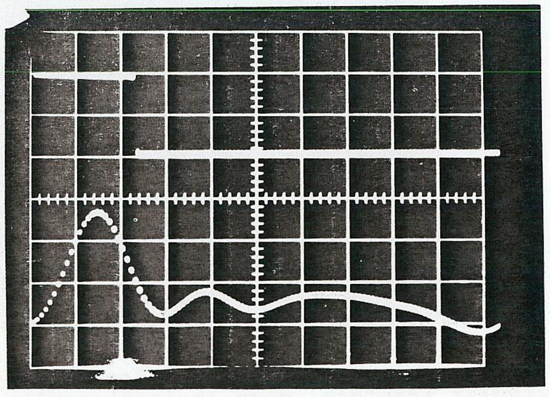

Fig. 2. A typical oscillogram of impact load-time history (lower) and the crack wire signal (upper).

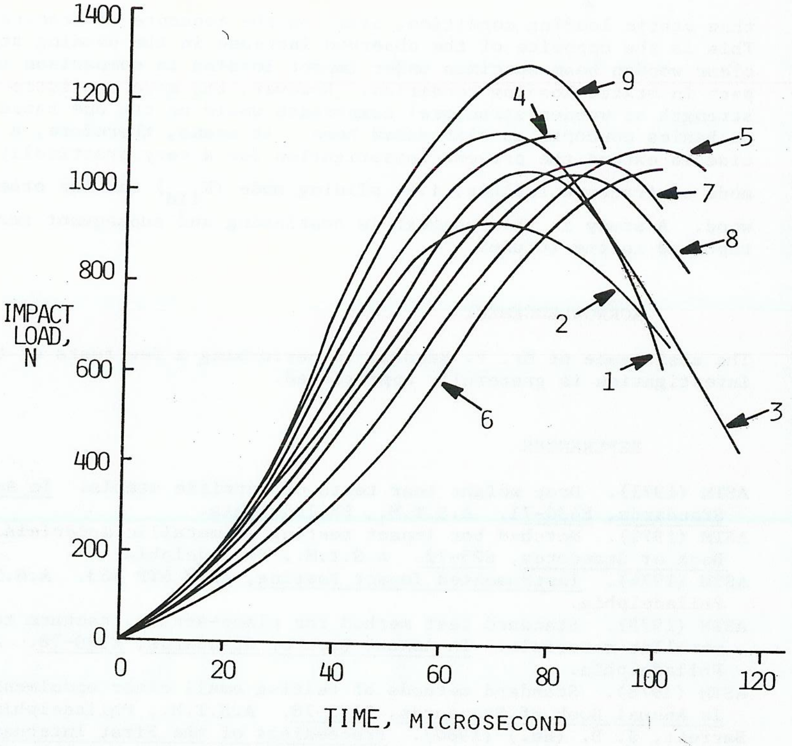

Fig. 3. Impact load-time relations of nine specimens.

The static fracture tests of three-point-bend specimens were conducted with an Instron Universal testing machine, at a crosshead speed of 0.5 mm/sec. The load-displacement relation, recorded in all experiments, was linear up to the fracture load for all specimens. The static fracture toughness, K_{IC} was computed from the expression given for the three-point-bend specimen in ASTM test procedure (A.S.T.M., 1978a).

DYNAMIC FINITE ELEMENT ANALYSIS

The dynamic finite element analysis employed in the present study has been described in detail by Mall (1980). Due to symmetry, only half of the specimen was analyzed. Figure 4 shows the finite element model, which consisted of eight-noded-isoparametric elements. The two elements at the crack tip were modified to incorporate the required inverse square root singularity by placing the mid-side node of the side connected to the crack tip at the quarter position adjacent to the crack tip. The material properties of eastern red spruce employed in analyses were; elastic modulus in longitudinal direction, E_L = 12,720 MPa, in transverse direction, E_T = 630 MPa, shear modulus in the

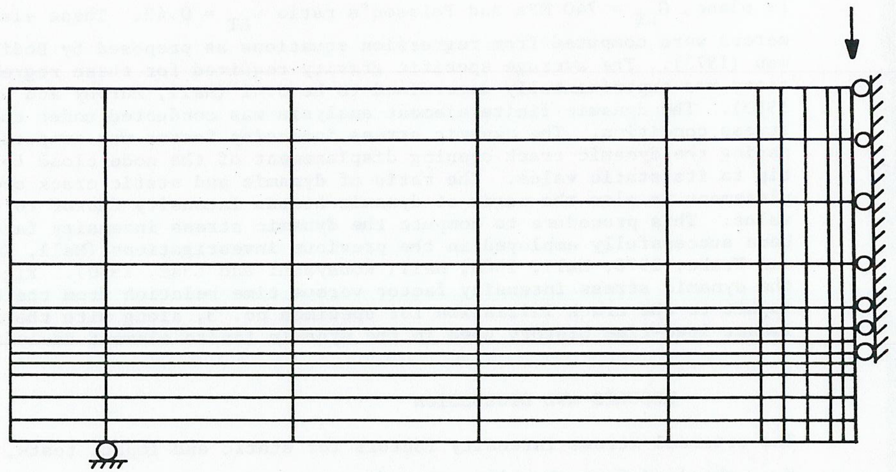

Fig. 4. Finite-element model.

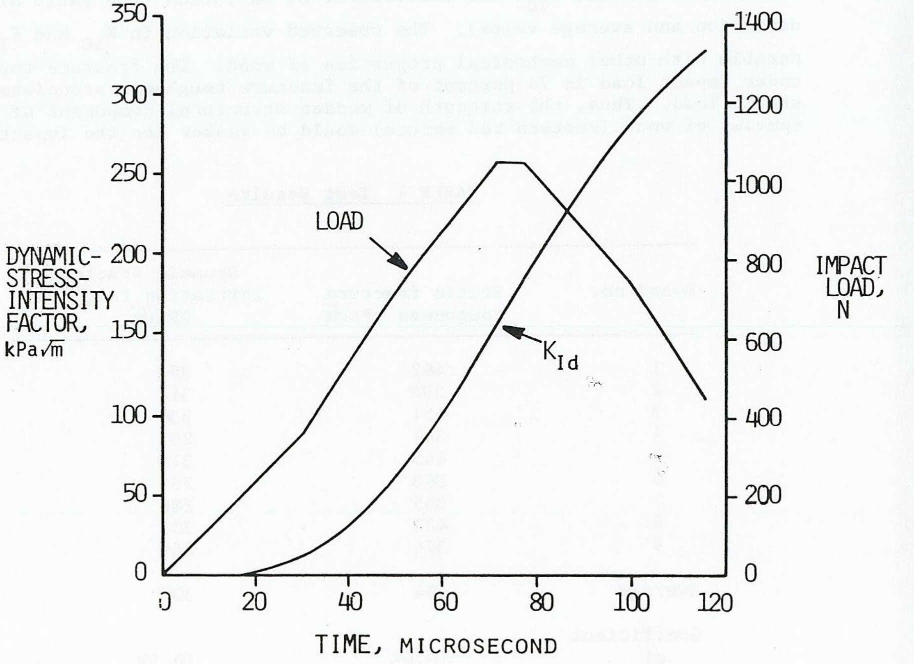

Fig. 5. Dynamic-stress-intensity factor and idealized tup load from start of impact to crack initiation of specimen no. 3.

LT plane, G_{LT} = 740 MPa and Poisson's ratio ν_{LT} = 0.42. These elastic parameters were computed from regression equations as proposed by Bodig and Goodman (1973). The average specific gravity required for these regression equations was experimentally determined to be 0.42 (Mall, Murphy and Shottafer, 1983). The dynamic finite element analysis was conducted under the plane stress condition. The dynamic stress intensity factor was computed by comparing the dynamic crack opening displacement of the node close to the crack tip to its static value. The ratio of dynamic and static crack opening displacement is also the ratio of dynamic stress intensity factor to the static value. This procedure to compute the dynamic stress intensity factor has been successfully employed in the previous investigations (Mall, Kobayashi and Urabe, 1978; Mall, 1980; Mall, Kobayashi and Loss, 1980). Figure 5 shows the dynamic stress intensity factor versus time relation from the time of impact to the crack initiation for specimen no. 3, along with the idealized impact load-time history used in the dynamic finite element analysis.

RESULTS AND DISCUSSION

The critical stress intensity factors for static and impact tests, K_{IC} and K_{Id}, obtained from the nine sets of measurements are given in Table 1. It also shows the average values of fracture toughness, K_{IC}, dynamic initiation fracture toughness, K_{Id}, and coefficient of variation (the ratio of standard deviation and average value). The observed variation in K_{IC} and K_{Id} is comparable with other mechanical properties of wood. The fracture toughness under impact load is 74 percent of the fracture toughness associated with the static load. Thus, the strength of wooden structural component of this species of wood (eastern red spruce) would be weaker for the impact loading than static loading condition, based on the concepts of fracture mechanics. This is the opposite of the observed increase in the bending strength of a clear wooden beam specimen under impact loading in comparison to its counterpart in static loading condition. However, the more realistic measure of strength of wooden structural components would be the one based on fracture mechanics concepts as elaborated here. It seems, therefore, a useful exercise to extend the present investigation for a very practically important mode of fracture failure, i.e. sliding mode (K_{IId}) and for other species of wood. A study in this context is continuing and subsequent results will be reported in the future.

TABLE 1 Test Results

Board no.	Static fracture toughness kPa√m	Dynamic fracture initiation toughness kPa√m
1	462	352
2	398	314
3	451	330
4	341	258
5	445	319
6	363	269
7	385	286
8	423	301
9	374	269
Average	404	300
Coefficient of Variation	10.6%	10.5%

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REFERENCES

ASTM (1971). Drop weight tear tests of ferritic steels. *In Annual Book of Standards*, *E436-71*. A.S.T.M., Philadelphia.

ASTM (1972). Notched bar impact testing of metallic materials. *In Annual Book of Standards*, *E23-72*. A.S.T.M., Philadelphia.

ASTM (1974). *Instrumented Impact Testing*, ASTM STP 563. A.S.T.M., Philadelphia.

ASTM (1978). Standard test method for plane-strain fracture toughness of metallic materials. *In Annual Book of Standards*, *E399-78*. A.S.T.M., Philadelphia.

ASTM (1978). Standard methods of testing small clear specimens of timber. *In Annual Book of Standards*, *D143-78*. A.S.T.M., Philadelphia.

Barrett, J. D. (Ed.) (1980). *Proceedings of the First International Conference on Wood Fracture*. Forintek Canada Corporation, Vancouver.

Bodig, J., and J. R. Goodman (1973). Prediction of elastic parameters for wood. *Wood Science*, *5*, 249-264.

Mall, S., A. S. Kobayashi, and Y. Urabe (1978). Dynamic photoelastic and dynamic finite element analyses of dynamic-tear-test specimens. *Exp. Mech.*, *18*, 449-456.

Mall, S. (1980). Dynamic finite element analysis of cracked bodies with stationary cracks. In P. C. Paris (Ed.), *Fracture Mechanics: Twelfth Conference*, ASTM STP 700, A.S.T.M., Philadelphia.

Mall, S., A. S. Kobayashi, and F. J. Loss (1980). Dynamic fracture analysis of notched bend specimens. In G. T. Hahn and M. F. Kanninen (Eds.), *Crack Arrest Methodology and Applications*, ASTM STP 711, A.S.T.M., Philadelphia.

Mall, S. J. F. Murphy, and J. E. Shottafer (1983). Criterion for mixed mode fracture in wood. *J. Eng. Mech.*, *ASCE*, *109*, 680-689.