Die-cutting toughness and cracking of corrugated board

Christer Fellers, Mats Fredlund, and Pia Wågberg*

A laboratory study evaluated the J integral and Liebowitz methods for evaluating cracking in corrugated board during die cutting. Since the Liebowitz method has the highest precision of the two methods, the authors recommended its use in further studies of the fracture toughness of paper.

This paper reports a study in which laboratory evaluation of linerboard-type papers is related to the production problem of cracking in corrugated board during die cutting.

The ability of paper to resist crack propagation is important in a number of other end-use situations like runnability of printing paper grades and the ability of a filled sack to resist crack propagation. The mode of fracture in the end-use situations described above is seldom the out-of-plane mode III, as in the Elmendorf tear test, but a fracture in the in-plane mode I. It has been shown that fracture toughness develops very differently with papermaking factors in the two modes. If paper properties are to be optimized for a given paper grade, it is important that paper be evaluated in the same mode as that experienced during the end use.

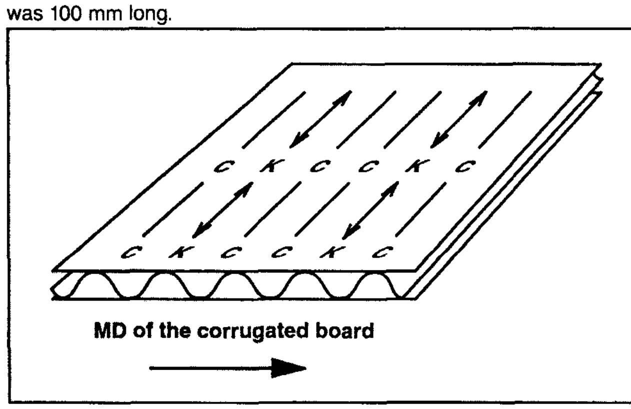
An ideal fracture toughness method should be based on fracture mechanics theories and should be able to provide data which would make it possible to calculate the cracking tendency in paper and paper products of different sizes subjected to different loading situations. A prerequisite for such a method is that it should be able to assess the cracking resistance of the paper in all climates at realistic elongation rates and should permit a grading of papers.

In this investigation, various papers with different furnishes have been converted to corrugated board by gluing the papers as double backer to single-face corrugated boards using the same corrugated medium. These corrugated boards have been die cut with a standardized die, producing cuts and creases. The total length of the cracks emanating from the cuts and creases has been measured and used after normalization as a measure of the cracking resistance of the papers. The term "die-cutting toughness number" has been introduced for this property.

*Wågberg currently works for SCA Research AB, Box 3054, S-852 03 Sundsvall, Sweden.

Fellers is principal research scientist and Fredlund and Wågberg are research physicists at STFI, Box 5604, S-114 86 Stockholm, Sweden.

1. Knife (K) and crease (C) pattern in the tested boards. The board dimensions were 300 mm × 300 mm. Each knife cut and each crease was 100 mm long.



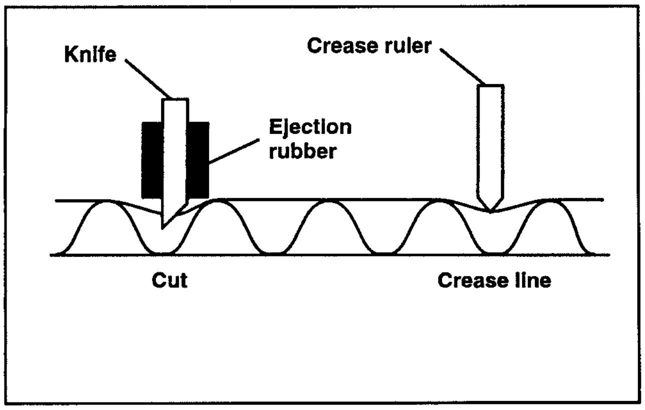
The same papers were then characterized by the conventional tensile test and by methods based on fracture mechanics: the J integral, the Liebowitz fracture toughness, and the Critical Stress Intensity Factor.

It was found that the J integral and the Liebowitz fracture toughness showed the highest correlation with the die-cutting toughness number.

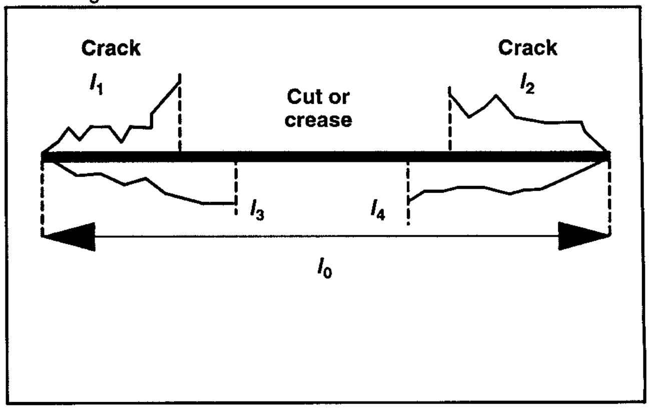
The J integral method has been used for paper characterization many times in the past, in contrast to the Liebowitz method which was only recently proposed for paper. The excellent correlation between the J integral and the Liebowitz fracture toughness found in the die-cutting trial motivated a second trial in which the fracture toughness values were compared. The commercial newsprint, kraft liners, and sack papers used in this investigation cover a wide variety of properties. To widen the range of the investigation, both the rate of elongation and relative humidity were varied.

The results from this trial also show an excellent correlation between the fracture toughness values obtained by the J integral and the Liebowitz methods. Since the Liebowitz method has the highest precision of

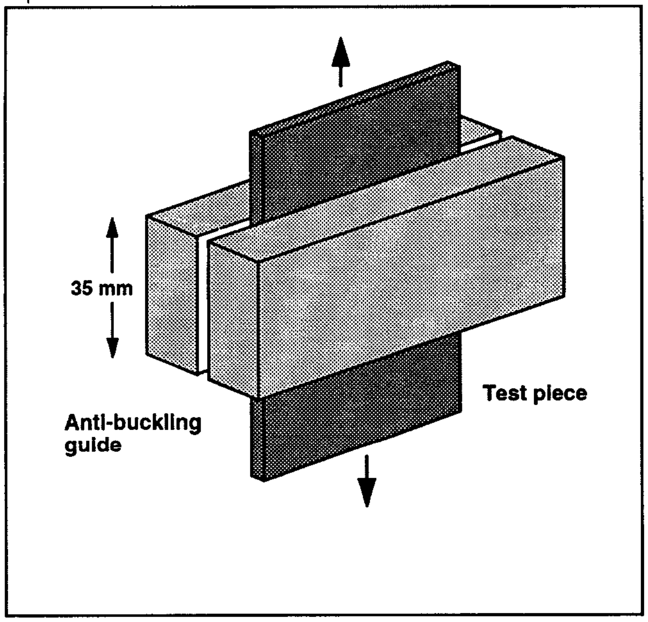
2. Penetration of the crease ruler and knife into the corrugated board



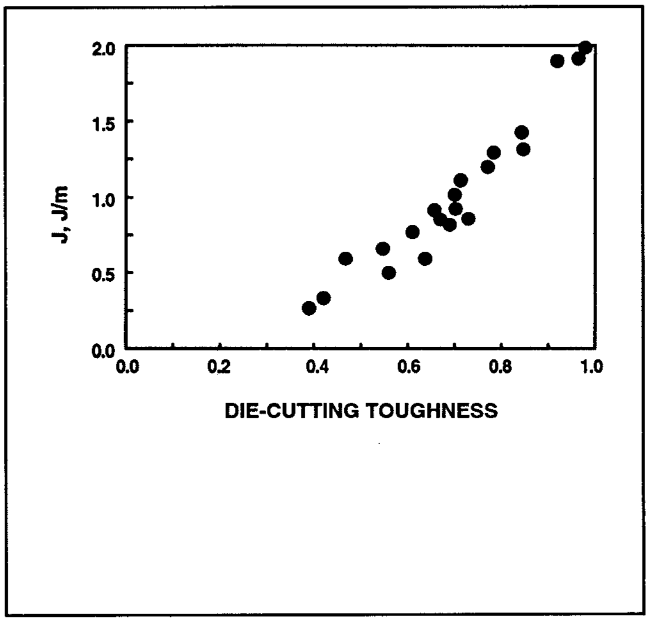
3. Cracks radiate outward from the cuts and creases. The projected crack length in the cut or crease direction was measured.



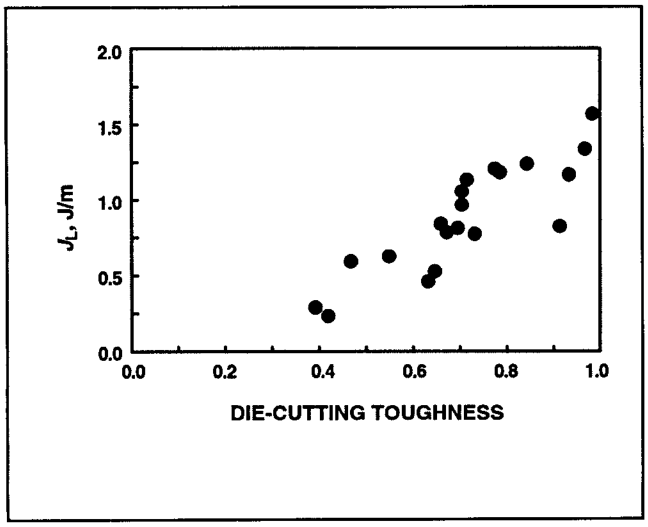
4. An anti-buckling guide was used in the fracture mechanics experiments



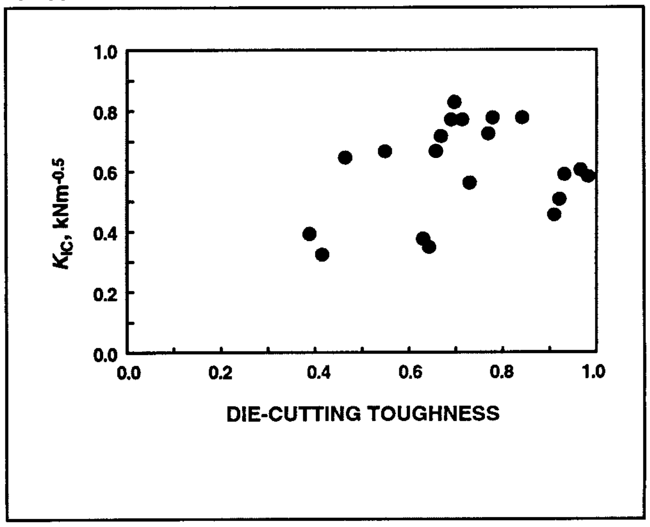
5. The J integral vs. the die-cutting toughness number



6. The Liebowitz fracture toughness vs. the die-cutting toughness number



7. The Critical Stress Intensity Factor vs. the die-cutting toughness number



the two methods, we recommend it for further studies of fracture toughness of paper.

Materials

Two trials were carried out. In the first trial, linerboard-type papers with a grammage of approximately 100 g/m^2 were made on the fourdrinier forming section of the STFI experimental machine FEX and dried off-line. Several types of pulps were used. These included five types of northern softwood pulps: bleached sulfate, unbleached sulfate (kappa no. 50), unbleached sulfate (kappa no. 90), oxygen-treated polysulfide, and alkaline sulfite anthraquinone. We also used two birch hardwood pulps: bleached sulfate and unbleached sulfate (kappa no. 80).

For the second trial, three types of commercial papers were used:

1. Newsprint (48.5 g/m^2, 758 kg/m^2 density, thermomechanical pulp and groundwood furnish)
2. Kraft liner (200 g/m^2, 732 kg/m^2 density, 80% softwood sulfate pulp and 20% recycled corrugated board furnish)
3. Sack paper (80 g/m^2, 721 kg/m^2 density without microcreping, 100% softwood sulfate pulp furnish).

Methods

Corrugated board manufacturing and die-cutting procedure

Laboratory-made corrugated boards were produced by ASSI Kraftliner in Sweden. The FEX-produced papers were glued to a commercial single-face corrugated board with a water-based polyvinyl acetate glue. The C-flute corrugated medium had a grammage of 112 g/m^2, and the corrugated board had a flat crush value of 390 kPa.

The machine direction (MD) of the papers was parallel to the MD of the corrugated board, except in one case when the paper was turned 90° so the cross direction (CD) of the paper was in the MD of the board.

The corrugated boards were die cut by ASSI Kraftliner in a laboratory platen press at realistic speeds. As shown in **Fig. 1**, each knife cut is placed between creases. The press and the die pattern were described in detail by Cavlin and Edholm (*1*).

In the die-cutting process, the knife and crease rulers penetrated and depressed the paper as shown in **Fig. 2**. The cuts and creases are not normally clean; cracks radiate outward from the cut or crease line. The crack length was determined by adding the projected length, l_n, in the cut or crease direction. The principle is shown in **Fig. 3** for four cracks.

The total crack length was normalized with respect to the total crease and knife length, l_0 12 × 100 mm, to give a number between zero and unity, corresponding to total cracking and no cracking, respectively. The value obtained is called the die-cutting toughness number, *D*. Average results were calculated from six corrugated board test pieces. The coefficient of variation was in the order of 6%:

$$D = 1 - l_n/l_0$$

Conventional paper properties

Tensile properties were evaluated in accordance with SCAN-TEST standard procedures and also at nonstandard humidities and rates of elongation.

The tensile test was performed with a 100-mm span length with a load cell of 1 kN. Tensile stiffness was evaluated from the maximum slope of the force-elongation curve with a stretch increment of 0.05%. The origin of the force-elongation curve was taken as the point where the maximum slope of the curve intersects the elongation axis.

Fracture mechanics

The *J* integral method, the Liebowitz method, and the Critical Stress Intensity Factor method, based on fracture mechanics, were all applied. These methods are described in the Appendix.

Test pieces had a free test span of 100 mm and a width of 50 mm. In the test pieces, center notch cracks of different lengths were made with a razor blade mounted in a small punch-press.

An anti-buckling guide modified from Westerlind *et al.* (*2*) and shown in **Fig. 4** was used in all the fracture mechanics tests. The guide rested on the center portion of the test piece to prevent it from bulging out-of-plane during the testing. The initial force of 0.1 N on the guide was provided by means of a precision micrometer supplied with a torque limiter. During the test, the distance was kept constant at the initial distance.

The same principles for gripping the test pieces and evaluation of the curves were followed for the fracture mechanics testing as for the tensile testing. Average results in MD and CD were calculated from 15 test pieces in each direction.

Testing equipment

The papers in the first trial were tested in a computer-controlled universal testing machine (L&W) at 20% RH, 50% RH, and 80% RH (at the SCAN-TEST standard rate of 0.36 mm/s).

The papers in the second trial were tested in a computer-controlled servohydraulic testing machine (MTS) at 0.2 mm/s, 2 mm/s, and 20 mm/s. In these tests, failure occurs in 5.0 s, 0.5 s, and 0.05 s, respectively, if a paper has a stretch at break of 1%.

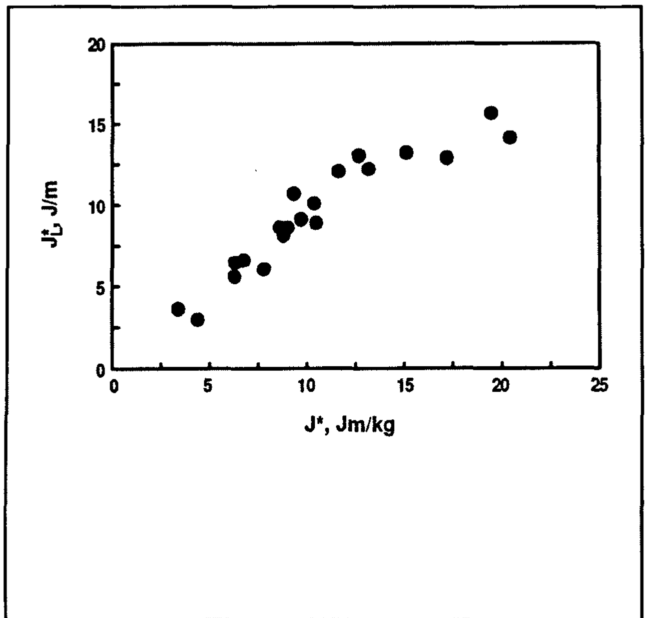
The testing was performed at 23°C at 20% RH, 50% RH, 70% RH, and 90% RH.

Results

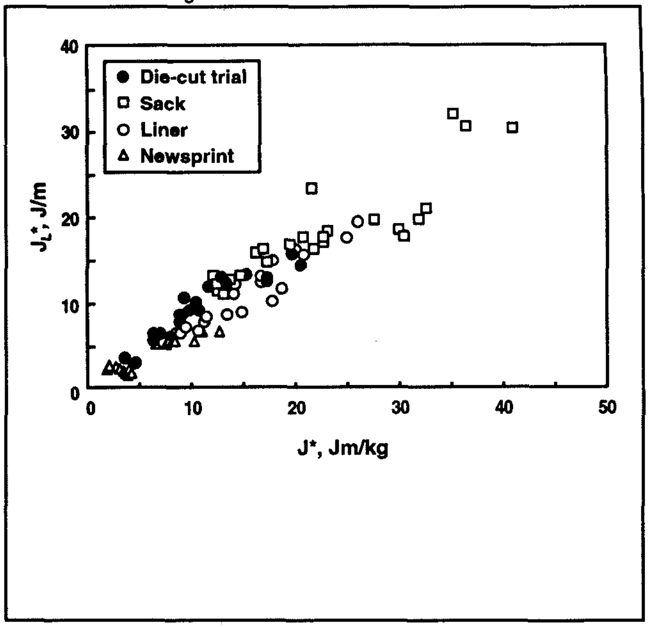
The cracking tendency of the liner during die cutting of corrugated board, characterized by the die-cutting toughness number, was compared with the results of the tensile test and with tests based on fracture mechanics theories. Both the *J* integral value and the Liebowitz fracture toughness (J_L) showed a high correlation to the die-cutting toughness number, shown in **Figs. 5 and 6**, in contrast to the Critical Stress Intensity Factor (K_{IC}), based on linear elastic fracture mechanics, in **Fig. 7**.

The tensile paper properties showed a poor correlation to the die-cutting toughness number.

In **Fig. 8**, the Liebowitz fracture toughness index is plotted against the *J* integral index for all the data in the



8. The Liebowitz fracture toughness index (J_L^*) vs. the J integral index (J^*) for all the data obtained in the first trial



9. The Liebowitz fracture toughness index (J_L^*) vs. the J integral index (J^*) for newsprint, kraft liner, and sack paper at different relative humidities and elongation rates

I. The coefficient of variation of the tensile stiffness, the J integral, and the Liebowitz fracture toughness

			Coefficient of variation, %					
			Newsprint		*Kraft liner*		*Sack paper*	
Property	*No. of test pieces*	*Crack length/ test piece width*	*MD*	*CD*	*MD*	*CD*	*MD*	*CD*
Tensile stiffness	10	0	3	6	4	3	6	7
J integral	15	0.4	19	42	12	23	30	30
	15	0.6						
J_L	15*	0.6	14	26	9	16	18	21

*In addition to 10 determinations of tensile stiffness in the MD and CD.

first trial. This excellent agreement was the prime motivation for the second trial.

Figure 9 shows the results of the second trial, embracing three commercial papers representing a wide variety of properties. To extend the range of the study, the papers were evaluated at various elongation rates and at different relative humidities. Figure 9 includes the data from Fig. 8. The correlation is excellent. The toughness values increase with relative humidity but are surprisingly independent of elongation rate within the range studied.

Table I shows the coefficients of variation for the tensile stiffness, the J integral, and the Liebowitz fracture toughness at 23°C, 50% RH, and at an elongation rate of 2 mm/s.

The Liebowitz fracture toughness is obviously more precise than the J integral, the reason being that the energy term U in the J integral is evaluated as the difference between two energies.

Discussion

The theories by Rice (*3*) and Liebowitz (*4*) are closely related, and one reason for the good correlation shown in this paper may be that identical properties are in fact measured by the J integral and the Liebowitz methods. Eftis *et al.* (*5*) showed that a true identity of the properties requires, among other things, that subcritical crack growth is absent, i.e., slow crack growth prior to the fast crack propagation rate at failure. Subcritical crack growth does occur for paper (*6*), but even when subcritical crack growth exists, the two properties are very close, both at the critical point of crack growth and at the point of break, as shown by Poulose *et al.* for steel and aluminum alloys (*7*).

The poor correlation with the strength-based Critical Stress Intensity Factor indicates that the cracking during the die-cutting procedure is dominated by the available energy in the system rather than by the maximum force.

The good correlation in this trial between the die-cutting toughness number and the two fracture-mechanics-based energy methods is not surprising, since the paper is loaded in the same in-plane mode I in the three cases in contrast to the out-of-plane loading mode III of the Elmendorf tear test.

The high correlation found between the nonlinear fracture-mechanics-based methods and the die-cutting toughness number indicates that relatively simple methods, using conventional tensile testing equipment and elongation rates, can grade the cracking tendency of paper when used as liners in corrugated board.

When all the tested papers in this investigation were included, covering a wide range of properties, rates of elongation, and relative humidity, the two energy-related, nonlinear fracture-mechanics-based methods correlated excellently. This gives us hope that the Liebowitz method especially, giving the lowest scatter, is of general value for estimating the fracture toughness of paper.

There are indications that the Liebowitz method can show the influence of pulp properties, degree of beating, and sheet forming conditions on the fracture toughness of paper, and such studies will be pursued.□

Literature cited

1. Cavlin, S. I. and Edholm, B., Packaging Tech. and Sci. 1: 25(1988).
2. Westerlind, B. S., Carlsson, L. A., and Andersson, Y. M., J. Mat. Science 26(10): 2630(1991).
3. Rice, J. R., J. Appl. Mech. 35: 379(1968).
4. Liebowitz, H. and Eftis, J., Eng. Fract. Mech. 3: 267(1971).
5. Eftis, J., Jones, D. L., and Liebowitz, H., Eng. Fract. Mech. 7: 491(1975).
6. Steadman, R. and Fellers, C., Proceedings of National Science Foundation Workshop (R. Perkins, R. Mark, and J. Thorpe, eds.), Dept. of Mechanical and Aerospace Engineering, L. C. Smith College of Engineering, Syracuse University, Syracuse, NY, 1990, p. 332.
7. Poulose, P. K., Jones, D. L., and Liebowitz, H., Eng. Fract. Mech. 17(2): 133(1983).
8. Begley, J. A. and Landes, J. D., ASTM STP 514: 1(1972).
9. Agarwal, B. D., Patro, B. S., and Kumar, P., Eng. Fract. Mech. 19(4): 675(1984).
10. Singh, R. K. and Parihar, K. S., J. Mat. Sci. 21: 3921(1986).
11. Uesaka, T., Handbook of physical and mechanical testing of paper and paperboard (R. Mark, ed.), Marcel Dekker Inc., New York, 1983, p. 77.
12. Uesaka, T., Okaniwa, H., Murakami, K., and Imamura, R., Japan Tappi 33(6): 403(1979).
13. Steadman, R. and Fellers, C., 1987 International Paper Physics Conference Proceedings, TAPPI PRESS, Atlanta, p. 173.
14. Bennett, K. A., Progress in paper physics—a seminar, Design criteria for paper performance, STFI, Stockholm, 1984, p. 114.
15. Seth, R. S. and Page, D. H., J. Mat. Sci. 9: 1745(1974).
16. Seth, R. S. and Page, D. H., Tappi 58(9): 112(1975).
17. Broek, D., The practical use of fracture mechanics, Kluwer Academic Publishers, Dordrecht/Boston/London, 1988.
18. Sih, G. C., Paris, P. C., and Irvin, G. R., Int. J. Fract. Mech. 1: 189(1965).
19. Baum, G. A., Brennan, D. C., and Habeger, C. C., Tappi 64(8): 97(1981).

We would like to express our gratitude to Stiftelsen Nils och Dorthi Troedssons Forskningsfond for its financial support. Thanks are also expressed to Sune Karlsson, Hilding Ekman, and L&W for their expert programming of the various computer systems, and to Berit Mollerberg and Tommy Floren for their help with the experimental work. For valuable discussions and editing, the authors express their gratitude to Borje Steenberg. The authors also extend thanks to J. A. Bristow for linguistic revision.

Received for review June 28, 1991.

Accepted Nov. 12, 1991.

Presented at the TAPPI 1991 International Paper Physics Conference.

Keywords: Break resistance, corrugated boards, cracks, die cutting, fracture, liners, mechanical tests, paper tests, toughness.

Appendix

The *J* integral fracture toughness

Rice (*3*) showed that the J integral for any nonlinear elastic body may be interpreted as the potential energy difference between two identically loaded bodies having neighboring crack sizes. As discussed by Begley and Landes (*8*), the limitations inherent in the theory rule out its application for materials that exhibit significant subcritical crack growth prior to failure. The practical implication of this is the choice of the critical point of crack extension. In spite of these limitations, the J integral theory has been explored for several materials such as steel in numerous investigations, for composites (*9*), polymers (*10*), and paper (*2, 6, 11–14*).

The procedure for evaluating the J integral for paper in our investigation is a straightforward application of the theory. **Figure 10** shows the principle.

Two types of test pieces with cracks of size c_1 and c_2 were prepared. Force-elongation curves were produced for each set of test pieces. Average curves were constructed.

The J integral values for papers were evaluated according to Eqs. 1 and 2:

$$J^* = U / [(c_2 - c_1)w] \quad (1)$$

$$J = J^* \times w \quad (2)$$

where

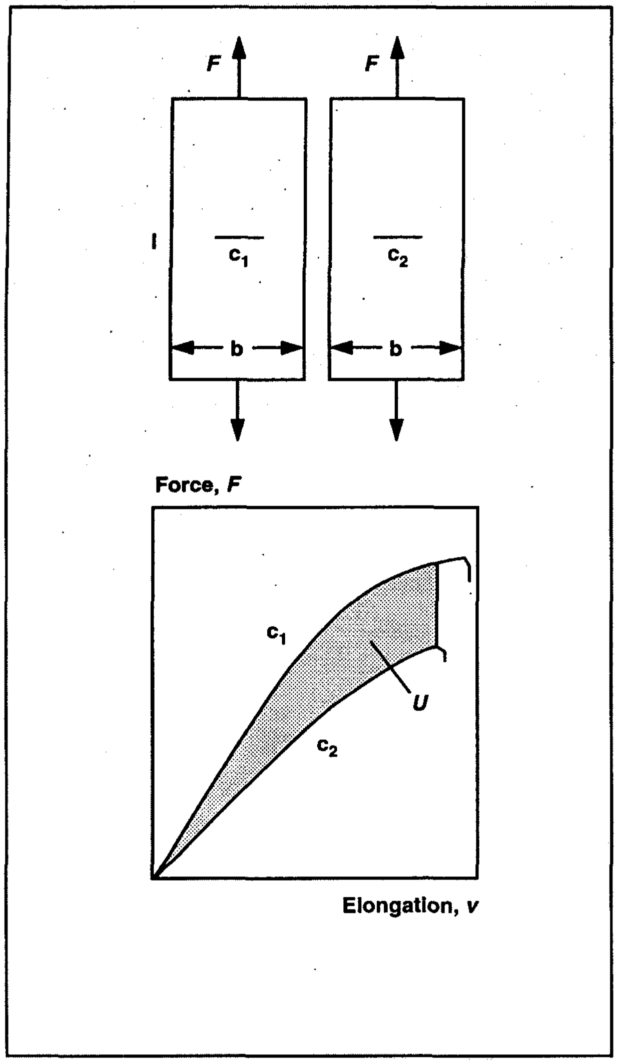
J^* = J integral index, Jm/kg

J = J integral, J/m

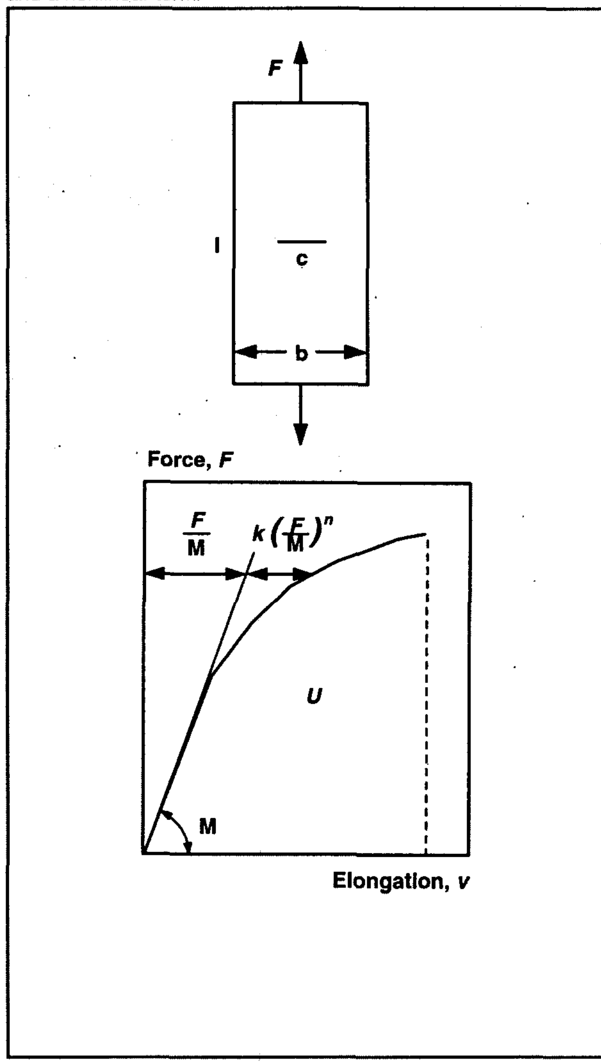
U = energy difference, J

c_2 = long crack (0.030 m)

10. Evaluation of fracture toughness according to the *J* integral theory (1 = 100 mm, b = 50 mm)



11. The test piece shape used in the Liebowitz method and the force-elongation curve of a precracked paper, described by a linear and a nonlinear term.



c_1 = short crack (0.020 m)

w = grammage, kg/m²

The elongation at break differs between the two types of test pieces. The critical point of crack extension is defined here as the elongation at failure for the test piece with the long crack.

The Liebowitz fracture toughness

Using the same definition as the *J* integral, Liebowitz and Eftis (*4*) developed a nonlinear fracture toughness parameter, which may also be regarded as a nonlinear extension of the classical linear elastic fracture mechanics theory reviewed by Seth and Page (*15, 16*). Westerlind, Carlsson, and Andersson (*2*) recently explored the method for use with paper. The nonlinear force-elongation curve used for the valuation of the Liebowitz fracture toughness is described by a three-parameter model (**Fig. 11**), which also shows the test piece shape. *M* is the maximum slope of the curve, and *k* and *n* are determined from two points of the curve by a procedure fully described elsewhere (*2, 4*).

The following symbols are used in the calculations:

v = elongation, m

F = force, N

F_c = force at failure, N

M = maximum slope of the force-elongation curve, N/m

k, n = parameters

l = 0.100 m

b = 0.050 m

c = 0.030 m

v_x = Poisson's ratio in the transverse direction

G^*_{xy} = shear stiffness index, Nm/kg

E^* = tensile stiffness index, Nm/kg

Index$_{eff}$ = effective

Index$_y$ = loading direction

Index$_x$ = transverse direction

J^*_L = Liebowitz fracture toughness index, Jm/kg

J_L = Liebowitz fracture toughness, J/m

K^* = Critical Stress Intensity Factor index, $Nm^{1.5}/kg$

K_{IC} = Critical Stress Intensity Factor, $Nm^{-0.5}$

w = grammage, kg/m^2.

The Liebowitz fracture toughness parameters are given as follows:

$$J^*_L = (1+\beta)K^{*2}/E^*_{eff}$$

$$J_L = J^*_L \times w$$

where

β = $[2nk/(n+1)]\,(F_c/M)^{n-1}$

K^* = $(F_c/bw)\,(\pi c/2)^{0.5} \times f$

f = function of the geometry, loading conditions, and crack length. For a center-cracked test piece subjected to a uniform stress we use $f = 1.3$ (*17*)

K_{IC} = $K^* \times w$

E^*_{eff} = $E^*y \times \sqrt[4]{\frac{E^*_x}{E^*_y}}$

E^*_{eff} is a function of the elastic properties in the loading and transverse directions (*18*) and is derived as follows (E^* = elastic modulus/density):

$$E^*_{eff} = (2E^*_xE^*_y)^{0.5} \times [(E^*_x/E^*_y)^{0.5} - v_x + E^*_x/2G^*_{xy}]^{-0.5}$$

Baum *et al.* (*19*) found the following approximate relations for paper:

$$G^*_{xy} = 0.387(E^*_xE^*_y)^{0.5}$$

$$(v_x \times v_y)^{0.5} = 0.293$$

Elasticity theory gives the expression:

$$v_x/v_y = E^*_x/E^*_y$$

A combination of these equations yields the expression for E^*_{eff} given above.