

Measurement of in-plane fracture toughness of paper

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ABSTRACT: *The in-plane fracture toughness of tough, ductile sheets such as handsheets of softwood kraft pulps can be measured, independent of specimen size, by the “essential work of fracture” method. The details of the method are described, and the validity of the approach is demonstrated by comparing results with theoretical estimates.*

KEYWORDS: *Fracture, hand sheets, kraft pulps, measurement, softwood pulps, test methods, theories, toughness.*

Fracture toughness is the resistance of a material to the propagation of a pre-existing flaw or crack. It is measured as the work consumed per unit surface area created during crack propagation. Fracture toughness determines the flaw-carrying ability of the material. Like elastic modulus, tensile strength, and extensibility, it is a fundamental property of the material.

The resistance of paper to crack propagation currently is measured by the Elmendorf or Brecht-Imset tear tests. This practice is questionable for the following reasons. First, for most end uses of paper where fracture toughness can be an important service parameter, stresses are applied in the plane of the sheet. However, in the Elmendorf and Brecht-Imset tear tests, the tearing forces are applied perpendicular to the plane of the sheet. Since the re-

sistance of a material to crack propagation depends on the mode of propagation, it is logical that the fracture toughness of paper should be measured for stresses in the plane of the sheet. It is worth noting that elastic modulus, tensile strength, and extensibility of paper are measured for stresses in the sheet's plane.

Second, our current industry practice of evaluating the strength potential of softwood chemical pulps involves measuring the Elmendorf or Brecht-Imset tear index at a given tensile strength of handsheets following beating or refining the pulp. Beating or refining, which increases the degree of bonding between the fibers in the sheet, decreases the sheet's out-of-plane tearing resistance, while the in-plane properties such as elastic modulus, tensile strength, and extensibility increase. Thus, refining to a high Elmendorf

or Brecht-Imset tear index contradicts the optimization of other important mechanical properties of the sheet. This casts doubt on the usefulness of the out-of-plane tear tests for evaluating the strength potential of softwood chemical pulps.

Measuring the in-plane fracture toughness of paper

Measurement of in-plane fracture toughness has been proposed as an alternative to the out-of-plane tear tests (1–6). The usefulness of in-plane fracture toughness in optimizing the reinforcing properties of bleached softwood chemical pulps was recently demonstrated (7). Unfortunately, the methods for measuring the in-plane fracture toughness of sheet materials, such as paper, are complex. They depend on the load-elongation behavior of the material, that is, on whether the material is elastic and brittle or elastic-plastic, tough and ductile (**Fig. 1**). The methods are particularly complex for tough sheets such as handsheets of beaten softwood kraft pulps. The background on the techniques of fracture mechanics used for measuring the fracture toughness of paper was recently reviewed (6).

Fracture involves creation of new surfaces at the expense of work. When a material containing a crack is strained, fracture processes such as fiber breakage and bond breakage in the case of paper are concentrated in the region just ahead of the

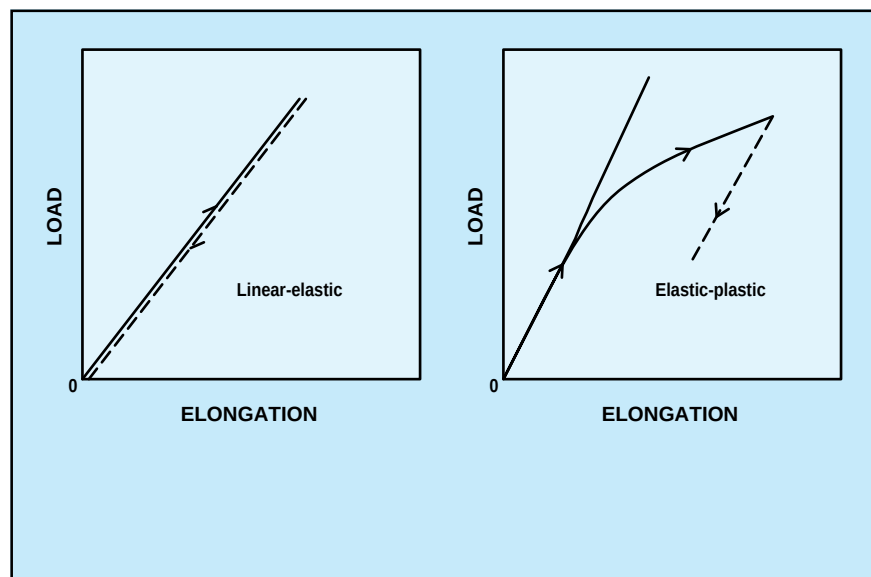
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crack tip. This region is called the fracture process zone. When the crack propagates, work is consumed in the fracture process zone. This work done per unit new crack area is the fracture toughness. It is a property of the material. This work is supplied by the strain energy in the material and the applied external forces. When an elastic material with a crack is strained, the fracture process zone is small, and all irreversible deformations associated with fracture are confined only to the thin boundary regions along the faces of the propagated crack. The deformations elsewhere are small and elastic. The experimental methods for measuring the fracture toughness of an elastic material therefore are relatively simple (6).

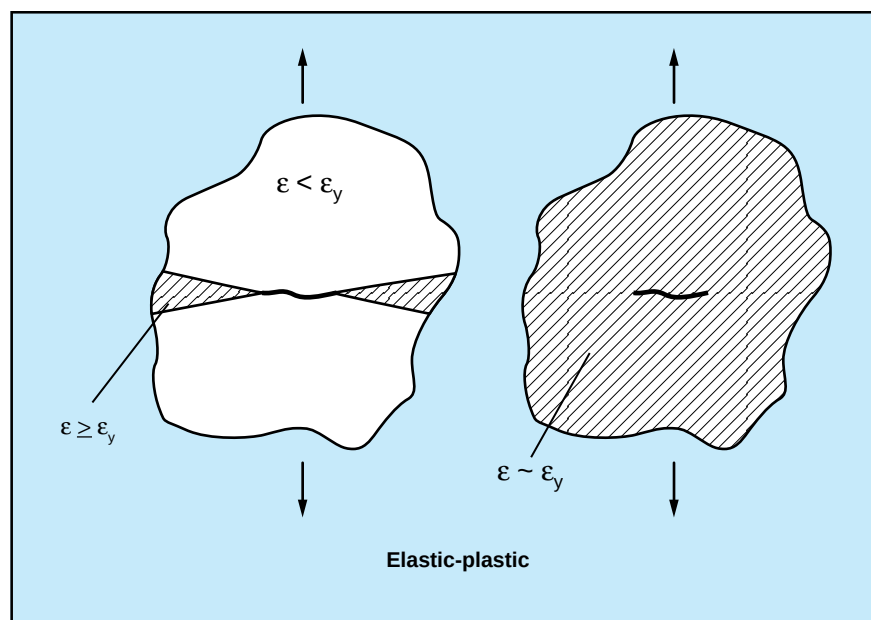
When a tough elastic-plastic material with low yield stress is strained, the material yields not only at the crack tip where the strain is high, but the material away from the crack tip can also yield (**Fig. 2**). This is because the material resists crack propagation and requires larger strain for the crack to propagate. Irreversible deformation in this case may no longer be confined to the fracture process zone as it is for an elastic material, but can spread throughout the material. The extent of deformation away from the crack depends on the size of the crack relative to the specimen width and on the toughness of the material. Thus, in addition to the work consumed in the crack tip process zone, work is also consumed in the yielded regions away from the crack. While the work consumed at the crack tip is essential to fracture, the work consumed away from the crack tip is not essential to fracture. The area under the load-elongation curve (**Fig. 3**) for the material represents the total work of fracture and combines the contributions to fracture and remote deformation. These two contributions are difficult to separate experimentally in an elastic-plastic material.

Two approaches have mainly been followed for measuring the in-plane

1. Load-elongation behavior of linear-elastic, and elastic-plastic materials. At a certain load, the elastic-plastic material yields. The material deforms irreversibly upon further straining, and its load-elongation curve deviates from linearity.



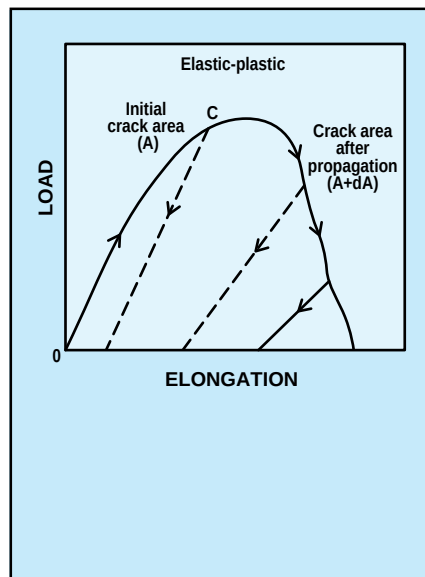
2. A stressed elastic-plastic panel containing a crack. The shaded areas show the material that is undergoing irreversible plastic deformation. ϵ is the local strain in the specimen, and ϵ_y is the yield strain of the material.



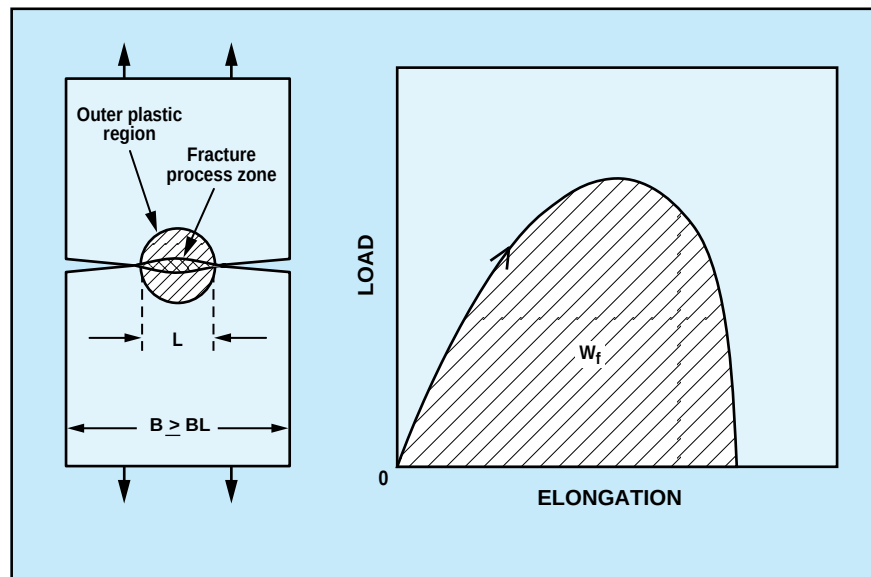
fracture toughness of tough ductile papers: the “J-integral” approach and the “essential work of fracture” approach (6). An important consideration in choosing the approach is that the method should determine a

material property, independent of specimen size. Because large changes occur in the load-elongation behavior of the sheet when a pulp is beaten or refined (e.g., the tensile strength can increase 3–4 fold, and the exten-

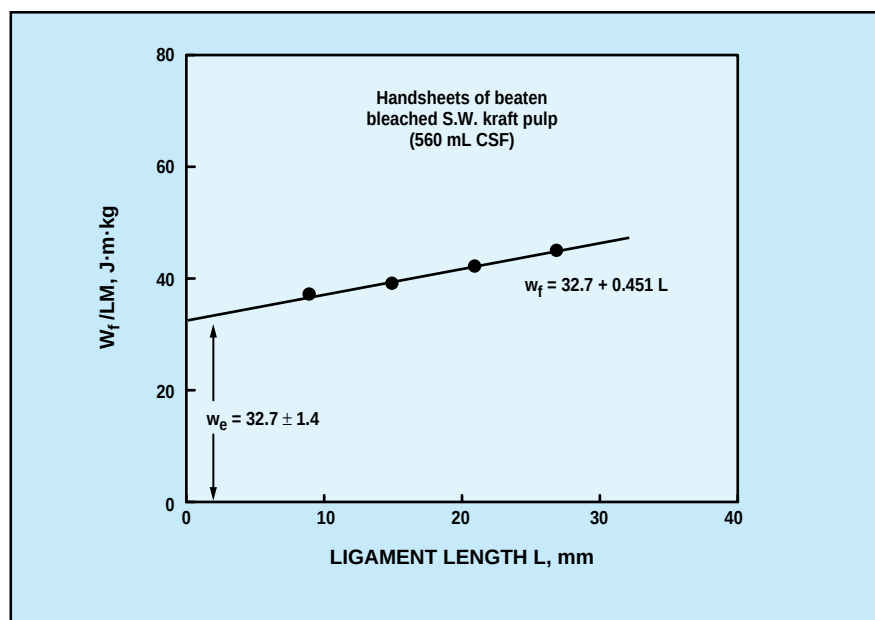
3. Load-elongation curve for crack propagation in an elastic-plastic material. Note that the elongation is not zero when the specimen is unloaded, indicating that work has been consumed in producing permanent deformation in the material away from the crack.



4. Schematic of measuring the essential work of fracture



5. Plot of total work of fracture against ligament length. The intercept gives the specific essential work of fracture or the fracture toughness of the material.



sibility can double), it is important to ensure that the changes measured in the sheet fracture toughness are real and not the artifacts of testing. Several authors have used the J-integral or similar non-linear elastic

energy release rate methods to measure the fracture toughness of paper. However, results independent of specimen size and crack geometry were not obtained (see, e.g., references in 3, 6; 8). On the other hand,

the essential work of fracture method was shown to give results independent of specimen size on laboratory-size samples of tough papers (3, 6), and was used extensively for handsheets of softwood chemical pulps (7). Recently, Mai *et al.* (9) measured the fracture toughness of paper from a J versus crack extension curve according to the ASTM Standard E813-89 (10). They showed that the results were similar to those obtained from the essential work of fracture method. The purpose of this report is to provide details of the essential work of fracture method.

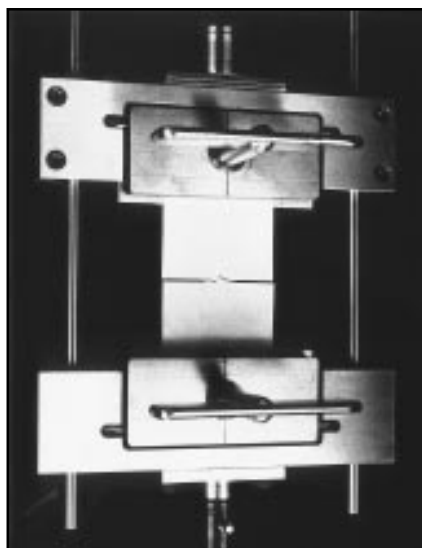
The essential work of ductile fracture

This approach is an attempt to separate experimentally from the total work in Fig. 3 the “essential” work consumed in the fracture process zone. This is done as follows:

Deeply double-edge notched tension (DENT) specimens containing varying ligament lengths L as shown in Fig. 4 are strained to failure and the total work of fracture W_f is mea-

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6. The 10-cm-wide clamps for measuring the work of fracture



7. The jig for making edge notches in paper specimens. Details of the clamps and the jig are available from the Institute.

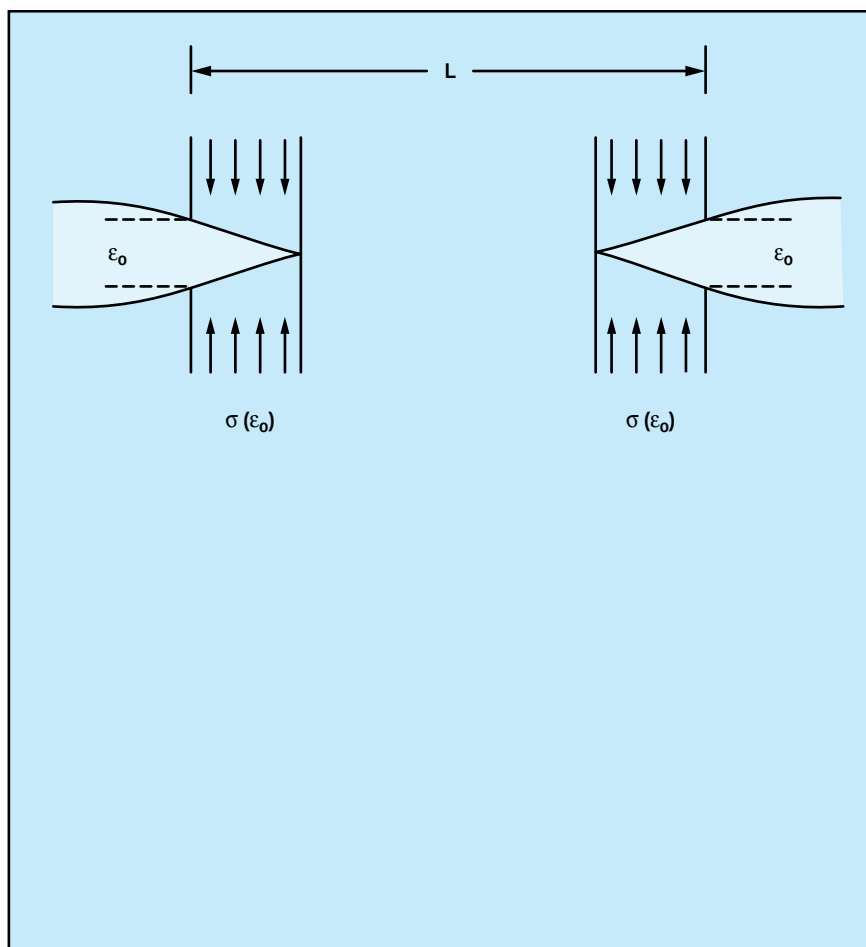


sured. When such a specimen yields completely before fracture, the plastic region in the specimen is confined to a circular area centered on the ligament. On dimensional grounds one can write:

$$W_f = W_e + W_p = Ltw_e + \beta L^2 tw_p \quad (1)$$

In this equation, W_e is the “essential” work consumed in the inner fracture process zone (Fig. 4), and W_p is the “non-essential” work dissipated in the outer plastic region. w_e in Eq. 1 is the work consumed per unit crack area in the inner fracture process zone, and is called the specific essential work of fracture. It is a material property. w_p is the non-essential work dissipated per unit volume of the material, β is a shape factor for the outer plastic zone

8. Schematic of stress and elongation at the crack tip at propagation



which depends on the specimen and crack geometry, and t is the specimen thickness. βw_p is not a material property. Rewriting the above equation gives:

$$w_f (= W_f/Lt) = w_e + \beta L w_p \quad (2)$$

If w_f is now plotted against L , a straight line is obtained whose positive intercept gives w_e (Fig. 5). The specific essential work of fracture w_e is independent of specimen size and is recognized as the fracture toughness of the material (3, 6). Measurement of the in-plane fracture toughness of a tough, ductile paper, therefore, involves simply measuring the total work of fracture W_f for a range of ligament lengths L , and determining w_e from the intercept of the (w_f, L) linear relationship (Fig. 5). The sheet thickness t in Eq. 2

can be replaced by sheet grammage M in calculating $w_f (= W_f/LM)$. This is equivalent to expressing results as work of fracture per unit area divided by the material density.

For Eq. 1 to hold, the ligament should remain in plane stress and should yield before fracture. For the ligament to yield, the length L should not be so large that the fracture process zones at the crack tips do not overlap. Since the fracture process zones at crack tips can be fairly large in tough sheet materials under plane stress (6), this condition is easily met for handsheets of softwood pulps. Further, in order that yielding does not spread to the outer edges of the specimen, the specimen width B must be large, at least three times the ligament length L . Based on extensive work with handsheets (7),

ligaments in the range $6 \text{ mm} \leq L \leq 27 \text{ mm}$ were found to be adequate, with specimen widths B in the range $20 \text{ mm} \leq B \leq 90 \text{ mm}$. Realistically, L should be larger than the size of the flocs in the sheet. Otherwise, the variability in W_f for small ligaments can be large. Although handsheets are well formed, to be safe, $L \geq 9 \text{ mm}$ was used. $L/B = 0.3$ was maintained for all L .

Tough sheet materials often buckle under in-plane tensile stress. In a buckled sheet, the fracture process zones may not remain in plane stress. However, the effect of buckling in DENT specimens of handsheets was found to be insignificant, and this was confirmed by using anti-buckling plates. They were two flat, rigid plates of Plexiglas, bolted together with a small gap remaining between them. The gap was chosen to be small enough to prevent buckling, but not to offer much frictional resistance to the movement of the sheet. The difference in W_f measurements with and without anti-buckling plates was less than 5%.

Another requirement of the method is that fracture be stable; that is, the strain energy of the test must dissipate in the specimen. In other words, catastrophic failure should be avoided. Fracture propagation is stable if the test is performed slowly and the test system's capacity for strain energy storage is small. A short specimen and a stiff testing equipment help. Stability was easily achieved for handsheets by using specimens of gauge lengths approximately 90 mm and the testing machine's crosshead speed of 2 mm/min.

Specimen geometries other than DENT, such as single-edge notched tension (SENT), can be used to measure the essential work of the fracture. However, in a test, specimens of different geometries should not be mixed; that is, geometric similarity should be maintained. The DENT geometry was preferred in our work.

The specific essential work of fracture w_e in Eq. 2 is obtained as the intercept of the linear plot in Fig. 5. The accuracy of the intercept depends on the number of ligament lengths used in the test and the replicates tested for each, and this can require a large number of specimens. In order to speed up the test, the minimum number of ligaments required and replicates for each were determined by statistical analysis of test results on handsheet samples using a large number of ligaments and replicates. At least 4 ligament lengths (e.g., 9, 15, 21, and 27 mm) in the range $6 \text{ mm} \leq L \leq 27 \text{ mm}$, with at least 10 replicates for the smallest ligament and at least 6 replicates each for the remaining three ligaments, were found to give w_e with relatively small uncertainties. A total of 28 specimens were tested to obtain the plot in Fig. 5. The pulp was beaten in a PFI mill. All results reported in this and subsequent figures were obtained at 23°C and 50% RH, and are based on air-dry grammages. Standard procedures of the CPPA Technical Section were generally followed for handling pulps, specimen preparation, and measuring physical properties.

Experimental setup

It is difficult to uniformly clamp a wide sheet of paper along its width, and to maintain uniform stress in the plane of the sheet. A pair of line-type clamps mounted on two guide rods with low-friction bearings was used (Fig. 6). The clamps were mounted on the Instron universal testing instrument. The clamping members were a rod and a flat plate, both of steel. The uniformity of clamping was tested by clamping hard on aluminum foil and by examining the indentation line. The clamps were slippage-free for loads much higher than those encountered during the tests on fracture specimens. The guide rods facilitate specimen handling and keep the specimen

under plane stress. It should be noted that crack propagation across the ligament will not be co-linear if the specimen is not in plane stress. This could happen for specimens with poor formation which tend to slip under the clamps at regions of low grammage, particularly if line-type clamps are not used.

The specimens for fracture tests were notched by using a simple jig shown in Fig. 7. It consisted of two sharp tool blades clamped between steel plates. The distance between the blades was adjusted by putting spacers of known length between them before clamping. The jig was placed vertically over a specimen backed by smooth cardboard, and hit gently with a hammer. In this way, sharp clean notches of known length could be introduced reproducibly.

Validation of measurements

Based on theoretical grounds and experimental results on a variety of materials, it is well established that the specific essential work of fracture w_e determines the plane stress fracture toughness of a sheet material, independent of specimen size (see, e.g., references in 3, 6; 9, 11–15). After having tested nearly 300 samples of paper over the past three years, it is reassuring that, once the experimental conditions prescribed for measuring w_e were met, the plots of W_f against L of Fig. 5 were found to be invariably linear, as predicted by Eq. 2, and the intercepts gave w_e with relatively small uncertainties.

We have also compared our results on w_e against theoretical estimates of fracture toughness from the estimated stress and elongation at the crack tip (Fig. 8). If it is assumed that the crack propagates when elongation at the crack tip reaches a critical value ϵ_0 and the corresponding stress $\sigma(\epsilon_0)$ at the crack tip is either the yield stress σ_y of the sheet or some higher value, such as the average of σ_y and the

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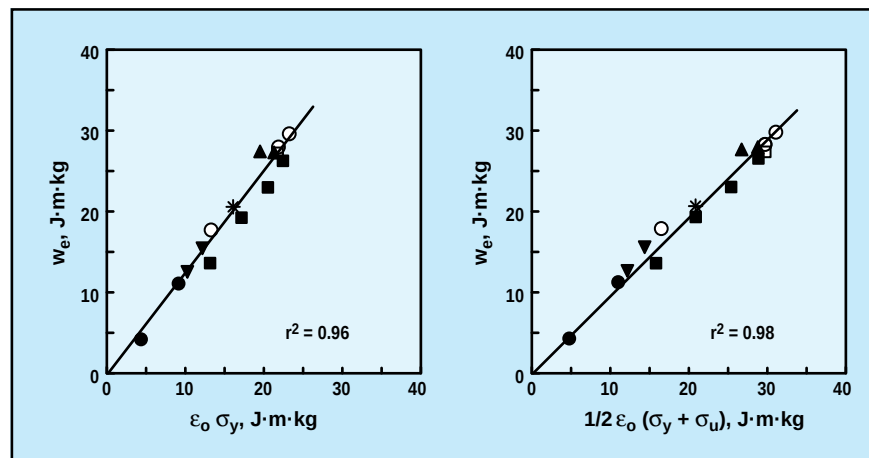
ultimate tensile strength σ_u of the sheet, then fracture toughness can be estimated as $\varepsilon_0 \sigma_y$ or $1/2 \varepsilon_0 (\sigma_y + \sigma_u)$. **Figures 9 through 11** show plots for a variety of pulps treated differently. The elongation at the crack tip ε_0 was estimated by plotting the elongation of the fracture specimens against the ligament length, which gives a linear plot similar to (w_p, L) plots of Fig. 5, and measuring the positive intercept ε_0 at zero ligament length (3). The yield stress was obtained from the load-elongation curves for unflawed specimens, and corresponds to the stress at which strain deviates from linearity by 0.2%. Good correlations between w_e and the estimated fracture toughness, like those shown in Figs. 9–11, and also shown earlier (3), lend support to the validity of the essential work of fracture method for measuring the fracture toughness of tough, ductile paper sheets. It is for this reason that the approach was accepted for measuring the in-plane fracture toughness of handsheets of reinforcement pulps (7).

Concluding remarks

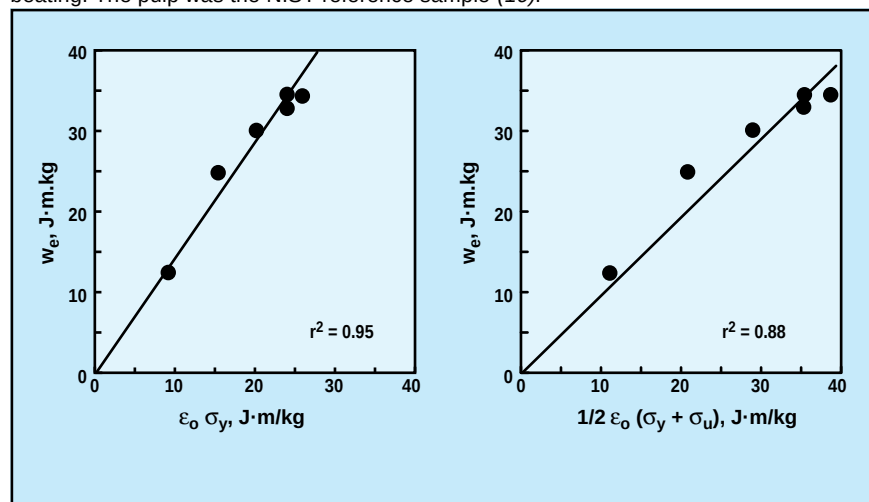
The “essential work of ductile fracture” method allows the successful measurement of in-plane fracture toughness, independent of specimen size, of tough sheets such as handsheets of softwood kraft pulps. The method though simple, is time consuming. However, specimen cutting, notching, testing, and data handling can be automated to save time.

The method is meant primarily for tough ductile sheets. In low-toughness brittle papers such as newsprint and other printing grades (strained in the machine direction), it may be difficult to have the ligaments yield completely before fracture, or to have stable crack propagation. The method based on the quasistatic crack propagation technique (17) is recommended for such papers. 

9. Specific essential work of fracture w_e against estimates of fracture toughness for handsheets made from various softwood pulps after giving different papermaking treatments as indicated. * = Standard handsheets of western hemlock (WH). The pulp WH was a laboratory-made, never-dried, unbeaten, unbleached kraft. ● = Standard handsheets made after drying WH at two different temperatures (23°C and 150°C) and reslushing. ○ = Standard handsheets made from WH but pressed at three different wet-pressing pressures (138 kPa, 1.38 MPa, and 3.45 MPa). ▲ = Standard handsheets made from WH after adding a bonding agent at two different levels. ▼ = Standard handsheets made from WH after adding a debonding agent at two different levels. □ = Standard handsheets made from a commercial, bleached kraft pulp of southern U.S. pines, beaten for 6000 revolutions in a PFI mill. ■ = Standard handsheets made from pulps of four different fiber length distributions. The pulps were produced by guillotining sheets made from a laboratory-made, never-dried, unbeaten, unbleached, softwood kraft pulp of western red cedar.



10. Specific essential work of fracture w_e against estimates of fracture toughness for handsheets made from a commercial, bleached softwood kraft pulp following PFI mill beating. The pulp was the NIST reference sample (16).



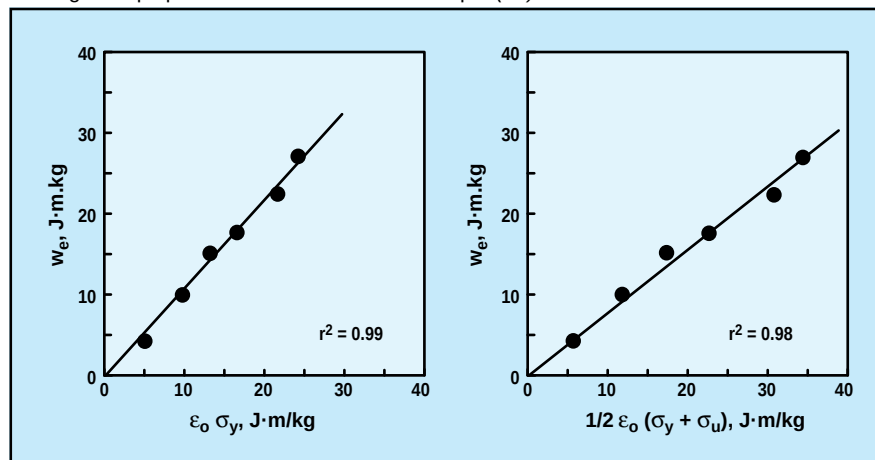
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I thank Gordon Robertson, Jim Simkins, and John Hoffmann for designing and constructing the clamps and the notching jig, and Yuxiu Peng of Nanjing Forestry University for the results presented in Fig. 9 which she obtained while at Paprican as a visiting scientist during 1991-92. I also thank John Hoffmann for his assistance in obtaining results in Figs. 5, 10, and 11, Wenjun Chen for providing consultation in statistics, and Kelly Wadham who prepared the manuscript and illustrations.

Received for review Jan. 23, 1995.

Accepted May 13, 1995.