Preferred citation: R.S. Seth. Plane stress fracture toughness and its measurement for paper. In **Products of Papermaking**, *Trans. of the Xth Fund. Res. Symp. Oxford, 1993*, (C.F. Baker, ed.), pp 1529–1552, FRC, Manchester, 2018. DOI: 10.15376/frc.1993.3.1529.

PLANE STRESS FRACTURE TOUGHNESS AND ITS MEASUREMENT FOR PAPER

R.S. Seth
Pulp and Paper Research Institute of Canada
3800 Wesbrook Mall, Vancouver, B.C., Canada V6S 2L9

ABSTRACT

Fracture toughness is a material's ability to resist propagation of a pre-existing crack. In most end uses where fracture toughness can be an important performance parameter for paper, stresses are applied in the plane of the sheet. Therefore, like tensile strength and elastic modulus, the fracture toughness of paper should be measured under in-plane loading. Our current industry practice of measuring the out-of-plane tearing resistance by the Elmendorf or Brecht-Imset tests seems inappropriate. Several techniques of fracture mechanics have been applied in recent years to characterize the plane stress fracture toughness of paper. An important consideration is whether a material property was measured particularly for tough papers. This contribution provides a background on these techniques.

INTRODUCTION

Fracture toughness is the ability of a material to resist propagation of a pre-existing crack. Like tensile strength and elastic modulus, it is a fundamental mechanical property of the material. During manufacturing, printing and many converting operations, when paper fails by crack propagation, stresses are applied in the plane of the sheet. Although the tensile strength and elastic modulus of paper are measured for stresses in the plane of the sheet, resistance to crack propagation currently is measured by the Elmendorf [1] or Brecht-Imset [2] tear tests, which apply tearing forces out of the sheet's plane. The resistance of paper to fracture depends on the failure mode, and for a test to be truly relevant, it must relate clearly to the end-use failure mode. Therefore the need exists to measure the fracture toughness of paper under in-plane loading.

Fracture mechanics is used to understand and measure fracture toughness [3-8]. There are two approaches to measuring fracture toughness – the energy balance approach and the stress analysis approach. The two are equivalent under certain circumstances. Based on these two approaches, several techniques have been used in recent years to characterize the plane stress fracture toughness of paper. However, an important question is whether a material property was measured, particularly for tough papers. The purpose of this contribution is to provide a background on these techniques.

Fracture involves creation of new surfaces at the expense of irreversible work. When a material containing a crack is strained, deformation, damage, and fracture processes are concentrated in the region just ahead of the crack tip. This localized region is called the fracture process zone. The irreversible work consumed in this zone, per unit crack area, is called the specific work of fracture, **R**, or the fracture toughness of the material. It is a material property. This work is supplied by the strain energy in the material and the applied external forces. The size of the crack tip process zone relative to the crack length, and the extent of the strains in the material away from the crack tip determine whether the fracture is elastic (brittle) or elastic-plastic (ductile); the appropriate experimental methods of measuring fracture toughness are also determined by this same consideration.

ELASTIC FRACTURE

In a material for which the fracture process zone is small, and all irreversible deformations associated with fracture are contained within this zone, and deformations in the rest of the material are below the yield strain of the material (Figure 1), the fracture is called elastic. During fracture, work consumed in the process zone is supplied by the strain energy of the elastic material that surrounds the crack. At fracture, the strain energy release rate **G** (= **-dU/dA**) reaches its critical value $\mathbf{G_c}$, which equals the specific work of fracture **R**; **U** is the strain energy in the material and **A** is the crack area. The two quantities **G** and **R** are quite distinct. Whereas **R** is a material property, the strain energy release rate **G** is a function of the specimen size, the crack geometry, the elastic properties of the material, and the loading conditions.

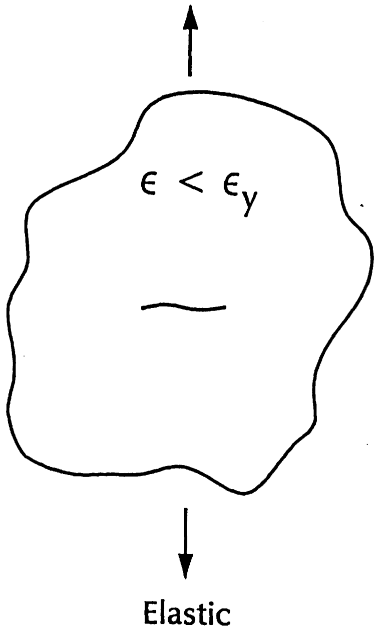

Figure 1. An elastic panel containing a crack and under stress (after [3]). ϵ is the strain in the specimen, and ϵ_y is the yield strain of the material.

The stress-strain curve for a linear elastic material is shown in Figure 2; the material loads and unloads along the same path. Crack growth in a linear elastic material can be represented graphically by the load-displacement curve shown in Figure 3. The curve is linear up to the point of crack propagation, and the displacement is zero when the specimen is unloaded. The area enclosed under the curve gives the work of fracture. The irreversible work consumed during elastic fracture is confined to thin boundary layers along the faces of the propagated crack.

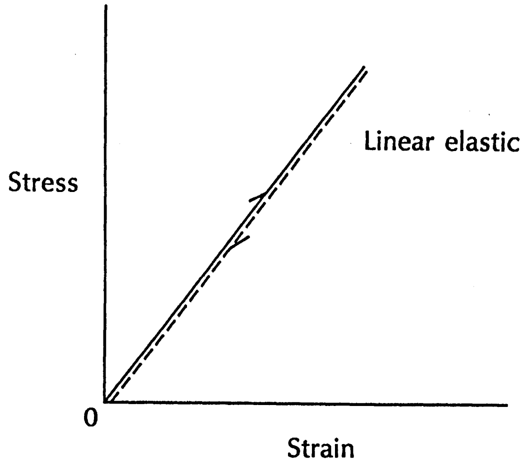

Figure 2. The stress-strain curve for a linear elastic material.

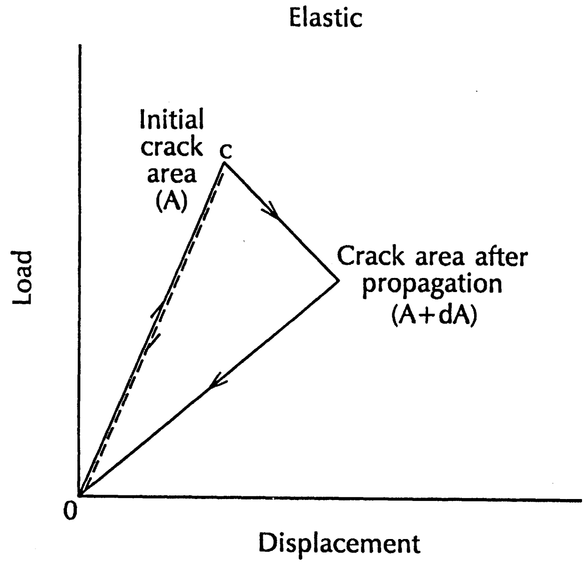

Figure 3. Load-displacement curve for crack propagation in a linear elastic material (after [3]). The displacement is zero when the specimen is unloaded.

The mechanics of elastic fracture can also be analyzed by the stress-analysis approach in terms of the elastic stress-strain properties of the material. The crack tip stress field is characterized in terms of the stress intensity factor, **K**, which describes the state of stress as a function of the specimen and crack geometry and the applied load. For a specimen of width **2b** containing a crack, and under a remotely-applied tensile stress $\boldsymbol{\sigma_c}$ at which instability occurs (Figure 4), the critical stress intensity factor $\mathbf{K_c}$ in plane stress is

$$K_c = \sigma_c\,(\pi a)^{\frac{1}{2}}\,F\left(\frac{a}{b}\right)$$

where **2a** is the crack length at instability. **F(a/b)** is a finite-width correction factor which approaches unity for an infinite panel, and can be calculated for various specimen and crack geometries.

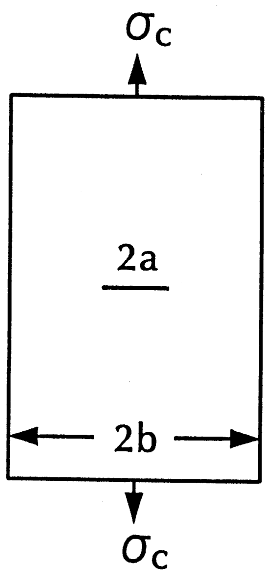

*Figure 4. A test specimen for measuring K_c. In practice, specimens with two edge cracks, each of length **a**, are preferred for testing paper in plane stress to avoid buckling.*

Most materials of interest are not truly linear elastic, but exhibit plastic deformation when strained to failure. If the plastic deformation at the crack tip is small, elastic stress analysis can still be applied, provided a correction is made for the region around the crack tip where the stress exceeds the yield stress σ_y of the material. This correction is made by adding a plastic zone of size r_y to the initial crack length **a**. For plane stress, r_y is given by

$$r_y = \frac{1}{2\pi}\left[\frac{K_c}{\sigma_y}\right]^2$$

The effect of the correction is to create a stress field identical to the elastic field, but shifted ahead by r_y, as if the crack tip were at the centre of the plastic zone of diameter **2** r_y (Figure 5). The crack is now longer than the original.

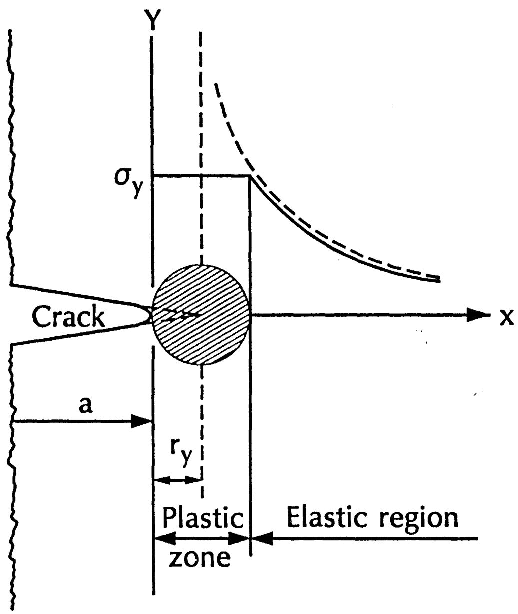

Figure 5. Crack tip plastic zone correction for small-scale plasticity.

For an isotropic material in plane stress, $\mathbf{K_c}$ is related to $\mathbf{G_c}$ by

$$G_c = \frac{K_c^{\,2}}{E}$$

where **E** is the elastic modulus of the material. For machine-made papers, which are regarded as orthotropic, **E** is replaced by an effective modulus [9].

In this stress-analysis approach, the determination of $\mathbf{G_c}$ involves, therefore, measuring the critical failure stress of a specimen containing a crack of known size, together with measuring its yield stress and elastic modulus. However, for a valid application of elastic fracture mechanics, the net stress applied over the uncracked region of the specimen at failure should be much less than the yield stress of the material; that is

$$\sigma_c \left(\frac{b}{b-a}\right) << \sigma_y$$

Furthermore, the specimen dimensions should be large enough that the specimen boundaries do not interfere with the crack tip stress distribution. In other words,

$$r_y << a << (b-a)$$

These conditions require using large specimens with suitable crack lengths, but the choice can be determined only by experiment; they are different for different materials [5]. $\mathbf{K_c}$ and $\mathbf{G_c}$ that are independent of specimen size are obtained only when these conditions are met. The size of the plastic zone in paper under plane stress can be large, and varies with specimen width (Table I). Seth and Page [9] found that even for newsprint, which can be regarded as elastic with small scale plasticity when strained in the machine direction, specimens wider than 10 cm were needed to obtain results independent of specimen width. For tougher papers, $\mathbf{K_c}$ and $\mathbf{G_c}$ depended strongly on specimen width, and much wider samples were required to meet the conditions of elastic fracture mechanics (Figure 6). Such large specimen widths are impractical for day-to-day testing.

The $\mathbf{K_c}$ and $\mathbf{G_c}$ approaches have been used by several researchers to characterize paper toughness [10-12].

Attempts to promote brittle fracture in otherwise ductile materials have been made in order to measure the work of fracture **R** directly [3]. By eliminating plastic flow in the material away from the fracture process zone, a ductile material can be made to fracture in a more constrained quasi-brittle manner, and the work of fracture **R** can be measured by the Gurney method [13]. Seth and Page [9] used this approach to measure the fracture toughness of paper, but were criticized [14] because conditions for such measurements were not entirely met for some of their tough papers.

*Table I. Data showing the variation of $\mathbf{r_y}$ with specimen width for Bond Paper 2 in Figure 6. The size of the plastic zone relative to the crack length gradually decreases with specimen width. Specimens of width **2b** and with two edge cracks, each of length **a**, were fractured in tension. The ratio **a/b** was 0.4.*

*Specimen width **2b**, cm*	*Crack length **a**, cm*	*$\mathbf{r_y}$, mm*	*(r_y/a), %*
5	*1.0*	*3.6*	*36*
15	*3.0*	*9.1*	*30*
25	*5.0*	*9.6*	*19*
36	*7.2*	*10.5*	*15*
48	*9.6*	*11.5*	*12*

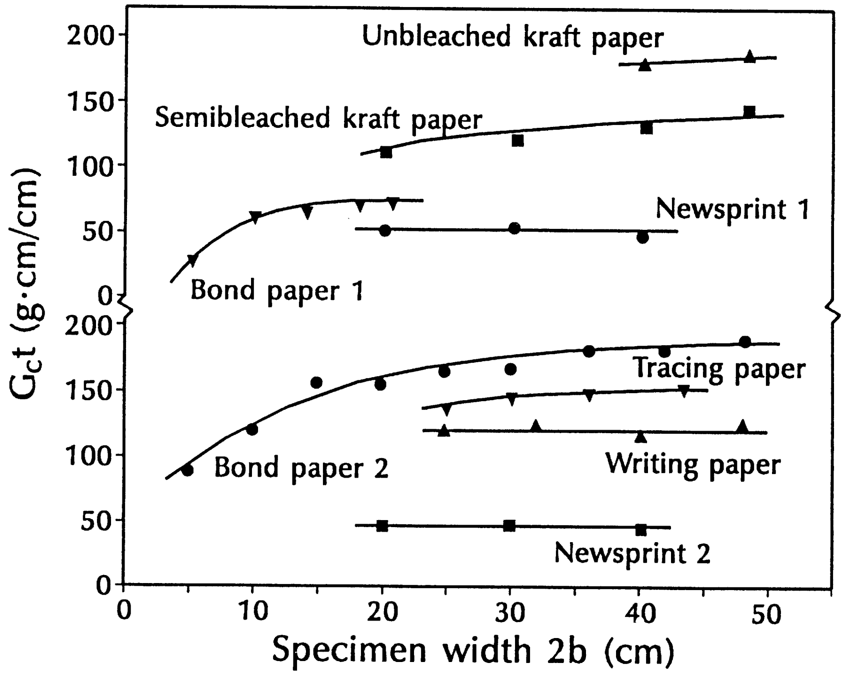

*Figure 6. Variation of **$G_c t$** with specimen width for crack propagating in the cross-direction of the sheet [9]; **t** is the sheet thickness. The sizes of the plastic zone relative to crack length **(r_y/a)** for the maximum specimen widths tested were ~ 4-6% for newsprints and ~ 12-13% for tougher papers. The ratio **a/b** ranged from 0.35 to 0.4.*

It is worth noting that the tearing of paper in the Elmendorf or Brecht-Imset tests (Figure 7) satisfies the conditions for elastic fracture (but in an out-of-plane mode). This is because all irreversible deformations associated with fracture are confined within the fracture process zone, and deformations elsewhere generally remain far below the yield strain of the material. The work of fracture is provided mostly by the external forces; the strain energies due to bending and stretching of the test piece are negligible.

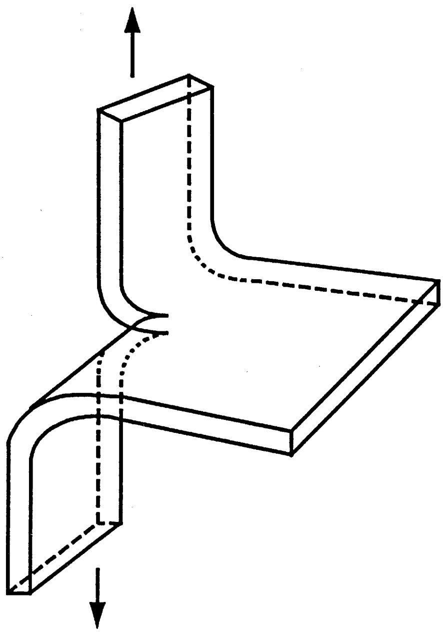

Figure 7. The Elmendorf tear test.

ELASTIC-PLASTIC FRACTURE

Most papers are elastic-plastic (Figure 8) and, depending on furnish composition and papermaking conditions, can be tough and ductile. When tough, ductile materials with low yield stress are strained, the material yields not only at the crack tip, but the rest of the material away from the crack tip also yields (Figure 9). Thus, irreversible deformation is no longer confined to the thin boundary layer along the faces of the propagated crack (as in elastic fracture), but is spread throughout the material. Therefore, in addition to the work required in the crack tip process zone, significant irreversible work is consumed in the yielded regions away from the crack. Within the fracture process zone, **R** is balanced by the critical potential energy of the strained ductile specimen. It is important to recognize that the plastic deformation outside the fracture process zone is not essential to the

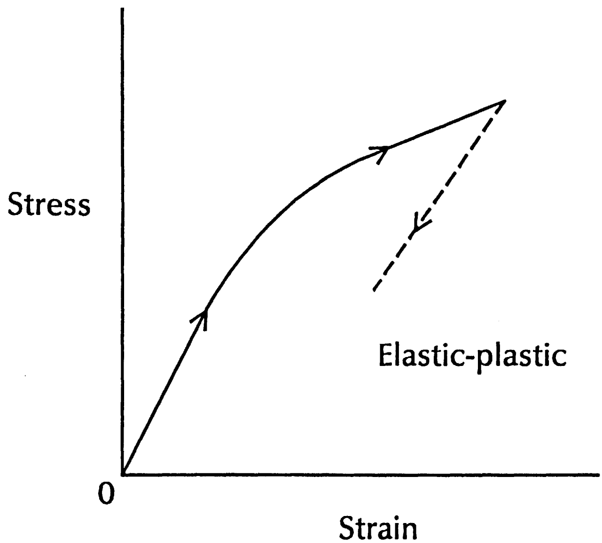

Figure 8. The stress-strain curve for an elastic-plastic material.

process of fracture, and the work dissipated in remote plastic flow depends on the size of the specimen, crack geometry and the level of strains in the specimen. Important consequences of the plastic flow include curvature in the load-displacement curve on loading, and displacement irreversibilities upon unloading, both in a specimen without a crack (Figure 8), and a specimen with a crack (Figure 10). The work during loading, given by the area under the load-displacement curve in Figure 10, represents the combined contribution to fracture and remote flow. These two works are difficult to separate experimentally, and this is what makes measuring the work of fracture (**R**) consumed in an elastic-plastic material intractable.

Two approaches have been used to determine the plane stress fracture toughness of tough ductile papers – the "J-integral" approach and the "essential work of fracture" approach.

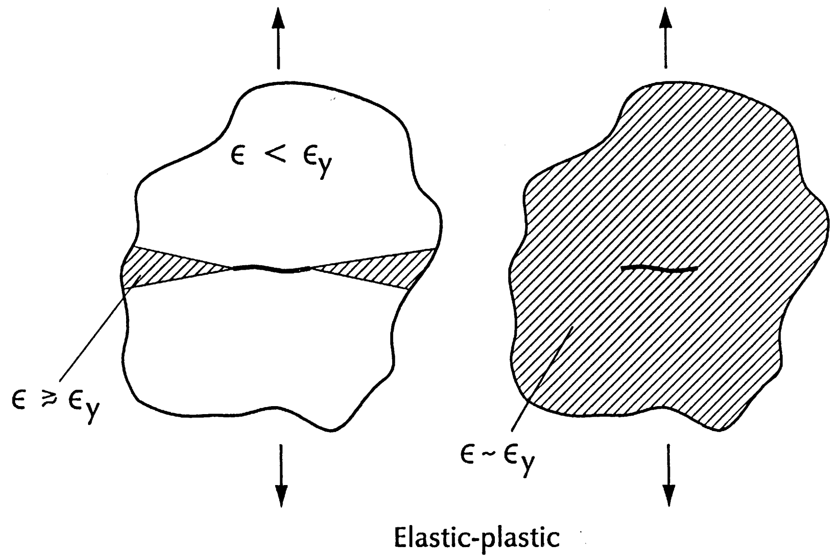

Figure 9. An elastic-plastic panel containing a crack and under stress. The shaded areas show the material that is undergoing irreversible plastic deformation (after [3]). ϵ *is the strain in the specimen, and* ϵ_y *is the yield strain of the material.*

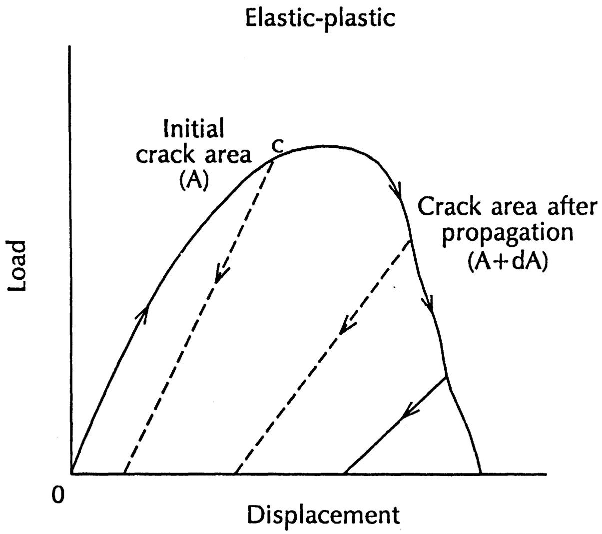

Figure 10. Load-displacement curve for crack propagation in an elastic-plastic material (after [3]). The displacement is not zero when the specimen is unloaded.

The J-integral

In the J-integral approach, an irreversible plastic material with a crack is idealized as a reversible non-linear elastic material.

Figure 11 shows the stress-strain behaviour of a non-linear elastic material. In comparison with an elastic-plastic material (Figure 8), the loading behaviours of the two are identical, but their responses are different when they are unloaded. The non-linear elastic material loads and unloads along the same path and returns to zero strain at zero stress; that is, the response, while elastic, is non-linear. The non-linear response to loading and unloading can be described by a power-law relationship between stress and strain (**Stress $\propto$ Strain^{n}**); the value of **n** is unique for a material. However, this is not the case for the elastic-plastic material, where a given strain can correspond to more than one stress, depending on whether the material is loaded or unloaded or cyclically loaded. The strain is not zero at zero stress. Because the non-linear response of the elastic-plastic material cannot be easily described, fracture in such materials is difficult to analyze.

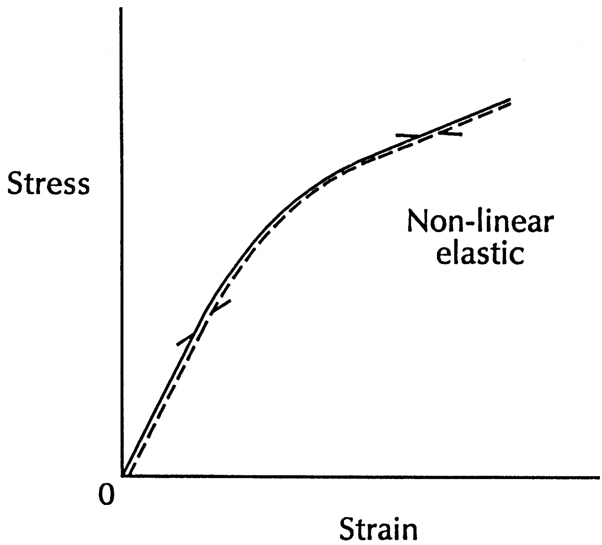

Figure 11. The stress-strain curve for a non-linear elastic material.

Rice [15] used non-linear elasticity theory for the analysis of a crack in a non-linear elastic material, and showed that the non-linear energy release rate, **J**, could be described by a path-independent contour integral around the crack tip. Like $\mathbf{G_c}$, it is argued that $\mathbf{J_c = -dU^*/dA}$ is the critical strain energy release rate for a non-linear elastic material at crack extension, where $\mathbf{U^*}$ is the potential energy of the non-linear elastic material. That is, fracture occurs when **J** reaches a critical value $\mathbf{J_c}$ which is a characteristic of the material.

Hutchinson [16] and Rice and Rosengren [17] independently showed that **J** uniquely characterizes crack tip stresses and strains in a non-linear elastic material, thus allowing **J** to be regarded as both an energy parameter and a stress intensity parameter, similar to **G** and **K** for the linear elastic material. They each assumed a power-law relationship between non-linear stress and strain.

If the stresses in both elastic-plastic and non-linear elastic materials increase monotonically, the responses of the two will be identical on loading, but not so upon unloading. Therefore, an analysis that assumes non-linear elastic behaviour may be valid for an elastic-plastic material provided no unloading occurs. However, as soon as the crack propagates, the material behind the new crack tip unloads, and this unloading is linear elastic. The **J** approach therefore is strictly limited to monotonic loading with no unloading, and non-propagating or stationary cracks. This is the major limitation of the J-integral approach to the characterization of elastic-plastic materials. The approach breaks down when the crack tip plasticity is not negligible and significant stable crack growth occurs before instability. Since these factors are specimen size and crack geometry dependent, $\mathbf{J_c}$ results independent of specimen size are difficult to obtain. This, in practice, seems to be the case for laboratory-size specimens of tough papers. Once again, much larger specimens than are practical may be required [3,5].

For a non-linear elastic material, there is no simple relationship between $\mathbf{J_c}$, load and crack length, similar to the one for $\mathbf{G_c}$ in the linear elastic case. $\mathbf{J_c}$ can be measured experimentally by invoking the energy release rate definition of **J**; that is, $\mathbf{J_c = -dU^*/dA}$ at instability [18,19]. In order to first obtain calibration curves, a number of specimens of the same size, geometry and material are prepared with varying initial crack lengths. The crack-size range should cover those expected in subsequent **J** testing. The load-displacement curve for each specimen is obtained without introducing appreciable crack extension. The area between two adjacent crack size loading curves, up to some fixed displacement, is measured and is assumed to be **Jtda**, where **da** is the crack size difference, and **t** is the specimen thickness (Figure 12a). A plot of **J** versus displacement is prepared for each pair of adjacent crack size loading curves; each such plot is associated with a mean value of crack size (Figure 12b). In subsequent **J** testing, the value of displacement at which fracture is seen to occur for a given crack size is measured, and the associated **J** is determined from the previously obtained calibration curves (Figure 12b). The value of **J** found in this way is the required $\mathbf{J_c}$. A figure like 12b applies only to the material, specimen size and crack geometry for which it is obtained.

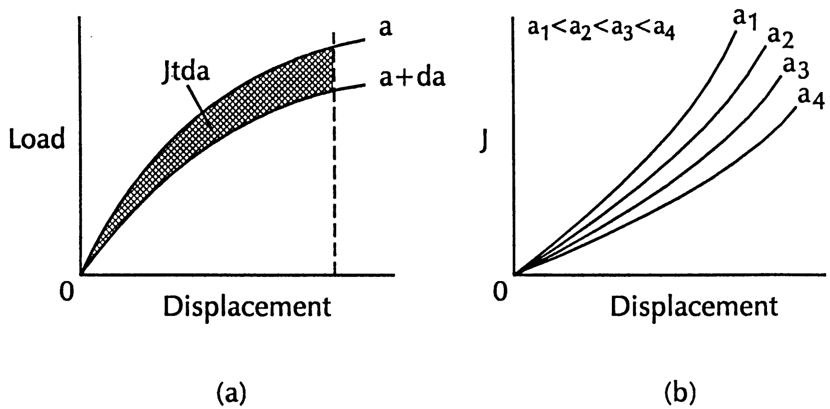

*Figure 12. Schematic of experimental measurement of **J**.*

Though fundamental in approach, the method requires a large number of specimens, and is cumbersome. Another significant difficulty in determining $\mathbf{J_c}$ lies in defining precisely the onset of crack growth.

Several simpler methods for measuring $\mathbf{J_c}$ that require fewer specimens have been proposed [3-5], and used for paper [20,21; see also references in 22]. However, it is not clear that they have provided results independent of specimen size and crack geometry.

The measurement of $\mathbf{J_c}$ from the more complex **J** versus crack extension plots [3,5] has not been attempted for paper. Appropriate specimen-size and crack-extension requirements have to be met to obtain valid results.

The essential work of fracture

In tough ductile sheet materials with low yield stress, the fracture process zone is less clearly defined, as it is surrounded by an outer plastic zone whose shape and size depend on the specimen size and crack geometry. Broberg [23] suggested that the total work of fracture, $\mathbf{W_f}$, can be considered as consisting of two components: the essential work $\mathbf{W_e}$ consumed in the inner fracture process zone, and the non-essential work $\mathbf{W_p}$ dissipated in the outer plastic region. $\mathbf{W_e}$ is associated with fracture. The essential work of fracture approach, therefore, is an attempt to separate the two components experimentally. Cotterell and Reddel [24,25] demonstrated that this could be done as follows.

Deeply double-edged cracked tension specimens are strained to fracture, and the total work of fracture $\mathbf{W_f}$ is measured for a range of ligament lengths **L** (Figure 13). When such a specimen yields completely before crack initiation, the plastic region is confined to a circular area centred on the ligament. On dimensional grounds one can write

$$W_f = W_e + W_p$$

$$= Ltw_e + \beta L^2 tw_p$$

In this equation, $\mathbf{w_e}$ 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. $\mathbf{w_p}$ is the non-essential work dissipated per unit volume of the material, $\boldsymbol{\beta}$ is a shape factor for the outer plastic region which depends on the specimen and crack geometry, and **t** is the specimen thickness. $\boldsymbol{\beta}\mathbf{w_p}$ is not a material property. Rewriting above equation gives

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

If $\mathbf{w_f}$ is now plotted against **L**, a straight line is obtained whose positive intercept gives $\mathbf{w_e}$ (Figure 14).

The specific essential work of fracture $\mathbf{w_e}$ has been shown to be a fundamental material property independent of specimen geometry

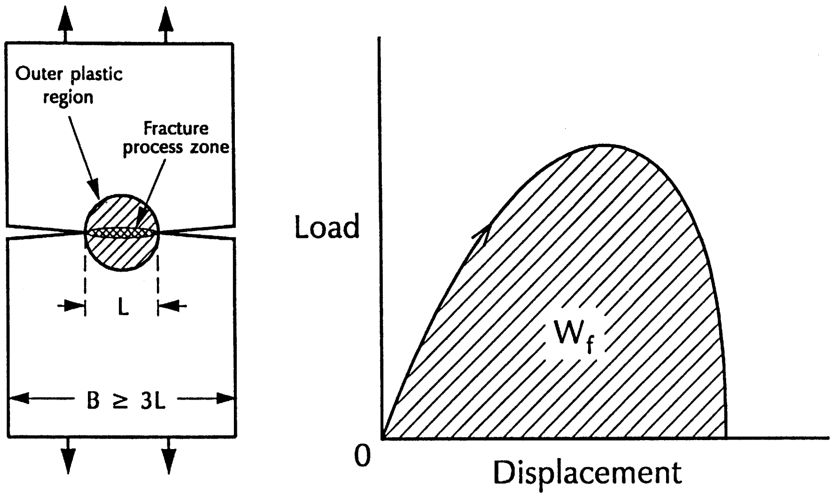

Figure 13. Schematic of measuring the essential work of fracture.

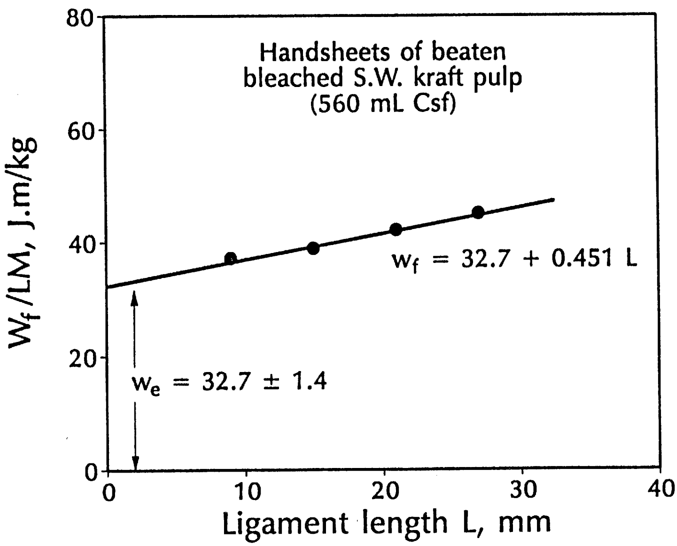

*Figure 14. Plot of total work of fracture against ligament length (Figure 13). The intercept gives the specific essential work of fracture or the fracture toughness of the material. The sheet thickness **t** is replaced by sheet grammage **M** in calculating w_f (= W_f/LM).*

[26,27] and has been identified as the fracture toughness $\mathbf{J_c}$ or **R** of the material [27-32]. This approach has been used extensively to measure the fracture toughness of metallic and polymeric sheet materials [24-33; see also references in 22]. The method is theoretically sound and experimentally simple; there is no ambiguity in the measured fracture toughness values. The equivalence of $\mathbf{w_e}$ and $\mathbf{J_c}$, both theoretically and experimentally, has been well established [27-32].

Recently, it has been demonstrated that the essential work of fracture approach can be applied to laboratory-size samples of paper [22]. The background to this approach, and the conditions for these measurements have been discussed [22]. The method has been used to determine the effect of fibre properties, pulping and papermaking treatments on the plane stress fracture toughness of softwood kraft pulps [34]. The measurements were made on handsheet samples.

Fracture toughness **R** should not be confused with tensile energy absorption, **TEA**; the two are different. **TEA** is the total area under the stress-strain curve of a specimen failed in tension without a pre-existing crack, divided by the specimen cross-sectional area. Whereas **R** is the work required in the crack tip process zone, **TEA** includes the irreversible work dissipated throughout the specimen.

CONCLUDING REMARKS

The choice of the method for measuring fracture toughness depends on whether the material is elastic, elastic with small-scale plasticity or elastic-plastic. Paper can be any of these depending on the furnish composition and papermaking conditions.

For papers with low toughness and high yield stress, the fracture process zone is expected to be small. Such papers include newsprint (Figure 15) and many printing-grade papers containing mechanical pulps. The machine direction is considered here as the direction of straining, with the crack propagating in the cross direction. The parameter $\mathbf{G_c}$, independent of specimen size, can be obtained for these papers on laboratory-size specimens. The fracture toughness of these papers can also be measured directly by the simpler quasi-static crack propagation method [13,35], as the conditions for these measurements can be easily met. For tougher papers, specimen widths required may become large and therefore, impractical (Figure 6).

For papers with high toughness and low yield stress, the fracture process zone can be large; the techniques of elastic-plastic fracture apply. Handsheets of beaten softwood kraft pulps are an example (Figure 15). The essential work of fracture method appears promising for such papers [22,34]. The method, though time consuming, is both simple and direct.

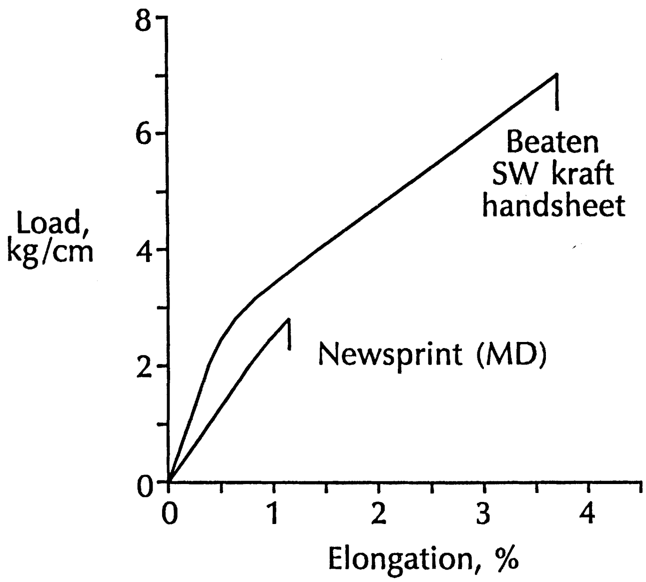

Figure 15. Load-elongation curves illustrating brittle and ductile papers.

Several measurements of fracture toughness parameters have been reported in the literature without resolving whether a material property, independent of specimen size, was obtained. How important is it that $\mathbf{G_c}$, $\mathbf{J_c}$ or $\mathbf{w_e}$ provide an unambiguous measure of the fracture toughness **R** of the material? It is important that they should, because the objective is to determine a material property which enables developing tougher materials that perform more reliably.

ACKNOWLEDGEMENTS

Gordon Robertson is thanked for many helpful discussions, and Wyn Walker for preparing manuscript and illustrations.

REFERENCES

1. "Internal tearing resistance of paper", CPPA Technical Section Standard D-9 (1977), and TAPPI Test Method T414 om-88.

2. "Testing of paper: Tear growth test according to Brecht-Imset", DIN Standard 53 115, December 1977.

3. Atkins, A.G. and Mai, Y-W., Elastic and Plastic Fracture: Metals, Polymers, Ceramics, Composites, Biological Materials, Ellis Horwood/John Wiley, Chichester (1988 reprint).

4. Broek, D., Elementary Engineering Fracture Mechanics, Kluwer Academic Publishers, Dordrecht (1991).

5. Anderson, T.L., Fracture Mechanics: Fundamentals and Applications, CRC Press, Inc., Boca Raton (1991).

6. Uesaka, T., "Design for testing paper and paperboard", in Handbook of Physical and Mechanical Testing of Paper and Paperboard, Vol. 1, (R.E. Mark, Ed.), Marcel Dekker, New York, 1983, p. 77.

7. Johnson, J.A., Bennett, K.A. and Montrey, H.M., "Failure phenomena", ibid. p. 145.

8. Helle, T., "Fracture mechanics of paper", in Design Criteria for Paper Performance, (P. Kolseth et al. Eds.), STFI-Meddelande A 969, 1987, p. 93.

9. Seth, R.S. and Page, D.H., "Fracture resistance of paper", J. Mater. Sci. 9 : 1745 (1974).

10. Heckers, W., Hart, D. and Göttsching, L., "Fracture mechanical investigation with paper Part II: Trials on the test method with newsprint paper, and Part III: Technological influence on laboratory sheets", Das Papier 34(7) : 255 and 34(10) : 421 (1980).

11. Pommier, J.C. and Poustis, J., "The in-plane fracture of paper – experimental determination of tear characteristics", Revue A.T.I.P. 37(6) : 300 (1983).

12. Weide, W., Ramaz, A. and Poujade, J.L., "Fracture resistance of newsprint", in Advances in Printing Science and Technology, (W.H. Banks, Ed.), Pentech Press, London, 1986, p. 136.

13. Gurney, C. and Hunt, J., "Quasi-static crack propagation", Proc. Roy. Soc. A 299 : 508 (1967).

14. Mai, Y-W., "Comment on 'Fracture resistance of paper'", J. Mater. Sci. 10 : 1271 (1975).

15. Rice, J.R., "A path independent integral and the approximate analysis of strain concentration by notches and cracks", J. Appl. Mech. 35 : 379 (1968).

16. Hutchinson, J.W., "Singular behaviour at the end of a tensile crack tip in a hardening material", J. Mech. Phys. Solids 16 : 13 (1968).

17. Rice, J.R. and Rosengren, G.F., "Plane strain deformation near a crack tip in a power-law hardening material", J. Mech. Phys. Solids 16 : 1 (1968).

18. Begley, J.A. and Landes, J.D., "The J-integral as a fracture criterion", ASTM STP 514, 1 (1972).

19. Landes, J.D. and Begley, J.A., "The effect of specimen geometry on J_{IC}, ASTM STP 514, 24 (1972).

20. Westerlind, B.S., Carlsson, L.A. and Andersson, Y.M., "Fracture toughness of liner board evaluated by the J-integral", J. Mater. Sci. 26 : 2630 (1991).

21. Yuhara, T. and Kortschot, M.T., "A simplified determination of the J-integral for paper", J. Mater. Sci. 28 : 3571 (1993).

22. Seth, R.S., Robertson, A.G., Mai, Y-W. and Hoffmann, J.D., "Plane stress fracture toughness of paper", Tappi J. 76(2) : 109 (1993).

23. Broberg, K.B., "Critical review of some theories in fracture mechanics", Int. J. Fract. 4: 11 (1968).

24. Cotterell, B. and Reddel, J.K., "The essential work of plane stress ductile fracture", Int. J. Fract. 13(3) : 267 (1977).

25. Cotterell, B., "Plane stress ductile fracture", in Fracture Mechanics and Technology, Vol. 2 (Sih, G.C. and Chow, C.L., Eds.), Sijthoff and Noordhoff, Alphen aan den Rijn, 1977, p. 785.

26. Mai, Y-W. and Cotterell, B., "Effect of specimen geometry on the essential work of plane stress ductile fracture", Eng. Fract. Mech. 21(1) : 123 (1985).

27. Paton, C.A. and Hashemi, S., "Plane-stress essential work of ductile fracture for polycarbonate", J. Mater. Sci. 27 : 2279 (1992).

28. Wnuk, M.P. and Read, D.T., "Essential work of fracture (w_e) versus energy dissipation rate (J_c) in plane stress ductile fracture", Int. J. Fract. 31 : 161 (1986).

29. Mai, Y-W. and Cotterell, B., "On the essential work of ductile fracture in polymers", Int. J. Fract. 32 : 105 (1986).

30. Mai, Y-W., Cotterell, B., Horlyck, R., and Vigna, G., "The essential work of plane stress ductile fracture of linear polyethylenes", Polym. Eng. Sci. 27(11) : 804 (1987).

31. Mai, Y-W. and Powell, P., "Essential work of fracture and J-integral measurements for ductile polymers", J. Polym. Sci. B(Polym. Phy.) 29 : 785 (1991).

32. Wu, J., Mai, Y-W., and Cotterell, B., "Fracture toughness and fracture mechanisms of PBT/PC/IM blend: Part I Fracture properties", J. Mater. Sci. 28 : 3373 (1993).

33. Hashemi, S. and O'Brien, D., "The essential work of plane stress ductile fracture of poly (ether-ether ketone) thermoplastic", J. Mater. Sci. 28 : 3977 (1993).

34. Seth, R.S., "Ranking reinforcement pulps by fracture toughness", CPPA 1993 Spring Conference Preprints, Paper 4B-1 (Extended Abstract).

35. Seth, R.S., "Measurement of fracture resistance of paper", Tappi 62 (7) : 92 (1979).

Transcription of Discussion

PLANE STRESS FRACTURE TOUGHNESS AND ITS MEASUREMENT FOR PAPER

Prepared contribution

R Seth, PAPRICAN:

THE J-INTEGRAL AS A FRACTURE TOUGHNESS PARAMETER OF PAPER

T Yuhara

FRACTURE TOUGHNESS AS A PULP CHARACTERISATION METHOD FOR RUNNABILITY ASSESSMENT OF PAPER

A Astrom (Paper presented by A Nordstrom):

(EDITOR'S NOTE: WHAT FOLLOWS IS THE PROCEEDINGS OF A DISCUSSION OF ALL THREE PAPERS)

Dr F El Hosseiny, Weyerhaeuser Paper Co

This question is addressed to whoever can answer it. For the past two decades fracture mechanics of paper was introduced hoping to be able to characterise the behaviour of paper in the converting process and especially press room newsprint runnability. Seth and Page have shown that newsprint runnability is governed only by the rare event phenomena irrespective of its fracture toughness. If fracture toughness or fracture mechanics failed to do what it was supposed to be doing, that is to predict the flow carrying ability of a sheet, what hope do we have for extending this study. We could do it for another 20 years and come to the same conclusion. Why are we continuing doing work in the fracture mechanics of paper?

R Seth

Yes, I was involved in that study. You are quite right. The reason for my getting back into fracture was for the softwood kraft market pulps and tear. Tear is a millstone around the necks of market kraft pulp producers. Tear goes down when you refine the pulp implying you shouldn't refine. Fracture toughness tells us now that you can refine without fear of losing tear because what matters in the end use processes is the stresses in the plane of the sheet, therefore don't be afraid to refine, and that was the purpose. If you wish I can draw curves of fracture toughness against refining and tear against refining; fracture toughness goes up and tear factor goes down. This convinces papermakers that there is a merit in refining and thus using the full potential of the fibre. We now have tear resistance also in plane stress, like tensile strength and elastic modulus, and they all increase as we refine, unlike the out-of-plane tear. That was the only reason I got into this and I think the industry does appreciate that.

Dr D Page, PAPRICAN

I guess my comment is similar to F El-Hosseiny's. There has been a lot of work on fracture mechanics and debate and how to measure fracture mechanics. But what surprises me is that fracture toughness has become a religion. When you actually look for the data to find out if it is important to runnability you will find one plot that R Seth and I published many years ago when we collected 1½ years runnability data. We measured fracture toughness of newsprints and obtained runnability data for a large press room and got a correlation which was significant but very poor between fracture toughness and runnability. It seems to me that the difficult step is to prove that in general it is worthwhile using fracture toughness as a means of evaluating pulps or sheets. That's the difficult step. The easiest step is what you three people are doing now, namely trying to devise a method for measuring it. I think the important step though has to be to show a relationship between end use and a test. I can visualise for example that you can take sheets or reels of paper which have 1% stretch to break and rereel them using 0.5% stretch they won't break, but use 1.5% stretch and they will. This will have nothing whatsoever to do with fracture toughness. What is the proper criterion for failure? I believe we don't know and I believe that's where the next step has to take place, not in a laboratory but in the workplace where the real data exist. In the absence of evidence we are at the mercy of evangelists and their beliefs.

Yuhara *(in response to El Hosseiny question)*
If we want to talk about runnability we have to cover all three factors discussed by Niskanen in the first presentation and also mentioned in my presentation. The three factors are the number of flaws present, uneven tension and finally the paper toughness. For example, Japanese newsprint does not always have high fracture toughness so the industry focuses on decreasing the number of flaws and controlling the calliper profile, especially in the cross machine direction. Not only calliper but also moisture content and of course the basis weight profile. These things influence the tension on the printing press, and the fracture toughness may not be the dominant factor. We must consider other things for good runnability.

R Seth
I agree with Dr Yuhara. We do measure tensile strength and other stress-strain properties, and write review papers on these properties. Why are we doing this; do these properties matter at

all. If we go back to basic materials science, it tells us that there are certain mechanical properties, and if they are OK, we have a hope that the material will survive and fracture toughness is one of them.

Dr K Ebeling, Kymmene Corp, Finland

Thank you for your answer to the first question Dr Seth. One comment I would like to make - it is not the papermakers, it's the pulp merchants that promote the importance of tear strength. I think they are so short minded that tear strength is the only thing they understand.

R Seth

It is unfortunate. We have to educate them.

Dr F-J Chen, Kimberly Clark Corp, USA

One of the key reasons for breaks is web non-uniformity which may be particularly sensitive to your notch method. What happens to the coefficient of variance in your measurement? Is the average value more important or is the coefficient of variance more important? Would the two numbers reported together give us better indication as to whether breaks may occur?

R Seth

I will pass this question because I am not measuring fracture toughness at present to relate to breaks. I am measuring only to evaluate pulps. So those who are doing it to predict breaks should answer this question.

Yuhara

Maybe we have to use some sort of safety assessment method for achieving the fracture toughness for high runnabilitv.

R Seth: *(Question for Yuhara)*
Let's go back to your figure 7 in the text on page 799. In each figure there are about 25-30 points. Which one of them can I call the fracture toughness value?

Yuhara: Actually as I presented in my conclusions, there is no way, so far, to evaluate the energy for crack extension. From that point of view none of those values have a physical meaning which relates to the energy available to drive the crack. Your method, the essential work of fracture cannot give the energy available for crack growth in a machine made paper.

R Seth
Because of the experimental difficulties? I'll come to that point later. So am I correct in assuming that the J methods that you have used, (and you are using 5 of them), none of them gave you an unambiguous result. Am I right in saying this?

Yuhara
Yes, absolutely right.

R Seth
As far as difficulties with my method are concerned, first of all my method may not work for brittle papers such as newsprint because of unstable crack propagation. It was not meant for newsprint, but for ductile sheets, and I have been using it for tough handsheets, sack kraft etc; it worked very well for copying paper. Further, if you have difficulties in having the two edge cracks not connect on propagation, there is nothing in that method that stops you from using a single edge notched sample. There will be experimental difficulties of keeping the clamps from turning. There are guided

clamps which we use and I am happy to give the drawings of them to anyone who wants them. These difficulties can be met, but you have to recognise that the essential work of fracture method is for ductile materials and that is what my February 1993 paper in Tappi said.

Dr J R Parker, Messmer Instruments, UK

I seem to remember from very old data that one of the few properties of paper that had any relationship to runnability was moisture content. I wonder if this gives any pointer to the sort of toughness measurement that might be appropriate.

R Seth

A small increase in moisture content can lead to a higher fracture toughness. It's a piece of work which we did 15-16 years ago, and that was the indication. We measured fracture toughness of newsprint between 40-60% humidity at that time and 60% humidity results were higher.

J Waterhouse, IPST, USA

We need to distinguish between rare events and fracture mechanics but I think it is clear that there are a number of different areas where fracture mechanics can be applied, and obviously rare events will sometimes occur. I always remember Christer Fellers showing the beer bottles on the floor because of failed packaging in one of his presentations on fracture mechanics. There are examples of scoring, durability, perforations, and more recently die cutting, so I think as we can analyse the end use application of paper more correctly, we can see quite a number of applications of fracture mechanics. Obviously fracture toughness is key to this and ultimately what we want to know is: how the processes at the micro mechanics level relate to fracture toughness, ie what do we have to do to improve the fracture toughness of paper? Also, does fracture mechanics give us any clues as to the ultimate strength properties of paper again going back to K Niskanen's excellent review paper this morning.

Prof M Kortschot, University of Toronto, Canada
Let me defend the use of fracture toughness. I think it is still true that in spite of the rarity of breaks in a printing press and in spite of the influence of moisture and other factors, some paper does run better than others. When papermakers have problems with runnability they have to respond by adjusting the furnish. We therefore need some method of addressing the relationship between furnish parameters and the eventual runnability. Intuitively it seems that fracture toughness is the most likely means of characterising this relationship, but I agree with Dr Page that we have to explore this in much more detail.

R Seth
There was an earlier question from Dr Chen that I tried to evade and that was regarding whether I was measuring an average value and what was the spread. If we look at the test, we are measuring an average in the same way as for example tear strength; an average value along a certain path. So, what I am doing is giving an average for the material that I am testing. If you want to see what is the spread or error in that value I would suggest that you look up the Tappi paper (February 1993) which explains the method and you will see that the measurements are fairly good, and the error is comparable to the error in tensile strength etc.

Prof H Kropholler, UMIST, UK

We seem to have a very powerful technique, lots of mathematics and different ways of doing it and there was one very interesting problem which I don't think has been mentioned. There is folklore in the paper industry that some grades of strong papers are best made with a wild formation, corrugating medium is one of these and Prof Göttsching showed some 15 years ago that this was folklore and not true. Another interesting one is sack kraft where it is suggested that the fracture strength is better if you have a wild formation. I don't really believe this but surely you could prove this with fracture mechanics.

R Seth

I will think about it.

Dr K Ebeling, Kymmene Corp, Finland

I think we have to keep the testing methodology on two levels in our minds. The process engineer would like to have a simple method to follow for example if the raw material he is using has a constant quality. As scientists we should have methods that allow us to understand what really is going on and allow us to predict how a better product should be made. The fracture toughness is very important for wood containing printing paper manufacturer because when you have a machine producing 250,000 tonnes a year and if you can save 1% - unit a year in your expensive chemical pulp by using pulp that provides a better fracture toughness to your web, you have earned your salary many times.

R Seth

I agree with you.