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Tearing and Fracture of Paper and Board

Niskanen and Kärenlampi in Niskanen’s book give a good account of Fracture Toughness.

Elmendorf Tear

The Elmendorf tear test is by far the most common tear test but probably also the most complicated and the least well understood. If, in the paper industry, somebody talks about "tear" without further elaboration, it is almost certainly Elmendorf that they mean. Industrial specifications for paper usually include a value for Elmendorf but the effect of furnish, refining and paper machine variables on its magnitude is often over simplified and, frequently, downright wrong. Please do not think that you completely understand this property just because of what you have been taught in a paper mill production or laboratory department. A complete understanding of Elmendorf tear is not what we will be aiming at here, as it would certainly become very complicated in a way which would not be at all helpful. We will be discussing how the test works, how the value obtained depends on paper structure and furnish and in which ways it is useful. In the subsequent sections we will be discussing alternative tests, which make more sense in certain respects and how these may be better indicators of paper machine and printroom runnability and end use properties.

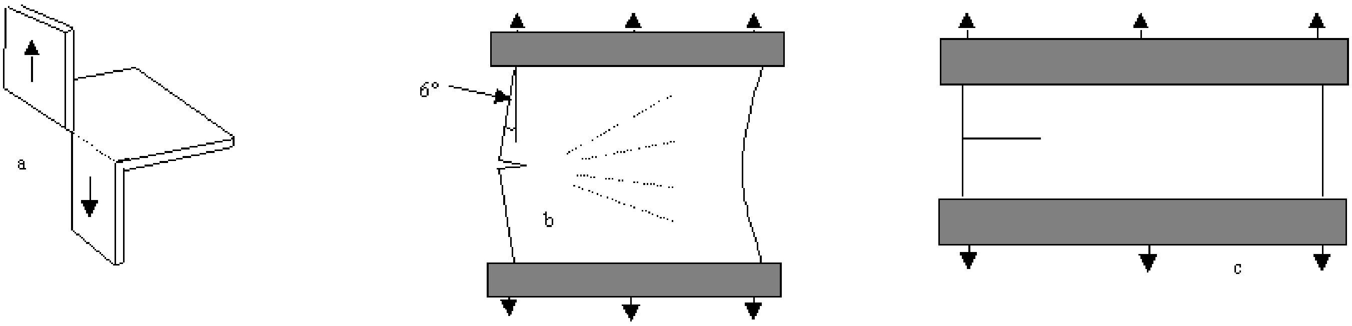

Figure 1 a)Schematic illustration of the Elmendorf test. The two flaps of paper (the sample is pre-cut) are clamped in separate jaws and a pendulum swing pulls them apart, tearing the sample. The energy removed from the pendulum by the process of tearing the sample is estimated from the final magnitude of the swing and this is the value given as tear strength (when divided by the length of the tear). In practice, of course, the result is directly read off the pendulum or is given by the digital readout of the more modern instruments, since the sample size and tear length are standardised. Sometimes several samples are torn together and it is assumed that the energy required increases linearly with the number, and this seems to work well. b) The In-Plane Tear test. c) Fracture Resistance test.

The mode of tearing is more or less as shown in the above figure, but the relative angle of pull changes continuously during the test. This means that the mode of failure is a continuously changing combination of in and out of plane tensile and shear.

The test is intended as a way of predicting the likelihood of runnability failures on printing and converting machinery and of end-use failures such as tearing in paper sacks or wrapping papers. There is no real evidence that Elmendorf works particularly well from this point of view, but it is intuitively measuring the right sort of thing, which seems to have been enough for its acceptance. The characteristic way that tear strength varies with refining is shown below in figure 2:

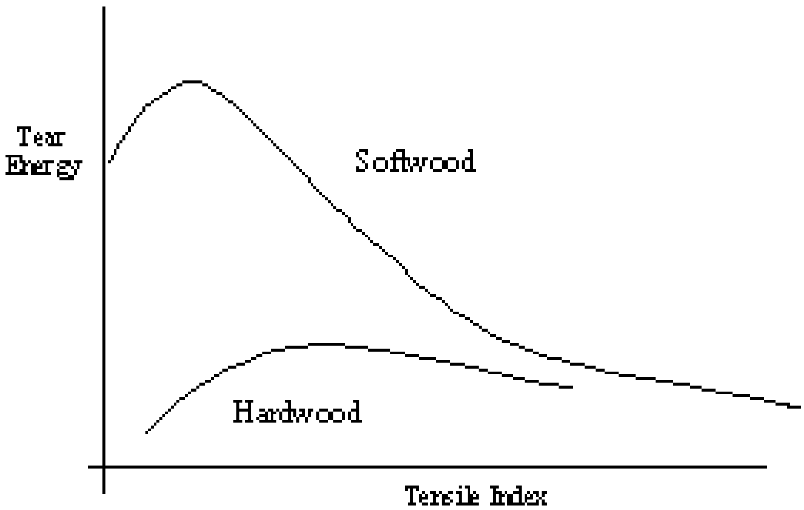

Figure 2 Typical curves showing the variation in Elmendorf tear strength with tensile strength for softwood and hardwood Kraft pulps.

In general, Elmendorf tear strength decreases with refining or wet pressing, after an initial rise, although this may not be true for some hardwood pulps. This means that, while the tensile strength of paper is increasing due to increased bonding between fibres, the tearing strength is decreasing. This is not because "tear strength depends solely on fibre length and the main effect of refining is fibre length reduction" although this is often heard round the industry. A more accurate and convincing explanation of the phenomenon is that during the complex failure in an Elmendorf tear test, some fibre segments are pulled out of the sheet and others snap. The work required to be done to "tear" a fibre in these two ways is different. Clearly, a fibre will not be broken if, at a lower force, it can be pulled out of the structure, but the force must be applied for a much longer distance, perhaps millimetres rather than microns. The work to pull out a fibre is therefore higher than that required to break one. As refining is increased, fibres become better bonded into the structure and the probability of a fibre segment being broken rather than pulled out increases. The total work required to tear the sample is therefore decreased and it is this work that we are measuring when we measure the backswing of the Elmendorf pendulum. Mathematically, this might be written:

$$\text{Tear Energy} = n_p w_p + n_b w_b$$

where n_p = number of fibres pulled out

w_p = work to pull out a fibre

n_b = number of fibres broken

w_b = work to break a fibre.

and $w_p > w_b$.

At very low levels of bonding w_p is also low, very few (if any) fibres are being broken and Tear increases with refining, but as soon as a significant number of fibres start to be broken Tear starts to decrease.

Seth and Page (1) looked at the effect of fibre length, strength and coarseness on Elemendorf tear strength.
Poor bonding – depends strongly on fibre length
Better bonding – depends on fibre strength squared
Amongst fibres of similar length and strength, coarser fibres make sheets with higher Tear Index.

Higher grammages, not surprisingly, have higher tear strength and to take account of this Elmendorf results are usually quoted as Tear Index, which is Tear strength divided by basis weight (units – mN m^2 g^{-1}).

Tear strength is a measure of the energy required to create new area by tearing. For this reason bulkier papers have higher tear strength (although this can also be understood from the likelihood that the degree of bonding is lower). Sometimes samples delaminate around the line of tear and strictly these are not good results and should be excluded, although often they are not. The tear strength can be apparently very large in such cases.

Increased fibre strength will result in higher tear strength not because it takes more energy to break the same number of fibres but because the number of fibres broken will be smaller.

CD Elmendorf tear is always higher than MD. This seems counter-intuitive until you realise that the CD result tears across the MD, i.e. the direction of the failure line is as it would be for a MD tensile.

Try tearing a piece of the paper-like material Tyvek which includes very strong and very long artificial fibres which are bonded into the structure with a resin– it is virtually impossible to do this by hand. Tyvek is, for obvious reasons, used for envelopes which are likely to contain sharp objects and for disposable overalls.

It may be that the real utility of the inclusion of a Tear value in the specifications of most paper grades is that it helps to prevent the paper from drifting towards extremes. Because tear reduces as tensile increases, it is necessary to have just the correct amount of refining, as well as a sensible amount of wet pressing in order to achieve both goals. This ensures that other properties such as opacity and printability are within reach and that diffuse concepts such as the "handle" or "rattle" of paper can be achieved.

There is an In-Plane tear test which involves a deliberate misalignment of the jaws in a tensile tester by 6°. The samples used are identical to those used in the Elmendorf and the initial slit and tearing length are identical. This test is supposed to give more accurate predictions of runnability, but only partially bridges the gap between the Elmendorf and the more theoretically accepted fracture resistance.

Fracture Toughness

When breaks occur on printing or converting machinery, the tension is normally far below the tensile strength of paper. The failure occurs because there is a defect which allows a tear to start and a catastrophic propagation follows. There is no theoretical or practical reason to suppose that the Elmendorf tear test has any relevance to this phenomenon and it is necessary to use Fracture Mechanics, which is widely used in other technologies for predicting infrequent failures which occur at well below the theoretical strength of a material due to small flaws. Web breaks are very infrequent and it is virtually impossible to test the paper in a way which reflects a genuine occurrence. There are often many kilometres (1000 km is a typical value) of paper between the sites of the flaws which would actually cause a break and there is no realistic chance of finding them! To compare runnability for two papers by measuring the distance between breaks is also impossible and would involve analysing data from 1000 to 10000 rolls in order to achieve statistical significance. It is, of course, highly likely that the paper would have changed over this period making interpretation impossible. Realistic flaws are small tears due to damaged reel edges, shives, water drops. Fracture toughness or fracture resistance is a material property which describes the ability of paper to resist a flaw becoming a growing crack. Larger flaws would mean that the fracture toughness would have to be higher to resist crack growth.

Yuhara and Kortschot (3) compared 2 papers using both tensile strength and tensile energy absorption for conventional 25 mm width samples and similar samples with notches of length 2, 4, 6 and 8 mm length. They discovered that, in neither case, did the undamaged result correctly predict the ability of the artificially flawed samples to resist tearing and failure. This clearly demonstrates the need for a separate measurement which predicts the likelihood of failure in damaged samples.

Fracture mechanics is relatively simple for materials which can be considered as elastic and is called Linear Elastic Fracture Mechanics (LEFM). The analysis becomes much more difficult for plastic and viscoelastic (like paper) materials. Papers such as mechanical printing grades are closer to being "elastic" and are described as relatively brittle, whilst others such as strong chemical pulp papers are more "ductile" and cannot be considered as being accurately described by LEFM. We will only consider LEFM theoretically but will discuss how the viscoelastic nature of paper can be taken into account when making measurements of fracture resistance.

Theory of LEFM

If an existing crack grows, elastic energy is released because stress vanishes at the crack faces. The basic concept of fracture mechanics, the Griffin Criterion, says that a crack cannot grow unless this released energy is at least equal to the energy necessary to overcome the fracture resistance (or toughness) of the material. In a linearly elastic body, the condition for crack growth is:

$$G = -\frac{d\Pi}{dA} = \frac{\beta\sigma^2 a}{E'} \geq G_c = R \qquad [1]$$

where

$G = -\frac{d\Pi}{dA}$ [J/m^2]	is the decrease in elastic energy per crack area increment (or the crack driving-force),
β	is a geometric factor,
σ	is the remote stress far from the crack,
a	is the crack length,
E’	is an elastic constant and
$R = G_c$	is the fracture energy of the material.

In isotropic paper under plane stress, E’ is the ordinary elastic modulus but in anisotropic paper it is given by a combination of the elastic constants.

A web with a crack releases energy at a rate G if the crack grows. According to equation [1], G is proportional to web tension squared and so, if the web tension increases, G will eventually reach the fracture energy of the material G_c = R. An infinitesimal increase in tension will then cause the crack to grow because it will then be energetically advantageous for this to happen, i.e. more energy will be released by the crack growing than has to be put in to cause it to grow. Of course, the value of σ (the applied stress) will then decrease and a will increase and G has to be re-calculated to see whether the crack will continue to grow or whether more applied stress is again necessary. This last point makes it easy to see why the geometric factor (β) is necessary since the stress would drop a lot for a narrow strip, where a was a significant proportion of the width, but, where the strip is wide and a is small (for example on a printing press), it is clear that the overall tension will be barely affected.

Fracture Toughness is defined as $K_c = \sqrt{G_c E}$ [2] for an isotropic material. K_c may also sometimes be called the "critical stress intensity factor" or "tenacity". If the web contains a flaw of size a, the critical web tension can be calculated from equation [1] and combined with the definition for fracture toughness to give: $\sigma_c = \frac{K_c}{\sqrt{\beta a}}$ [3]. As previously discussed, β is a geometric factor which depends on the flaw size, a, and the web width.

In many circumstances the fundamental, known quantity is not the web tension but the speed difference or draw in the gap between two components. For flaws of a fixed size it follows that the critical strain at which crack propagation will begin is proportional to K_c/E. This is a useful result since it suggests that, for a lower modulus, crack propagation will not start until a higher strain is reached. This means that paper with a higher moisture content, and therefore lower modulus, will withstand higher strains before failing. This formally explains the fact that printers prefer to be sold paper which has been reeled up at a higher moisture content, even though they are buying more water. It also explains why newspaper printers do not like to run paper which has been stored for any period because they feel it will have dried out and become more likely to give breaks.

The above discussion is the basis of linear elastic fracture mechanics (LEFM) and it holds only if the fracture process and the surrounding plastic deformations occur in a zone that is small compared with all the dimensions of the object, including the size of the crack or flaw. This is certainly not always true, but if you want to find out more you will need to consult a textbook on fracture mechanics, as a deeper theoretical discussion is outside the scope of this course.

Measurement of Fracture Toughness

Measurement of fracture toughness of paper and board is difficult to perform accurately because of the plastic deformations which occur near the crack-tip. It is also necessary to keep stored elastic energy to a minimum in order to allow the applied stress to drop quickly when the crack lengthens. The load must be applied at a speed which is slow enough to avoid overshooting of the critical web tension.

A number of different tests are described here and all are likely to be done on a standard tensile tester. Most require a sample which has one or two pre-cut slits or notches. It is possible that special jaws will be used to ensure that the jaws remain parallel at all times. Paper is not an elastic material and has significant plasticity so that LEFM is not really valid. All of these measurements attempt to take this into account in some way but all give slightly different results for the fracture energy and fracture toughness. There is some doubt as to which (if any) of the measurements gives the best indication of the likelihood of breaks on printing and converting machinery.

Direct Measurements on Short Samples

This direct measurement of fracture energy takes no account of the viscoelastic nature of paper but has been used with some success by, for example, Seth and Page (2) to demonstrate the principles of fracture resistance. It is certainly more appropriate to relatively brittle papers than to relatively ductile ones. They discuss sample design at some length.

With a short specimen the fracture failure is much more controllable. This is often said to be due to the amount of stored energy available for continuing to propagate the failure once it has started being much larger. This is true, but whether the crack continues to grow does not directly depend on the amount of energy available, stored or otherwise, and is entirely described by equation [1]. In fact, the crack will only get longer if the stress, σ, is above a critical value. There is no doubt that there is more stored energy in a longer sample: to get to a particular value of stress, it is necessary to put in an amount of strain determined by the Young’s modulus, and cross-section of the sample and, for a longer sample, this will mean that the increase in length of the sample (measured in real-world units like mm and not in a dimensionless way like strain) will be bigger. Since energy is force x distance, there will be more stored energy. When the sample starts to fail and the cut in the sample grows, due to G being over G_c temporarily, the applied stress will drop because of the lengthening of the sample. The length of the crack, a, has grown, so the stress required to make $G > G_c$ will be reduced and the crack may continue or stop despite the decrease in stress. This lengthening of the sample will be much the same for a long and short sample in mm but as a percentage will be much higher for the short sample, i.e., strain will be reduced much more for the short sample and, therefore, so will stress. Stress is, therefore, rather more likely to decrease below the new σ_c. Alternatively, the same amount of energy will be lost due to the creation of the extra crack length, but because of the much higher stored energy in the longer sample, the energy will decrease by a smaller percentage, force will remain higher and it is much more likely that σ will remain above the recalculated σ_c. If stress is below the critical level, it does not matter how much energy is stored the crack will not grow.

Sometimes controlled failure of the type which can be obtained with a suitable, short sample is described as "sub-critical", but this seems to be misleading because, the stress is certainly repeatedly going over the critical level, although only briefly. There is sometimes discussion of genuine sub-critical failure, which is a creep phenomenon. In the same way that a tensile sample will eventually break under any applied load, a crack will eventually grow under any applied load.

Obviously, another key to whether the crack stops and only starts again when the jaws of the tester separate further, is the amount by which stress overshoots σ_c in the first place. This will be determined by the rate of loading or straining of the test; the slower this is the more likely that the overshoot will be small. Unevenness in the sample, particularly formation, causing differences in strength across the sample, may result in prolonged tears due to stress being locally higher due to the low weight at a point rather than because of high tension. This may lead to some samples in a batch failing catastrophically and having to be ignored.

Sample design can also be used to keep the critical stress at a level which would be in the linear elastic region of a conventional tensile test. In other words, plastic deformation could be minimised by keeping the applied stress below the yield point of the paper.

Seth and Page (2) used samples which were approximately 150 *mm* wide by 50 *mm* long, with an initial cut of approximately 50 *mm* in one side. The rate of straining used was 1 *mm/min*.

The fracture energy (G_c) is estimated as the area under the stress-strain curve after crack propagation begins, until final failure, multiplied by the length over which the crack has propagated and the sample thickness. Fracture Toughness is calculated from equation [2].

The J-Integral Method

The J-integral is defined using a line integral along a path surrounding the crack tip, which sums the stored energy and change of energy due to displacement at each point. The J-integral is used for a variety of materials where a non-linear approach is required. It is defined as:

$$J = \oint_{\tau} \left(W - \underline{T} \frac{\partial \underline{u}}{\partial x} \right) dS \qquad [2]$$

where	W	is the elastic strain energy density,
	$\underline{T}$	is the outward traction vector,
	$\underline{u}$	is the displacement vector,
	x	is the direction of crack propagation,
	τ	is an anti-clockwise contour through the material beginning on the lower crack surface and ending at any point on the upper crack surface. (This is for cracks propagating to the right).

This value can be calculated numerically using special engineering software packages employing finite element methods but this is not routinely used for paper problems. Instead it is the interpretation of the J-Integral as being the energy available for crack propagation which is valuable. If the energy required to initiate crack propagation (*W*) is measured for 2 different initial notch lengths (a_1 and a_2), it is reasonable to suppose that the difference between the two is same as the energy which would have been required to lengthen the notch by the amount of the difference in length (Δa). The energy release rate, or J-Integral, for any given strain is then calculated from:

$$J_c = -\frac{\Delta W}{\Delta a} \qquad [3]$$

where	c	denotes that this is the critical value of the J-integral
	ΔW	is the difference in energy per unit thickness for the onset of crack propagation for the crack lengths a_1 and a_2

The onset of crack propagation can be difficult to determine and often it is taken as the position of maximum sample tension. This method can be tedious because it is necessary to use a number of different notch lengths. J_c approximates to G_c for purely elastic materials.

A variety of other methods exists for estimating J_c using single specimens but these can be considered to be outside the scope of this course.

Essential Work of Fracture

This method requires the total energy which is supplied to break a double-notched sample to be measured. This energy is consumed by rupture at the crack and also by plastic yielding in the zone around the crack. The first element is proportional to the ligament length *L* (the distance between the notches) and the second to L^2 and:

$$W_{tot} = \left(W_e L + \beta W_p L^2 \right) t \qquad [4]$$

where	W_{tot}	is the total energy required to make the tear (*J*),
	W_e	is the essential work of fracture (*J/m²*)
	L	is the ligament length (*m*)
	W_p	is the plastic work of fracture (J/m²)
and	β	is a shape factor for the plastic zone (m^{-1}).

$\frac{W_{tot}}{Lt}$ is measured for several values of L and the results are extrapolated to $L = 0$, giving an estimate of W_e, which has been taken as a direct estimate of fracture energy, which approximates to a material property. t can be replaced by grammage to give specific essential work of fracture. The dimensions of the sample must be designed so that the fracture is stable – see discussion above – and L must be < 1/3 of the width of the sample. Seth (5) gives detailed descriptions of sample designs and experimental techniques. Yuhara and Kortschot (3) showed that essential work of fracture measurements can be similar to results for J_c from the multiple specimens method.

It is frequently stated that a requirement for an essential work of fracture measurement is that the sample should yield completely before fracture or fracture energy will be overestimated. This suggests that the method is more suitable for strong ductile papers (such as those made from chemical softwood pulps) rather than brittle papers (such as mechanical pulp papers) for this reason. Seth (5) suggests that a quasistatic direct method such as that described in (2) should be used for more brittle papers.

Cohesive Crack Modeling

Tryding and Gustafsson (4) have described a way of estimating fracture properties of paper in a way which is related to previous work in the field of concrete. This method allows the use of a relatively narrow sample without notches, although it is still important that failure is controlled. Their method relies on the idea that, once failure has started, the strip can be considered to consist of two parts: the failure zone, which will be getting longer although the load is now falling, and the rest of the sample, which is undamaged and will therefore get shorter as the sample is slowly unloaded during failure. By separating the two, the fracture zone can be characterised in isolation.

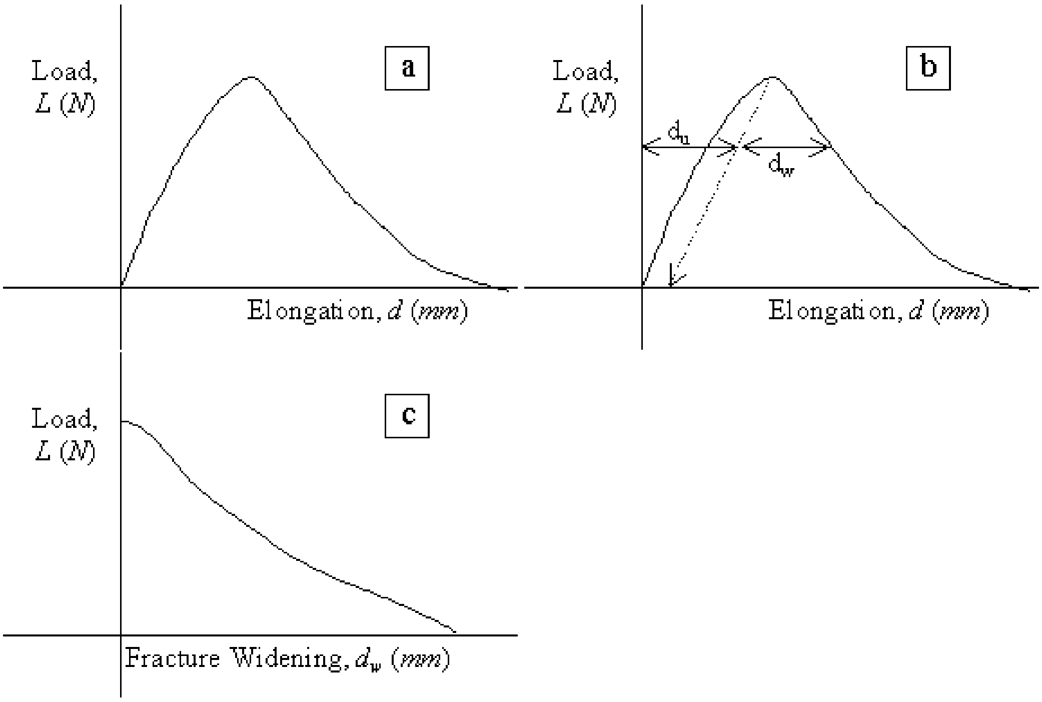

Figure 1 a shows the load / elongation curve for a controlled fracture failure. **b** shows how, after fracture initiation, the elongation can be divided into an unloading part and a fracture widening part. **c** shows fracture widening plotted alone.

The undamaged part of the strip will decrease in length approximately elastically, with the same modulus as the unstrained strip. This means that, as in figure 1b, the unloading is approximately parallel to the steepest part of the loading curve. In practice, the unloading part of the curve will be determined by allowing a sample to unload before failure is initiated. The widening of the damaged part can therefore be calculated as a function of load (figure 1c) and characterises the fracture properties of the paper. Fracture energy, G_f, (J/m^2) can be calculated:

$$G_f = \frac{\int_0^{w_0} L \, dd_w}{bt} \qquad [5]$$

where L is load (N),
d_w is fracture widening (m)
b is sample width (m)

	t	is sample thickness (*m*).
and	w_0	is the widening of the fracture zone which corresponds to complete separation (*m*).

This estimate of fracture energy can be considered to be equivalent to G_c or J_c. The maximum slope of the curve shown in 1c is also thought to be a useful parameter. Note that, instead of dividing by *t*, it is common to divide by grammage to get a property which can be called *specific fracture resistance.*

The test can be performed using a 15 *mm* width strip, using a 5 *mm* test span and a rate of deformation of 0.25 *mm/min.*

Cyclic Loading Method

Batchelor and Wanigaratne (6) achieved a similar result to the cohesive crack modeling approach described above by repeatedly cycling a double-edge notched sample through progressively higher strains until finally reaching failure.

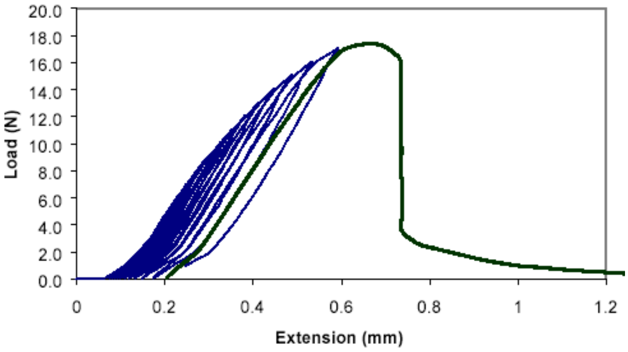

Figure 2 Cyclic loading of a sample. The bold line represents the final cycle when failure occurs (used by permission from reference (6)).

The majority of the plastic work has been done during cycles prior to the last one so that the energy consumed during the final cycle approximates well to the essential work of fracture. Batchelor and Wanigaratne showed an excellent correlation between essential work of fracture and the new measurement for a variety of 12 laboratory papers and 8 commercial machine-made papers. They used a sample width of approximately 15 *mm*, a ligament length of 5.1 *mm*. Sample length is not stated, it can be expected to be shorter than a tensile specimen to minimise stored elastic energy and, although the rate of straining is also not stated, it is likely to be of the order of 1 *mm/min.*

Relationship to Other Properties

Fracture resistance will initially increase with tensile strength, at low levels of refining, but as the paper becomes more brittle it will eventually decrease. The ranking order of different papers by tensile strength and fracture resistance is not likely to be the same.

At high levels of refining, fracture resistance will initially increase with moisture content (6) up to a maximum at around 6 % moisture content, decreasing more slowly at higher moistures. At lower levels of refining, similar but less pronounced behaviour is observed. These observations were made for one chemical pulp but it seems reasonable that similar effects may be seen with other furnishes.

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