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FRACTURE MODES OF SHEET MATERIALS

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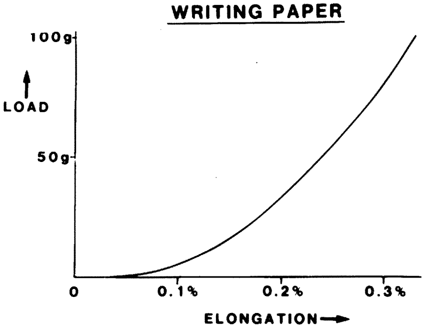
I would like to draw your attention to the fact that the fibres of which paper is made retain their individuality in the sheet, even in dense papers.

In many experiments, conditions are such that the discontinuous structure of paper has little chance to show. This is why the modulus of elasticity, for example, comes out the same whether it is determined by bending, by a sonic method, or by stretching in a tensile tester of standardised inertia. Such experiments assure us that the laws of continuum physics are consistent and that it is still worth reading and studying them. In fact, two of this morning´s papers demonstrated, in essence, that instruments and experimental conditions can be chosen so that even paper, this very discontinuous material, obeys the laws of continuum mechanics: while this is a tribute to the skill of the experimenters it is of very little value in understanding the behaviour of paper in many cases of its use and handling.

When I look from here at the sheets of paper which you have in front of you, I find I cannot distinguish them from sheets of plastic of the same colour. I would have to come closer and use a magnifying glass to see their discrete fibrous structure. Similarly, the discontinuous structure of paper becomes more evident under experimental conditions of magnification and dilution, and under many practical conditions of handling and usage, for example of continuous stationery printing machines.

The case of magnification is shown in the first two illustrations. They simply illustrate the effect of magnifying the elongation scale by a factor of 1,000. The first slide shows the load-elongation curve of a writing paper.

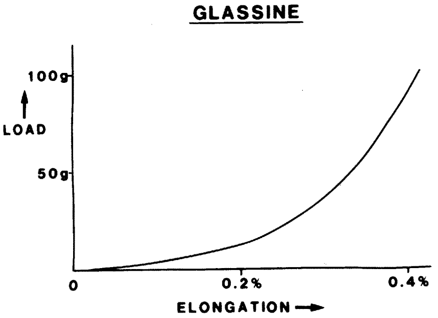


SAMPLE LENGTH 10cm FULL SCALE DEFLECTION 100gm
WIDTH 1.5cm
CROSSHEAD 0.1cm min(1% min rate of elongation)
CHART SPEED 100cm min(i.e.1000x magnification)

Fig 1

I avoid using the phrase stress-strain curve because there is no meaningful definition of stress at all in paper in any direction, tensile or shear. We apply a load which causes a deformation, which we then measure. With large enough magnification, you can see that the curve is convex with respect to the strain axis.

Figure 2, the second slide, illustrates the same curve for glassine, which is a more highly bonded paper.



SAMPLE LENGTH 10cm FULL SCALE DEFLECTION
WIDTH 1.5cm
CROSSHEAD SPEED 0.1cm/min(1%/min rate of elongatio
CHART SPEED 100cm/min(i.e.1000x magnification)

Fig 2

In this case the curve is more pronounced and you can see there has been just over 0.4% elongation at a load of 100 g, instead of the 0.3% of the previous slide.

What is the modulus of elasticity here?

I have yet to see a theory to describe this kind of behaviour, though I have spent several days in a customer's printing shop where it was causing trouble. That was practical paper physics.

So much for magnification.

The case of dilution is illustrated by very fine papers, such as single ply tissue or lens cleaning paper, which both show the fibrous structure of paper very clearly. These papers and the very dense ones, such as glassine, all show a discrete fracture mechanism, proving that the fibres retain their individuality. One of the features of this mechanism is that the failure period is very much longer than the failure-free strain period that precedes it.

Fracture is not an incidental occurrence, as has been suggested this morning, with some nuisance value because it spoils the mathematics of continuum mechanics, but a very important practical event in the life of the paper. And it is also the most direct manifestation of the discontinuous fibrous structure of the material.

So the remainder of this presentation deals with fracture.

Die Kugeln	The Spheres
Christian Morgenstern(1)	
Palmström nimmt Papier aus seinem Schube	Palmström takes some paper from a drawer
Und verteilt es kunstvoll in der Stube	Distributing it artfully around the floor
Und nachdem er Kugeln draus gemacht	And, after he has formed it into tight
Und verteilt es kunstvoll, und zur nacht	Spheres, artfully distributed for the night
Und verteilt die Kugeln so (zur nacht)	He so distributes (for the night) these spheres
dass er, wenn er plötzlich nachts erwacht	that he, when he wakes up suddenly in the night
dass er, wenn er nachts erwacht, die Kugeln	That he, wakening in the dead of night, then fears
knistern hort und ihn ein heimlich Grugeln	Paper crackling and a secret shuddering fright
packt (dass ihn dann nachts heimlich Grugeln	Attacks him (so that in the night terrible fears
packt) beim Spiel der packpapiernen Kugeln	Attack him) being spooked by packing-paper spheres

This `nonsense´ poem, written around the turn of the century, records an observation which no doubt most of us have made. the discrete, statistical manner in which paper relaxes from an imposed strain. If you want to try it tonight in your bedroom, say with the sheets on which this Prepared Discussion Contribution is printed, you may find it effective to screw two sheets together: no marks for guessing why. It is an example of the fact that the response of paper to changes in its physical environment is, like that of many other materials, statistical in nature.

This particular relaxation behaviour is found with several sheet materials, whether they have an inhomogeneous structure such as paper or certain metal foils, or a homogeneous structure such as cellulose film or certain plastic foils. One feature typical of <u>inhomogeneous</u> sheet materials, however, is the response to an increasing tensile load. Such a load leads, of course, to eventual fracture. There are two points to note. The first is that this fracture is a statistical event which progresses in steps of individual fibre or fibre bond failures. The second is that the fracture process starts soon after the application of the load and that, at constant rate of elongation, the fracture period can be fifty or more times as long as the initial failure-free straining period. Such a response pattern would not easily be deduced from an analysis of load-elongation curves obtained under standardised test conditions with instruments of conventional inertia. It is the result of the discontinuous fibrous structure, perhaps more than any other structural feature, which distinguishes paper from other sheet or foil-like materials. It is this fibrous structure which causes the responses of paper to changes of its physical environment to be statistical in nature.

The detection of the statistical nature of tensile failure is based on the sounds which are emitted every time a fibre or fibre bond fails in a sudden jerk: `clicks´, as we call them. A pair of fibre ends is under load and therefore strained prior to fracture. The sudden release on parting causes them to vibrate for a short period of time, and this is audible as a click. You can hear such clicks when you tear a piece of paper `zero span´-fashion between the thumb and forefingures of both hands very slowly close to one ear. The noise made when paper is torn rapidly, is nothing but an `avalanche´ of clicks.

In order to detect and record the statistical response of paper to changes in its physical environment, the rate of elementary events making up the response must be compatible with the resolution of the detecting device. From a distance, a sheet of paper hanging on the wall cannot be distinguished from a sheet of plastic of the same colour, but a simple inspection with a magnifying glass is sufficient to reveal the difference between the two. As for tensile failure, under conventional test conditions, there is no qualitative difference between the failure of a sample of plastic film and a sample of paper. Nor does a cine recording show a difference: on one frame the sample is still in one piece, on the next it is broken. (The fracture loads and strains can, of course, be very different.) To improve the resolution means to reduce the rate of individual fibre or bond failures to a level low enough for detection and recording. This can be done either by using very thin samples or by applying very low rates of strain, or both.

Those of you who have been around long enough may remember that, at the Oxford symposium 1961, twenty years ago almost to the day (26th September), a sound film(2) was shown of the fracture of very thin paper with a basis weight of $2.5 g/m^2$. Figure 3 shows a section of it. The purpose at that time was to estimate the number of fibre bond failures necessary to cause the separation of the sample into two parts. This was achieved by applying the theory of extremes to the statistical geometry of these very thin ("2-D") sheets(3). The agreement with values observed experimentally was quite reasonable: the prediction was within 14% of the observation.

In 1967, C.T.J. Dodson, as part of his Ph.D. thesis at Brunel University, investigated the failure <u>rate</u>, i.e. the number of bond failures per unit time at constant rate of elongation, for thin sheets. This investigation was stimulated by the observation that a typical sequence starts very slowly, with bond

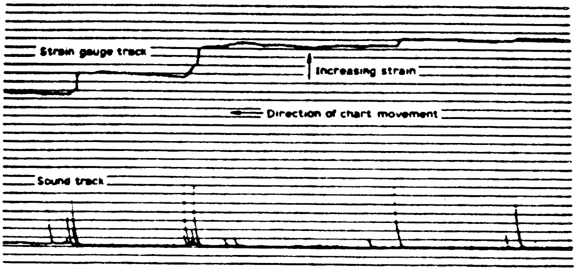


Fig 3—Fracture of thin paper

failures occurring irregularly over the sample area. The failure rate then increases as one area of the sample emerges as the weakest and failures occur only there with increasing rapidity. The end of the process is a very long tail of isolated failures which continues long after the sample appears to have broken, until the last pair of fibres has parted. Usually, the first accelerated failure rate (or `avalanche′) is followed by a second, and even third, smaller, avalanche, separated from each other by periods of low failure rates. Dodson based his analysis on partitioning the total energy input, i.e., the area under the load-elongation curve, into the elastically stored strain energy and the irreversibly expended bond failure energy. For an experimental verification of the model, a recording tensile tester was fitted with an integrator which produced a continuous record of the total energy input as the sample was extended at a constant rate. This was fed into an analogue computer programmed with the energy partitioning function. The computer in turn drove an x-y plotter to obtain the bond failure energy as a function of the time. This computed bond failure function was compared with the record of bond failures made by the tensile tester.

Figure 4 shows such a comparison.

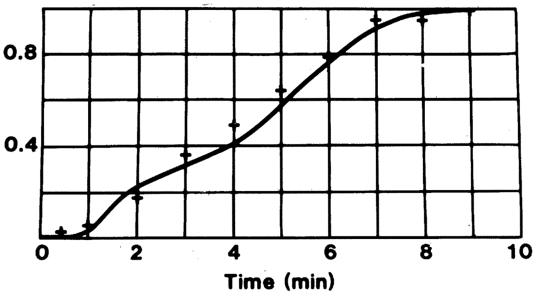


Fig 4—Experimental failure rate (+) and spent fracture energy (—) for thin paper.

The agreement is remarkably good to the point that even the slowing-down and subsequent acceleration of the failure rate is seen on both records. This effect was soon recognised to result from the co-operative failure of many neighbouring bonds in quick succession, after which the sample relaxed and required an extended period of strain with little happening before the failure rate accelerated again (macro-relaxation). The fracture record was found to be independent of the rate of strain from 5% per minute to 100% per minute. It means that the conversion and re-distribution of strain energy is so fast that it causes no detectable micro-relaxation effects in this range of straining rates.

The sound recording equipment described in ref.(3) was used to record the fracture sounds of a number of commercial papers. The samples were typically 30 x 10 mm in size and the rate of elongation was typically 0.85 mm/min, i.e. 2.8% per minute. Two observations made quite generally were the following:

1. The fractures occurred in sequences of audible failure sounds (clicks) very similar to those of thin sheets. This mode of fracture is therefore typical of any and not just of very thin paper.

2. More often than not, the failure sequence, after a slow and tentative start, reaches an avalanche-like intensity followed, after periods of relative calm, by (usually smaller) second and third avalanches.

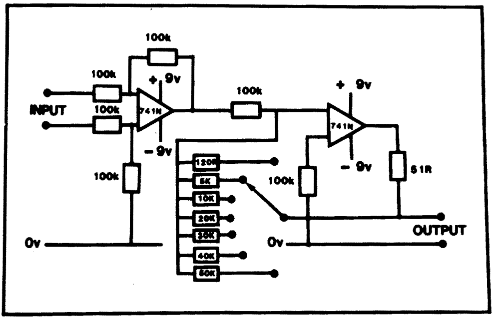


Fig 5—Differential input signal amplifier.

Whilst the sound recordings were quite clear and very convincing, they were not good enough, because of considerable background hum, for making permanent records in the form of oscillograms which could be used for quantitative evaluation. Work on this equipment therefore discontinued until December 1980 when David McLaren Raeside used modern discriminating and filtering equipment to produce `clean´ (i.e. background-free) recordings. Figure 5 shows the circuit diagram.

This was done in preparation for an M.Phil. thesis at Brunel University on relating fracture modes of paper (and other sheet materials) quantitatively to their structures. The work had hardly begun after designing and building the equipment when, tragically, David died in a road accident on 3rd May 1981.

The following six figures are extracts from the film shown. The sample size is 30 x 10 mm everywhere and the rate of elongation is always 0.85 mm/min. In Figures 6 - 9, the acoustic gain on recording as well as the oscilloscope amplification and time base are the same. in Figures 10 and 11 they vary as indicated.

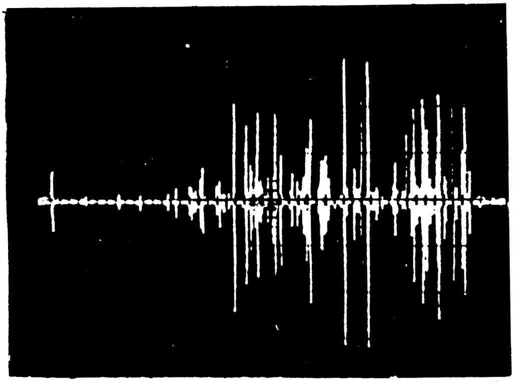


Fig 6—The first 25 seconds of the straining of writing paper, 80 g/m^2. There is a 7–8 second build-up of strain energy with a few isolated failures of weak bonds (low amplitude) before the main failure avalanche sets in, extending over about 15 seconds. This is followed by irregular shorter failure clusters and finally isolated failures. The entire fracture process extends over 2½ minutes, compared with 5–6 minutes and about 200 bond failures for 2.5 g/m^2 samples as shown in (3).

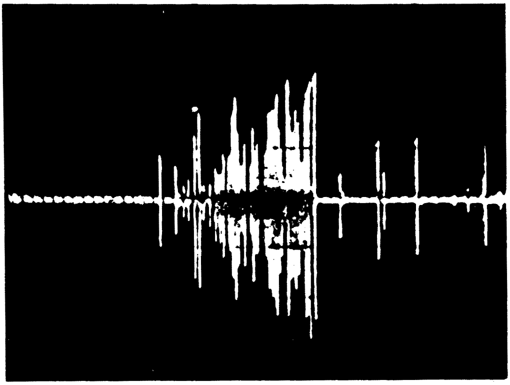


Fig 7—The first 25 seconds of the straining of glassine, 40 g/m^2. Again there is an initial straining period which, unlike the previous recording, is free of failures. The structure is denser with fewer 'loose ends', the load builds up to a higher level, and the release through bond or fibre failures is more erruptive (i.e. the failure rate is higher) and shorter. Note the increase of the amplitude during the first avalanche, which is very clearly audible, in contrast to Figure 4. The last pulse on the right is the beginning of a second, smaller avalanche, and a third begins 48 seconds after the start. The fracture period lasts 92 seconds.

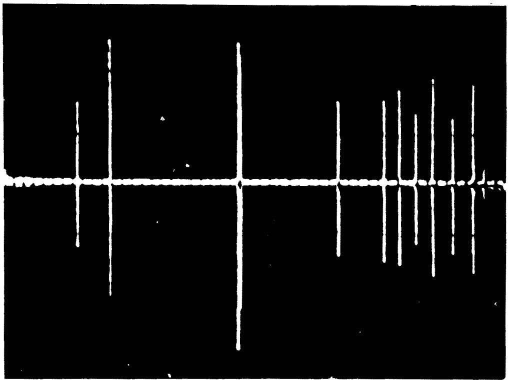


Fig 8—25 seconds of the straining of 9μ aluminium foil. The parting of crystallites is equivalent to the parting or fracture of fibres in paper. There is an initial period of weak bond failures (low amplitudes) but there is no pronounced avalanche anywhere. Aluminium foil cannot store elastic strain energy to an extent similar to paper. Bond failures occur virtually at random over the total fracture period of 2½ minutes.

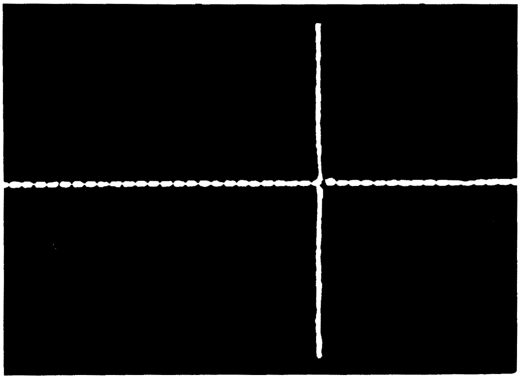


Fig 9—The straining and fracture of cellulose film, 34 g/m^2. Time base 25 sec. The capacity for storing elastic strain energy is greater than that of paper. The failure-free period is twice as long as in Figures 4 and 5, but the release occurs in a single fracture. This fracture mode is typical of a 'homogeneous' material, that is one with inhomogeneities on a scale well below that of structural elements which can vibrate in air with audible frequencies.

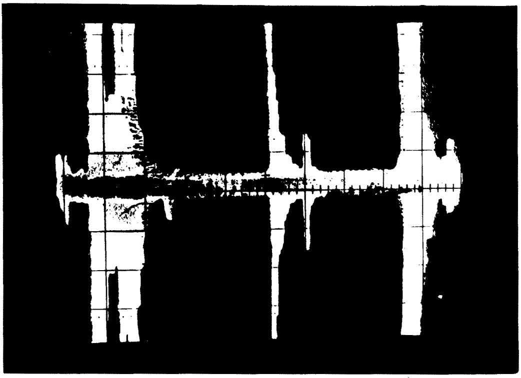


Fig 10—Two seconds of the straining of a heavily latex-impregnated paper, 180 g/m^2. Latex bond failures produce reverberating sounds, rather like muted strings. The fracture noises of this very strong material are much louder than those of ordinary paper. The recordings fill the height of the screen although the oscilloscope amplification was reduced. The time base was also reduced in order to enhance the appearance of reverberation. The two peaks in the centre with almost no reverberation are probably due to fibre or fibre bond failures, but this would have to be confirmed by frequency analysis. Similar failure pulses dominate the beginning and the end of the fracture period.

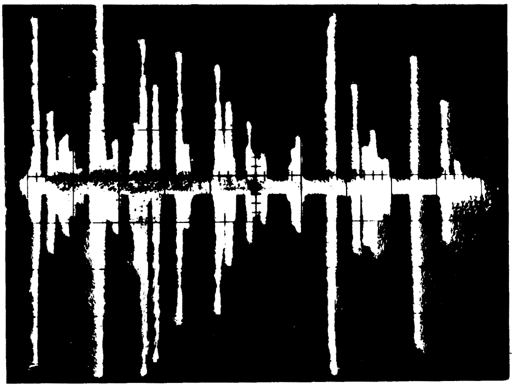


Fig 11—The first 25 seconds of the straining of foam-laid paper, 45 g/m^2. The relatively uniform structure of this material results in clusters of bond failures with almost equidistant spacing, rather like the periodic 'landslides' (or 'catastrophes) when digging a tunnel through a sand heap on the beach, representing a uniform grain structure. The sound level is fairly high (oscilloscope amplification much reduced), probably because the structural elements are bundles of fibres rather than individual fibres. There is no initial fracture-free straining period.

These then are some of the recordings which D.M. Raeside left behind. They show clearly that there is a relationship between the structure of a sheet material and its mode of fracture as detected by sound emission. Recordings like these can therefore be regarded as fingerprints typical of each structure. The quantitative treatment is still outstanding. Such a treatment may well have to abandon or considerably modify conventional continuum concepts. It may have to accept the fact that paper has a discontinuous structure and consists, in its simplest form, of fibres or bits of fibres between bonds, called free fibre lengths, and gaps between them. Two potentially useful mathematical tools were referred to earlier. One is the theory of extremes to deal with countable weakest-line failures(3), the other is Dodson's device of transforming the x-y co-ordinates of a sheet of paper to g-θ co-ordinates, where g is the free fibre length, having a negative-exponential distribution, and θ its angle with a fixed direction, having a uniform distribution.* (Note that thin paper is obviously discontinuous in real (x-y) space but a continuum in g-θ space(4). Whether this device can be modified to suit heavier and denser paper remains to be seen.)

Some of the relationships between structure and fracture mode are already discernible, for example a progressive shortening and intensification of the fracture period with increasing density of the paper, or a tendency towards regular pulsations during the fracture period with increasing small-scale uniformity. To relate the fracture mode quantitatively to such structural or structure-determining variables as basis weight, density, DMD, fibre length and weight per unit length, etc., will be a considerable challenge. It will also be highly rewarding because, since sound emissions start well before mechanical damage is visible, any advance will be applicable to the pre-rupture deformation behaviour of paper and other inhomogeneous sheet materials.

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* These distributions apply to random paper or (nearly enough) to laboratory handsheets. For machine-made papers, the two distributions are structural parameters which have to be determined independently.