A note on the mechanism of tearing strength

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ABSTRACT: For sheets bonded beyond the point of maximum tearing strength, tearing energy is proportional to the square of fiber strength. This suggests that the energy of tear derives primarily from the release of energy when fibers fail, rather than when bonds break or fibers pull out. This contradicts the conventional theory of tear and a new explanation of tearing strength is proposed.

KEYWORDS: Energy, fiber bonding, strength, tear strength, tensile strength, zero span tensile.

It has been known for at least half a century that the Elmendorf tearing strength of paper made from softwood chemical pulps first increases with degree of bonding, passes through a maximum, and then declines. Tear strength is greater the higher the fiber length and fiber strength.

The currently accepted explanation of these phenomena was formulated by Van den Akker almost 50 years ago and published in "Instrumentation Studies XLVI" *(1)*. In his pioneering effort, Van den Akker proposed that the work of tear was consumed by two processes: (a) stretching individual fibers until they break in tensile failure, and (b) pulling individual fibers out of the network against frictional forces. He hypothesized that the work of fiber failure was small compared with the work of fiber pull-out, since the frictional forces act successively along the entire length of each fiber as it is withdrawn from the sheet.

He thus explained the effects of bonding, fiber length, and fiber strength in the following way: Initially in a lightly bonded sheet, the work of pull-out is low, so that tear strength is low. Thus tear strength first rises with bonding degree but passes through a maximum as the proportion of fibers that are broken increases. Because the energy of pull-out far exceeds the energy of fiber failure, the tearing strength drops as bonding is increased further and as more fibers fail rather than pull out. Sheets of higher fiber length have a higher tear strength because of increased work of fiber pull-out. Similarly sheets of higher fiber strength have a higher tear strength because more work can be done as more fibers are pulled out and not broken.

The only modification to this explanation was proposed in 1969 when Ivanov and Leshchenko *(2)* suggested that the work of fiber pull-out should not be regarded as frictional, but rather should be associated with the energy of breakage of fiber–fiber bonds. Shallhorn and Karnis *(3)* provided a mathematical theory based on these concepts.

It is important to recognize that, since the formulation of this explanation, there have been no experiments that either unequivocally support or refute the central hypothesis. It is not known by independent evidence that the energy of pulling out fibers is much greater than the energy released by fiber failure. This is unfortunate, since what was originally presented as a tentative model has become, by default, accepted.

Certain evidence obtained since Van den Akker's paper casts doubt on this mechanism of tear. For example, it was shown by Helle *(4)* that during tearing failure of a well-bonded sheet, 90% of the fibers crossing the rupture line failed. It seems somewhat perverse to ascribe the failure energy of the sheet to the 10% of fibers that pull out rather than the 90% that fail.

Furthermore, we now know that the energy of failure of individual fibers is certainly not too small to account for a substantial part of the tearing energy consumed. The zero-span tensile strength of a well-bonded kraft sheet is about 220 N·m/g, the load to break all the fibers crossing

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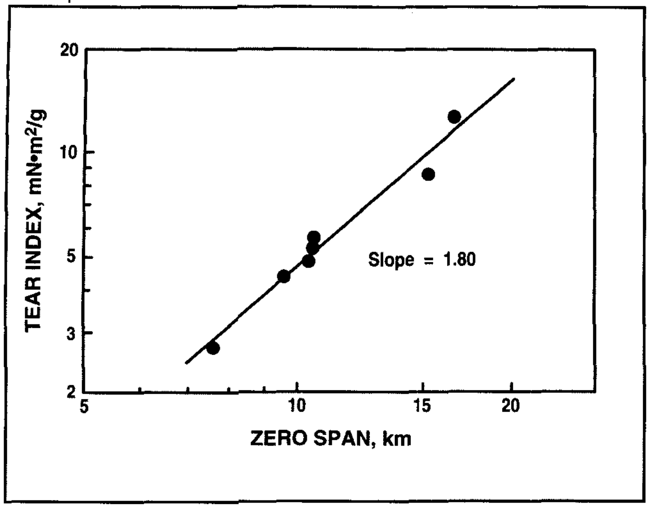
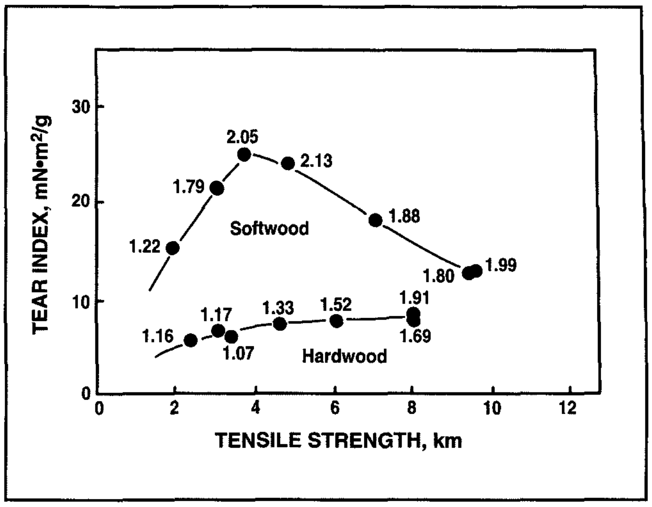
1. Plot of logarithm of tear index against logarithm of zero-span strength, for a 40 min. Valley beaten, dried, bleached softwood kraft pulp. The strengths are changed by vapor-phase acid hydrolysis. The plot shows that tear index is proportional to zero-span strength raised to the power 1.80.



2. Plot of tear index against breaking length for a dried bleached softwood kraft and a dried bleached hardwood kraft, Valley beaten. The numbers beside the points indicate the power of the relationship between tear index and zero-span strength for each beating degree.



the rupture line is at least 8/3 of this value *(5)* and could be appreciably more since not all fibers break at the same extension *(6)*. The stretch-to-break of fibers of low fibril angle is around 5% *(7)*. If we assume that the span along the fiber length over which the load is transmitted during tear failure is of the order of 1.5 mm, then the energy to break all the fibers in the sheet across the rupture line is:

$$(1/2)(8/3) \times 220 \times (1.5 \times 5/100) \text{ mNm}^2/\text{g}$$

$$\text{or } 22.0 \text{ mNm}^2/\text{g} \qquad (1)$$

It is proposed that this energy may be equated to the tearing energy, although it must be halved since the force in the conventional tear test is exerted over twice the length of the torn distance.

The resulting value of 11.0 mNm²/g for the tearing energy is certainly of the same magnitude as the tearing energy of a well-bonded sheet.

The purpose of this note is to review recent experiments that suggest that the energy of tear failure derives principally from the energy released when fibers fail, rather than when fibers pull out.

The effect of fiber strength

In a recent publication, Seth and Page *(8)* described the results of experiments designed to determine the effect of fiber strength on tearing strength. This was accomplished by vapor-phase hydrolysis of handsheets, which reduced fiber strength without affecting other properties, such as elastic modulus, scattering coefficient, density, or ply-bond strength or shear strength of the fiber–fiber bond *(8)*. They found that, for a softwood kraft pulp, a hardwood kraft pulp, and a TMP, tear strength depended on fiber strength as measured by zero span strength according to a power that depended on the degree of bonding. The power was low for lightly bonded sheets but was about two for well-bonded sheets. It was noted that a power of two would be expected if the work of tear arose from fiber failure, since the work of failure of any elastic material of constant elastic modulus is proportional to the square of its strength.

This work has now been extended to examine the effect of fiber strength on tear strength over the entire range of beating for another softwood and a hardwood bleached kraft pulp. The techniques used to change fiber strength were described earlier *(8)*.

Plots of the logarithm of tear strength against the logarithm of zero-span strength were obtained for various degrees of hydrolysis, as described earlier and illustrated in **Fig. 1**. The slopes were determined from least squares fits, and had an average standard error of 0.1.

The plot of **Fig. 2** shows tensile and tear values for a Valley beating run, together with, for each bonding level, the values of the power n of the relationship:

$$\textit{Tear strength} = k\ (\textit{zero-span strength})^n$$

For the softwood pulp, the power increases with bonding and when the tear strength reaches a maximum the power is not significantly different from two. It remains at two as bonding is increased further. For the hardwood pulp, the power is lower and increases gradually as bonding is increased. The power of two is not approached until the sheet is highly bonded, and the maximum in tear is reached.

A new mechanism of tearing strength

These results suggest a new mechanism for tearing strength. They suggest that the energy released when fibers fail is a much greater part of tearing energy than has been thought. Below the maximum tear strength, energy is consumed both by the release of energy upon fiber failure, and by some other cause, presumably the release of energy when fiber–fiber bonds fail. For sheets bonded beyond the maximum of tear strength, the proportionality of tear strength to the square of fiber strength suggests that the release of energy upon fiber failure accounts for a large part of the work of tear. This is not to say that the energy dissipated is stored solely in the fiber that fails, but rather in it, and a *zone surrounding* the fiber. Upon fiber failure, it is this stored energy that is released and lost to the system. According to this model, the drop in tear with increasing bonding arises from the smaller fiber span and smaller rupture zone within which the strain energy of fiber failure is released in well-bonded sheets. This seems to be borne out from the well-known observation of the reduction in size of the rupture zone with increased bonding. Similarly the increase of tear with increasing fiber length would be considered to arise from an increase in the size of the rupture zone with increasing fiber length.

The explanation given here is put forward tentatively, but it seems to explain the main features of the evidence. It is hoped that it may form the basis for further work on the tear mechanism.

Conclusion

The currently accepted mechanism of tearing strength is in question. The energy consumed when fibers are strained to failure seems to play a much larger role than has hitherto been suggested. A new model of the tear mechanism has been tentatively proposed.

Experimental

Handsheets were prepared and properties measured according to CPPA standard methods. Tear strength was measured using the 4-ply Elmendorf test. TJ

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