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MAJOR FACTORS GOVERNING NEWSPRINT STRENGTH

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Synopsis Tensile test failure lines across 15 mm wide strips of uncalendered newsprint were found to pass largely through areas of below average grammage. The breakline in commercially calendered newsprint passed largely through areas of above average grammage. At intermediate degrees of calendering both higher and lower than average grammages were involved. Tensile tests of 0·5 mm wide calendered newsprint samples also showed an inverse relationship between strength and grammage. The number of sulphite fibres and their angles to the machine-direction of the paper (the straining direction) were also shown to influence tensile strength.

Introduction

IN RECENT years, a number of theories have appeared that endeavour to explain the tensile behaviour of paper in terms of structural and bonding considerations of fibre networks.[1, 2] The latest work by Page[3] and Kallmes[4, 5] linking paper strength to paper structure concludes that paper weakness is associated with below average grammage, lesser bonded area and weaker bonds.[6] This has been confirmed by Lyne,[7] who showed that the tear line on newsprint handsheets takes the path of least resistance by passing around the high grammage flocs. In addition, a more detailed confirmation has been obtained by Tydeman.[8] He showed that the tensile breakline passed through the low grammage regions of kraft paper.

Our work on uncalendered newsprint has confirmed the association of tensile failure with linked areas of below average grammages. Additionally, it has shown that in standard, commercially calendered newsprint, tensile failure is largely associated with linked areas of above average grammage.

Under the chairmanship of Dr H. Corte

Part 1—The influence of calendering upon the strength of newsprint and upon the micro grammage distribution of its line of tensile rupture

Method

TEN tensile strips per newsprint sample studied were laid alongside calibrating samples of newsprint of different grammages and a contact X-ray photograph was taken. The tensile strips were ruptured and the location of the breakline on the X-ray film determined.

An optical densitometer with an aperture of 0·3 mm diameter was used to examine the local optical transmittance of the X-ray negatives—

1. At randomly selected spots over the whole of the tensile strip.
2. Along the break-line.

Results

The salient features of the results obtained are shown in Fig. 1 and 2, where the abscissa has a probability scale.

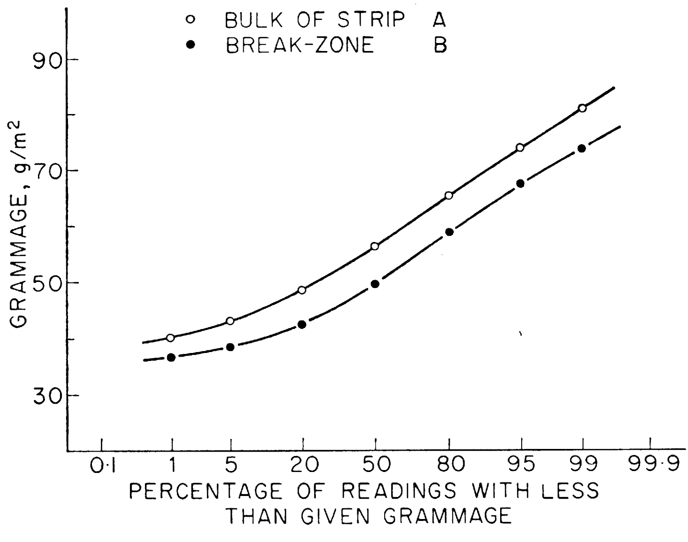

Fig. 1—Grammage frequency distribution of 0·3 mm diameter microspots in uncalendered newsprint and along its line of tensile failure

Curve A of Fig. 1 shows the frequency distribution of grammages of 0·3 mm diameter spots randomly located over the area of a sample of uncalendered newsprint. Curve B shows the like distribution as measured along the lines of tensile failure. Clearly, the break-line has passed through a higher than average proportion of the lower grammage spots. The median grammages are—for all the paper, 56·5 g/m²; along the break-line, 50 g/m². These results are in agreement with those of Lyne *et al.*[7] and Tydeman & Hiron.[8]

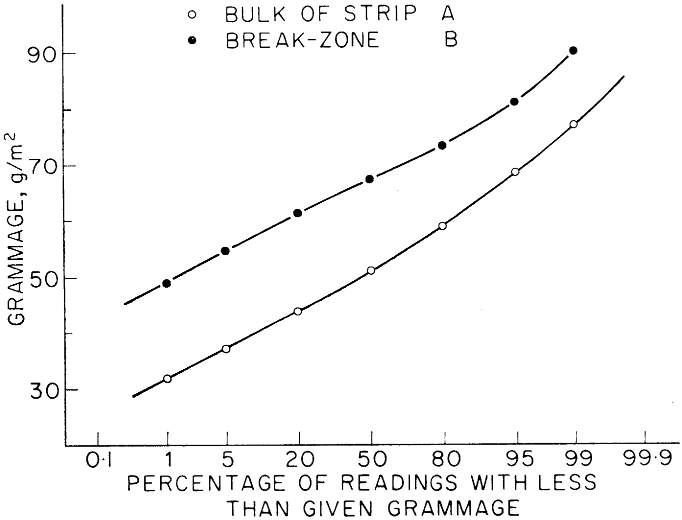

Fig. 2—Grammage frequency distribution of 0·3 mm diameter microspots in commercial newsprint and along its line of tensile failure

Fig. 2 shows like data obtained on testing commercially calendered newsprint from a different papermachine. Curve A again showing the grammage distribution of random spots now lies well below curve B—the grammage distribution along the tensile failure lines.

The median grammages are now—for all paper, 51·1 g/m²; along the break-line, 67·4 g/m². These results do not agree with the previous references.[7, 8] Calendering has apparently introduced another factor into the relationship between local grammage and tensile failure.

Macmillan,[9] Wultsch[10] and Howe [11] have shown that strength is lost on calendering newsprint. Table 1 gives breaking length and grammage data for the samples represented in Fig. 1 and 2. The calendered paper (sample 2) has a breaking length of only 75 per cent of that of the uncalendered paper (sample 1).

The same uncalendered newsprint represented in Fig. 1 was laboratory calendered at low speed. Fig. 3 shows random spot and tensile break-line distributions of grammage on this uncalendered newsprint after laboratory calendering. Again, curve A is the grammage distribution for the bulk of the paper and curve B along the break-line. The gentler laboratory calendering has produced a relationship between curves A and B that is intermediate between those of the uncalendered paper of Fig. 1 and the commercially calendered paper of Fig. 2. Average tensile strength of this paper (sample 3, Table 1) is also intermediate.

TABLE 1—SUMMARY OF AVERAGE MEASUREMENTS

The effect of various degrees of calendering on the average breaking length, grammage and grammage in the break-line for normal (100 mm × 15 mm) tensile test samples of newsprint

Calendering conditions	*Tensile strips*				*Randombreak-line grammage, g/m²*
	Caliper ×10³, cm	*Breaking length, km*	*Grammage Break-line, g/m²*	*Grammage Random, g/m²*	
Uncalendered	14·73	5·80	51·80	57·50	+5·70
Industrial (heavy) drastic	8·13	4·32	67·62	51·40	−16·22
Laboratory (light) gentle	8·13	5·46	53·12	55·72	+2·60

Discussion

The shift in mode of tensile failure from a course largely through low grammage spots to one through an increased proportion of high grammage spots, appears to be associated with calendering. Fig. 4 shows the tensile strength of a newsprint paper after various degrees of calendering as a function of the smallest calender roll nip clearance to which it was subjected. A single lot of uncalendered paper was laboratory calendered under a wide variety of combinations of calender roll temperature (23–135° C), paper moisture (6–11 per cent), nip pressures (0–1 000 N/cm) and number of passes (1–20) through the calender nip. The calendered papers were tested for machine-direction tensile strength. Each data point in Fig. 4 represents the average tensile strength of all samples that in calendering were subjected to minimum clearances within ±0·00125 cm of the indicated values.

The original data indicated that the curve shown was unique in that none of the variables of moisture, number of passes through the nip, graduation of nip pressure in successive nippings or temperature had any effect on the relationship between tensile strength and the minimum nip clearance to which the paper had been exposed.

Obviously, calendering damages newsprint strength. The damage is directly related to the least thickness to which the paper is compressed at any nip in the calendering. Furthermore, for a desired final caliper after calendering, a judicious choice of the processing parameters will reduce the springback of the sheet, hence increase the minimum in-nip thickness and reduce the damage experienced.

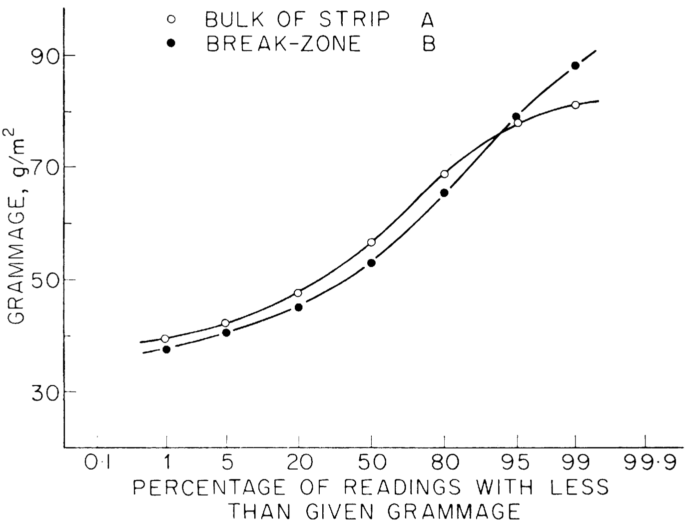

Fig. 3—Grammage frequency distribution of 0·3 mm diameter microspots in laboratory calendered newsprint and along its line of tensile failure

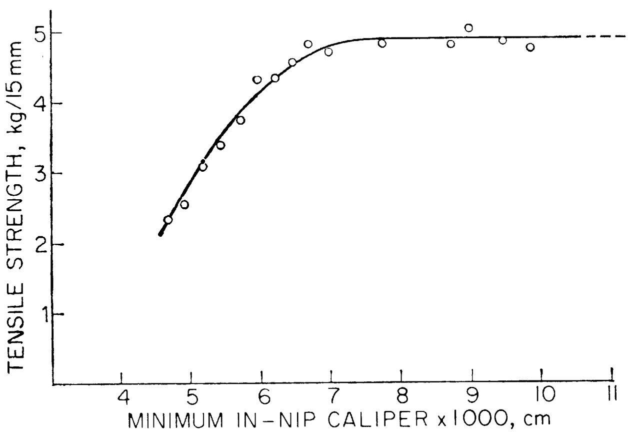

Fig. 4—The effect of the minimum nip clearance during laboratory calendering upon newsprint average tensile strength

The newsprint whose grammage distribution is represented in Fig. 2 had an average grammage of 51 g/m². The highest grammage microspot found in it was 96 g/m². The effect of passing areas of 51 and 96 g/m² through a nip of fixed clearance must be quite different. At a minimum nip clearance of 0·0056 cm (such as might be expected on a commercial newsprint calender), these two areas would have densities of 0·92 and 1·72 g/cm^3, respectively. Since the latter figure substantially exceeds the densities of both solid wood substance (about 1·55 g/cm^3) and cellulose (about 1·65 g/cm^3), fibres in such areas must obviously have been crushed and must have flowed laterally in such degree as to limit the density to something below one or other of the above values. Such action must seriously weaken both the fibres within the heavy microspots and the adjacent sheet structure. It seems entirely reasonable, in the light of the data, to expect that the strength of microspots of above average grammage will be reduced in some proportion to their excess weight and may, indeed, be brought to zero strength at or above some critical value.

It may be remarked that the demonstrated weakening effect of shives(12, 13) is probably largely, if not entirely, due to the fact that they constitute a linked series of very high grammage microspots subject to the weakening effect of calendering crushing as here described. In further confirmation, Macmillan(9) has shown that shives in uncalendered newsprint can have a minor reinforcing effect.

Tydeman's paper and this are alike in assigning the location of tensile rupture lines to the presence of a linked series of weak spots constituting, together, the weakest section across the sample. In Tydeman's samples, these spots were weak because of low grammage; in ours, they were weak because of crushing damage resulting from above average grammage. In both instances, it was possible to select, on Tydeman's contact negatives and on our X-ray plates, several linked series of areas along one of which breaking could be expected and along one of which breaking did occur.

Part 2—The effect of grammage and fibre orientation upon the tensile strength of newsprint

Introduction

THE work in Part 1 suggests that a strip of paper may, in rough analogy, be viewed as a set of parallel chains, each containing links having a wide range of strength values. Simultaneous rupture of the parallel sets of chains does not occur by the breaking of the weakest link in each of the chains, but rather by the breaking in each chain of a link of minimum—or more than minimum—strength that happens to be located close to similar weak links in adjacent chains.

Part 2 of this paper deals with tensile tests done on machine-direction strips 0·5 mm wide in the cross-direction. The narrow width was used to limit the number of hypothetical 'chains' across the width of the sample to permit the clarification of the individual effects of the measured parameters.

Method

From a sample of newsprint that had been previously offset printed with 100 gauge lines per inch running in the cross-direction, machine-direction strips approximately 25 mm long and 0·5 mm wide were cut and tested for tensile strength. After rupture, the broken ends were examined under a microscope and a piece of about 0·5 mm long was cut from each broken end.

The original length of this break-zone sample was measured using a microscope micrometer and the printed gauge lines. The width was also measured by micrometer and the combined weight of the two break-zone pieces was determined by microbalance. The pieces were selectively stained and examined under a microscope to establish the number of sulphite fibres running across each break together with the angle of each to the machine-direction.

A 1 mm long piece was also cut, at a randomly chosen location, from each sample. These pieces were subjected to the same examination as the break-zone samples.

Analysis of the data from this test suggested that the number of crossings of sulphite fibres over one another (here called crossovers) could be an important factor in the tensile strength variation among samples. Because the crossovers could not be measured, reconstructions of the sulphite fibre networks were undertaken using random number techniques. An area 10 cm $\times$ 5 cm corresponding to the 1 mm long by 0·5 mm wide sample was drawn on graph paper and the X and Y axes were divided into one hundred divisions numbered 0–99. For each sulphite fibre in the sample, random numbers between 0 and 9 were taken five at a time. The first two numbers gave the Y position; the second two the X position; the fifth determined whether the fibre angle running through the XY position was clockwise (if even) or anti-clockwise (if odd) to the machine-direction. The simulated fibre was drawn in through the XY position at the angle actually measured for the test strip being simulated and of such length as to intersect two boundaries of the 10 cm $\times$ 5 cm area. For each break-zone sample, three such reconstructions were made. The simulated average number of crossovers, average crossovers per sulphite fibre, average total length of sulphite fibres and average fibre length were established.

Observations and results

The raw data are collected in appendix 1.

Fig. 5 shows the frequency distribution of the number of sulphite fibres in the random and break-zone samples. All corresponding percentiles of the break-zone samples have approximately 20 per cent less sulphite fibres than the random samples. Given the well-established fact that sulphite pulp

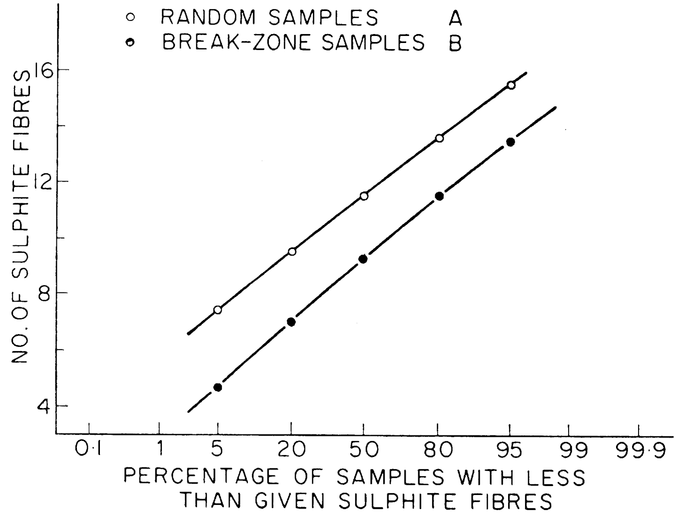

Fig. 5—The frequency distribution of sulphite fibres found in 0·5 mm^2 samples of commercial newsprint taken at random and at the location of tensile failure

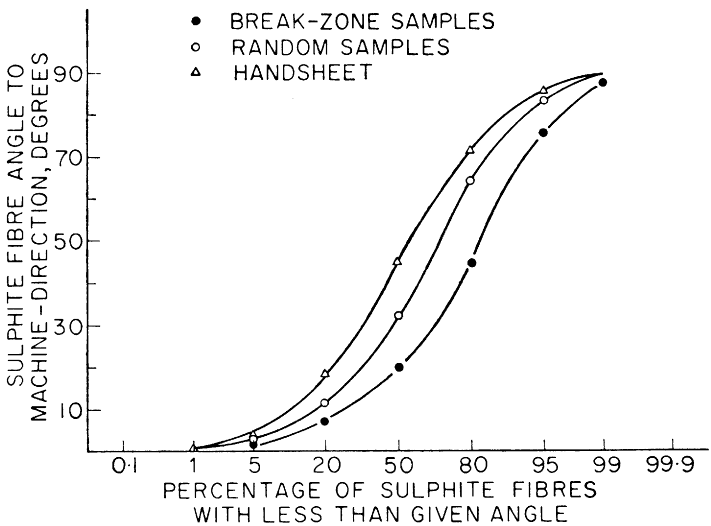

Fig. 6—The frequency distribution of the angle to the machine-direction of sulphite fibres found in 0·5 mm^2 samples of commercial newsprint taken at random and at the location of tensile failure

addition fortifies newsprint, this difference is no doubt one of the factors in the location of the break.

Fig. 6 is the plot of the distribution of angles of sulphite fibres for the break-zone and the random samples, together with the expected (fully random) distribution for a handsheet. The random samples group contains about 25 per cent more sulphite fibres than the break-zone sample group. Both groups contain roughly the same number and distribution of fibres over the range 0°–30° to the machine-direction. The remaining sulphite fibres of the random sample group are distributed fairly evenly over the 30°–90° range. In contrast, the frequency of the break-zone sample group sulphite fibres falls steadily in the 30°–90° range.

Fig. 6, surprisingly, shows that the sulphite fibres have a higher component of machine-direction orientation among the break-zone samples than for the random samples. Generally, fibre orientation increases the newsprint strength in the direction of the orientation at the expense of the strength in a direction normal to the orientation. Were all the fibres machine-direction oriented, there would be no fibre crossings, hence little interfibre bonding and strength. It would appear reasonable, therefore, to hypothesise that the strength of newsprint is governed by both the degree of fibre orientation and the extent of the fibre angular dispersion. We believe that this is the explanation for the apparent paradox of Fig. 6, in which the frequency distribution line of the random samples lies between the lines for the handsheet and the break-zone samples, instead of to their right as might reasonably be expected.

Fig. 7 shows the plot of the grammage distributions of the break-zone and the random groups, neither of which are normal. Each of the 43 strips tested contains 25 portions each 1 mm long, one of which is the break-zone. Thus, the 43 break-zone samples are drawn from a population of 1 075 such pieces. Here, the break-zone sample is shown to be more likely to be of higher or lower grammage than the population.

By comparison, in Fig. 2, each of the ten tensile strips used comprise $(100\times 15)\div(0{\cdot}3)^2 \simeq 19\,000$ independent, 0·3 mm diameter locations. Thus, the 200 break-zone grammage samples are drawn from a population of 190 000 independent, available locations. In this instance, the grammage distribution of the break-line samples follows a distinctly higher grammage distribution path than the population from which it was drawn. Again neither of these distributions is normal.

There is no contradiction between these two results, merely a confirmation of and an extension to our thesis that the tensile break-line of newsprint is the result of the chance occurrence of a succession of weak spots created by the action of calendering upon the points of highest local grammage.

In part 1, we demonstrated the importance of the calender damage at the

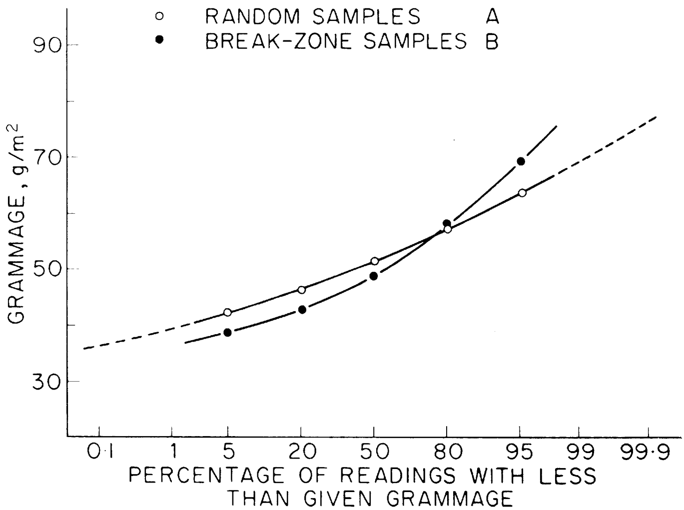

Fig. 7—The frequency distribution of grammage found in 0·5 mm² samples of commercial newsprint taken at random and at the location of tensile failure

highest grammage points in newsprint with respect to the location of the break-line. In this section, we demonstrate that the fibre orientation is also a relevant factor associated with the break-line location. In part 3, we shall demonstrate that averaging permits the elimination of the effects associated with the local variation of fibre orientation. Clearly, local newsprint strength is governed very largely by local grammage and the degree of local interfibre bonding; provided sufficient readings are taken, the latter factor may be ignored.

Our thesis demands that the grammage range of the break-zone samples stretches roughly from the highest value found in the population to some lower value. In Fig. 2 and 7, the highest grammages in the populations are 96 and 77 g/m², respectively; whereas the highest grammages in the break-zones are 96 and 75 g/m², respectively. For Fig. 2, there are 20 grammage measurements associated with a break-line and it is reasonable to ignore the local variation in fibre orientation. Furthermore, in each tensile strip, the number of independent sections that could be viewed as a break-line path is 333 (that is, the number of separate 0·3 mm diameter spots that could be fitted into the 100 mm long strip).

Now, if the lowest grammage found in the break-line is exceeded by a fraction X of the population, this lower limit value is defined by the equation—

$$X^{20} = (333)^{-1}$$

and equals 45 g/m². This figure compares very favourably with the 47 g/m² actually found. For Fig. 7, the situation is somewhat different: 1 075 locations are assumed to be divided at random into 43 strips, each comprising 25 locations, one of which is the break-zone of that strip. If the fibre orientation effect could be ignored, the break would occur at the highest grammage zone in each strip; hence, the most probable estimate of the lowest of these would approximate to the lowest grammage value found among the break-zones. In reality, however, there is no question of averaging and eliminating the fibre orientation effects; furthermore, a poorly bonded low grammage zone may be weaker than a well-bonded high grammage zone. As a result, the lowest grammage found for the break-zones (37·5 g/m²) tends to approach the lowest value in the population (36 g/m²).

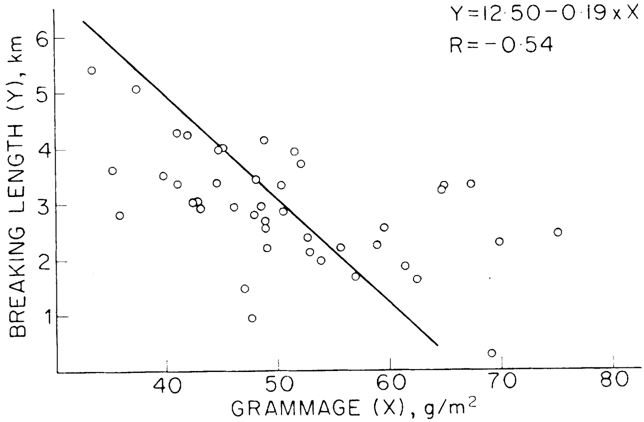

Fig. 8—Breaking length plotted against grammage for 0·5 mm² break-zone samples of commercial newsprint

Fig. 8 shows the plot of break-zone breaking length against grammage. The negative relation is apparent, but there is considerable scatter and the correlation is poor. It may be shown that those points above the regression line tend to correspond to higher estimates of total interfibre bonding than those points below; the latter tend to correspond to estimates below average of total interfibre bonding.

Part 3—The reconstruction study

To BRING out more clearly the adverse relationship between the newsprint strength and grammage caused by the calendering, it was felt necessary to standardise the data in such a way as to eliminate the major sources contributing to the variance. These sources are principally—

1. The experimental error.
2. The fraction of sulphite fibres in the break-zone, whose increase at fixed grammage not only increases the number of fibres available for bonding, but also increases the proportion of the stronger inter(sulphite)-fibre bonds.
3. The normal direct and proportional effect of increasing grammage upon tensile strength.

To simplify analysis, we have assumed an artificial, layered paper structure of which the first layer was the break-zone sulphite fibre reconstruction as described above. Such a layer is here called a *basic layer*. The remaining groundwood formed the other layers, their number being governed by the grammage and weight fraction of sulphite fibre in the break-zone. For convenience, it was assumed that each layer of groundwood fibre had the same fibre orientation distribution, total fibre length and total number of interfibre crossovers as the reconstructed sulphite fibre network. Such layers are also basic layers. Hence, the inverse of the total number of such layers (sulphite and groundwood) gives the number fraction of sulphite fibres among the total making up the break-zone.

Thus defined, the basic layer of the break-zone sample is variable, since it is based on the number of sulphite fibres in a specific sample. On this basis, no intersample comparison is valid. This approach was extended to conceive of the break-zones as being made up of a number of *standard layers*, identical for all break-zones. A standard layer was defined as having an arbitrarily chosen total length of fibre, which was the same for all break-zone samples and its fibres had the same fibre orientation as the basic layer obtained upon reconstruction. The reconstructions for each break-zone sample gave the number of sulphite fibres and their total length, thus yielding an average length per fibre within the sample area. This average length for each sample was applied to the fixed, arbitrary, total fibre length of that sample, assumed for a standard layer, to give a hypothetical number of fibres for the standard layer of the sample.

A surrogate for the degree of bonding in the reconstruction samples was obtained by taking the ratio of the number of sulphite fibre crossovers to the number of crossovers possible if each fibre crossed all the others. This ratio is here called *crossover efficiency*. Since the arrangement of the fibres in the standard layer was assumed to be the same as that in the statistically reconstructed sulphite layer, it was then assumed that the relative degree of bonding in the standard layer of any sample was in proportion to its crossover efficiency.

The calculated hypothetical number of fibres in the standard layer of a given sample determines the maximum possible number of crossovers in that layer. Multiplying by the crossover efficiency for the same sample gives a relative estimate of the number of crossovers.

Finally, since groundwood crossovers and sulphite crossovers can be expected to give bonds of quite different strengths, an adjustment has been made for this.

The extent of the interfibre bonding of a standard layer remains a constant characteristic of the newsprint studied, at any grammage, provided sufficient samples are tested to average out sulphite content and fibre orientation variations.

We compared the break-zone samples on the basis of the tensile strength of their standard layer, which was determined as follows.

We established—

1. The number of separate standard layers that made up that sample.
2. The extent of the interfibre bonding of the whole break-zone after allowing for the number of standard layers present and the bonding within and between them.
3. The number of independent standard layers that together would give the same extent of interfibre bonding as calculated for the whole break-zone.
4. The parameter obtained by dividing the number of independent standard layers into the newsprint tensile strength.

The reader is referred to appendix 2 for the rigorous explanation of the method used here and to appendix 3 for the information it gives.

TABLE 2—THE RELATION BETWEEN AVERAGE TENSILE PER EQUIVALENT STANDARD LAYER AND THE AVERAGE EFFECTIVE BONDING PER STANDARD LAYER FOR VARIOUS BREAK-ZONE GRAMMAGE GROUPINGS

Grammage			*Reconstruction data*		
1	*2*	*3*	*4*	*5*	*6*
Range, g/m^2	*Number of samples No.*	*Average,* g/m^2	*Average effective bonding per standard layer,* $ML^{-1}T^{-2}$	*Average tensile per equivalent standard layer, kg/15 mm*	$10^2 \times$ *ratio tensile bonding* $(5 \div 4)$ L
<40	5	36·35	25·6	0·39	1·52
40–44	6	42·17	23·2	0·33	1·42
44·0–48·5	8	46·50	21·0	0·23	1·10
48·5–52	8	49·67	22·1	0·27	1·22
52–56	5	53·55	22·0	0·22	1·00
57–63	5	59·96	23·0	0·20	0·87
>64	6	68·59	22·7	0·19	0·84

The results of this approach are summarised in Table 2, which shows, for the break-zone samples, the average tensile strength of the standard layer, the average extent of interfibre bonding of the standaıd layer and their ratio for several grammage groupings. As expected, the estimate of the average extent of interfibre bonding is substantially constant for all grammage groupings.

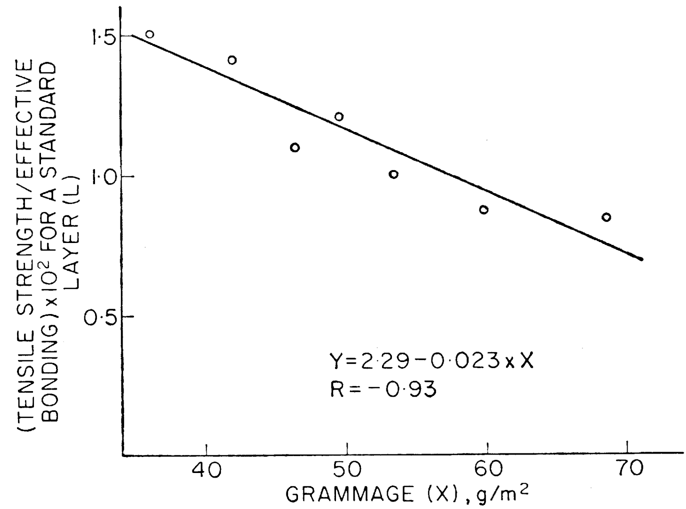

Fig. 9—Average ratio of tensile strength to effective bonding of a standard layer against average grammage for groupings (by grammage) of 0·5 mm² break-zone samples of commercial newsprint

Fig. 9 shows the plot of the ratio of tensile strength to the estimated extent of interfibre bonding for the average standard layer against the group average break-zone grammage. The highest strength is obtained at lowest grammage and there is a steady decline with progressively increasing values. The negative relation is clearly established with a very high degree of correlation ($R = -0{\cdot}93$) and it seems reasonable to conclude that, were the averages composed of more data points, an even higher degree of correlation would be obtainable. This is because, in addition to the sources of variation we have deliberately set out to remove, the averaging process would remove much of the variation arising from the statistical nature of the reconstruction work and from the small size of the break-zone, which rendered variable certain parameters normally constant on the macroscale. Such parameters include bonding strength, fibre shape and size and crossovers per reconstruction.

Concluding remarks

The location of the rupture line in paper is governed by the chance occurrence of a suitable line of successive weak spots and this in turn is governed by the local variability of the paper. For paper made from a single grade of pulp, there are two major sources of local variation—

1. Grammage.
2. Fibre orientation and dispersion.

For paper such as newsprint, which is made from a mixed pulp, there is a third factor—

3. The concentration of the fortifying pulp.

For commercial newsprint, we have shown that the tensile rupture line is associated with a lower-than-average proportion of sulphite pulp fibres. Furthermore, those sulphite fibres that do exist in the rupture line possess a relatively higher component of machine-direction orientation and a lower degree of angular dispersion than exists in the rest of the web. Additionally, we have discovered that, for commercial newsprint, the rupture line is governed by the chance occurrence of a line comprising the higher grammage spots in the web. This appears to contradict the prior theory that the location of the rupture line is governed by the chance occurrence of a suitable succession of lower grammage points. This unexpected reversal is due to the damage done to the newsprint web at its points of higher grammage by the calendering process.

As a result of the nature of the calendering process and the springback characteristics of groundwood, there are few qualities of paper that suffer a greater degree of calender damage than do the newsprint grades. Most papers are subjected to less drastic calendering and for these the rupture line will normally be expected to consist of a succession of weak spots made up of both the highest and the lowest grammage spots of the web. In any event, all future attempts to develop realistic models governing the relation of strength to structure for commercial papers will have to take account of the effect of calendering.

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***Appendix 1**—Summary of results*

Summary of the information obtained upon testing and examining the 0·5 mm² random and break-zone samples of commercial newsprint

The random sample

Sample number	*Grammage, g/m²*	*Angles of individual sulphite fibres to the machine-direction*	*N*
1	53·02	22, 23, 26, 29, 33, 38, 53, 57, 58, 58, 62, 63, 69, 81	14
2	43·65	6, 8, 9, 12, 12, 17, 25, 45, 46, 52, 54, 90	12
3	50·52	2, 6, 16, 21, 21, 28, 31, 40, 42, 50, 58, 59, 79, 87	14
4	59·66	3, 10, 18, 18, 26, 30, 36, 47, 52, 60, 62, 63, 64, 70, 77	15
5	53·24	3, 4, 6, 12, 36, 43, 46, 48, 49, 50, 55, 84, 86	13
6	45·67	3, 3, 6. 13, 37, 53, 84, 89	8
7	57·01	1. 6, 7, 18, 19, 19, 21, 24, 27, 36, 37, 41, 47	13
8	54·83	3, 4, 7, 8, 25, 27, 28, 39, 47, 60	10
9	51·71	1, 4, 4, 5, 6, 16, 19, 20, 21, 26, 31, 34, 44, 58, 70, 90	16
10	44·63	12, 13, 28, 35, 38, 40, 59, 65, 71, 77, 82, 83	12
11	61·32	3, 7, 10, 10, 11, 11, 16, 47, 60, 73	10
12	47·79	4, 6, 11, 14, 16, 18, 19, 27, 30, 31, 32, 49, 58, 74, 83, 85	16
13	52·19	8, 10, 13, 18, 41, 65, 83, 87	8
14	53·06	5, 5, 8, 14, 22, 62, 62, 64, 76	9
15	46·02	8, 30, 32, 37, 40, 45, 68, 78, 80, 88	10
16	51·05	6, 13, 14, 15, 19, 20, 20, 24, 30, 32, 37, 38, 40, 43, 49	15
17	43·86	10, 12, 15, 18, 19, 24, 27, 30, 40, 68, 88	11
18	55·32	0, 1, 20, 20, 25, 25, 26, 34, 45, 88	10
19	54·78	7, 7, 11, 22, 28, 31, 32, 33, 50, 57, 59, 70, 77	13
20	63·31	1, 1, 2, 3, 18, 24, 24, 27, 43, 52, 54, 55, 82	13
21	55·07	5, 18, 18, 20, 32, 34, 55. 56, 62, 66, 81, 82	12
22	41·79	0, 2, 4, 4, 6, 43, 72, 87	8
23	57·17	0, 14, 20. 38, 42, 67, 71, 82	8
24	45·48	17, 17, 19, 20, 22, 25. 25, 32, 37, 55, 58	11
25	51·19		
26	50·14	12, 24, 40, 40, 58, 67, 68, 74, 88, 89	10
27	50·07	1, 2, 7. 12, 17, 30, 30, 32, 32, 38, 44, 51, 66, 67, 77	15
28	51·04	2, 8, 10, 12, 47, 54, 80	7
29	45·09	3, 5, 7, 19, 22, 22, 23, 39, 46, 47	10
30	43·42	1, 1, 5, 8, 12, 13, 13, 14, 15, 27, 37, 39, 48, 60, 78	15
31	47·66	1, 7, 10, 19, 21, 29, 52, 55, 65, 66, 81	11
32	58·02	2, 4, 6, 6, 10, 18, 20, 40, 42, 44, 45, 51, 51, 54, 88	15
33	56·79	3, 16, 16, 27, 40, 61	6
34	45·42	1, 6, 6, 7, 11, 18, 46, 64, 72, 86	10
35	52·56	7, 18, 25, 27, 46, 50, 57, 60, 62, 63, 68, 82, 88	13
36	36·38	5, 7, 12, 12, 16, 22, 22, 37, 38, 43, 53, 55, 72	13
37	62·96	9, 19, 21, 29, 39, 44, 45, 50, 60, 67, 70, 85	12
38	42·65	4, 10, 11, 16, 18, 20, 23, 29, 42, 64, 77, 81	12
39	58·09	1, 11, 14, 14, 26, 26, 29, 65, 77	9
40	68·04	4, 4, 5, 14, 21, 22, 29, 45, 80	9
41	67·34	3, 7, 20, 32, 32, 34, 50, 57, 60, 61, 63, 82, 85	13
42	51·08	7, 13, 20, 28, 47, 58, 58, 67, 68, 70, 74, 82	12
43	57·29	0, 4, 7, 14, 15, 28, 49, 70, 88	9

The break sample

Tensile strength, kg/15 mm	*Breaking length, km*	*Grammage, g/m²*	*Angles of individual sulphite fibres to machine-direction*	*N*
1·92	3·62	35·32	5, 5, 7, 7, 8, 12, 13, 15, 20, 25, 52, 55	12
1·51	2·81	35·84	14, 15, 19, 23, 24, 36, 64, 64, 77	9
1·05	1·49	47·00	5, 12, 15, 15, 26, 27, 35	7
0·70	0·98	47·74	7, 9, 19, 22, 24, 34, 35, 45	8
2·72	5·42	33·44	1, 3, 4, 16, 30, 31, 38, 38, 43, 59, 60	11
2·11	3·53	39·85	5, 6, 26, 39, 44, 52, 78	7
2·07	3·36	41·11	0, 9, 12, 14, 15, 16, 21, 30, 37, 51	10
1·94	3·04	42·51	11, 11, 14, 15, 34, 51, 69	7
1·97	3·06	42·92	16, 18, 24, 25, 25, 41	6
1·63	2·21	49·06	4, 18, 28, 65, 70	5
2·84	5·07	37·31	2, 2, 5, 7, 12, 19, 19, 28, 75	9
2·65	4·30	41·18	1, 3, 7, 10, 11, 13, 20, 20, 30, 30, 37, 85	12
2·68	4·25	42·08	1, 5, 5, 10, 19, 21, 27, 30, 40, 46, 48, 51, 78, 82, 88	15
2·53	2·90	43·21	1, 2, 4, 12, 18, 18, 21	7
2·29	3·41	44·72	0, 2, 3, 4, 7, 17, 25, 27, 39, 55	10
2·67	3·96	44·96	1, 3, 10, 13, 14, 20, 35, 36, 40, 44	10
2·73	4·02	45·30	1, 3, 4, 7, 20, 21, 30, 32, 35, 41, 46	11
2·06	2·97	46·17	0, 9, 9, 14, 15, 22, 32, 45, 51, 70	10
2·03	2·81	48·07	2, 7, 9, 13, 15, 15, 18, 20, 21	9
2·48	3·44	48·07	2, 3, 7, 12, 13, 13, 26, 33, 35, 36, 47, 50, 79, 81	14
2·17	2·97	48·64	7, 9, 9, 15, 21, 24, 37, 41, 47, 85, 89	11
1·99	2·70	49·02	12, 13, 18, 19, 20, 27, 38, 63	8
1·91	2·59	49·02	2, 2, 4, 7, 19, 20, 21, 23, 25, 40, 41, 56, 77	13
2·52	3·33	50·41	4, 5, 6, 21, 24, 42, 43, 55, 75	9
2·18	2·87	50·56	2, 2, 4, 7, 14, 15, 15, 20, 23, 31, 53	11
1·93	2·43	52·83	0, 8, 13, 23, 26, 29, 30, 61	8
1·71	2·15	53·08	10, 14, 17, 22, 26, 44, 53	7
1·62	2·00	53·96	0, 2, 15, 19, 20, 21, 59, 78	8
1·51	2·23	55·74	3, 8, 13, 13, 14, 21, 31, 33, 43, 46, 65, 71, 74	13
1·46	1·70	57·06	16, 17, 34, 39, 51, 66	6
0·31	0·30	69·17	11, 12, 13, 29, 32, 40, 62, 85, 86, 89	10
3·04	4·14	48·98	4, 4, 4, 15, 21, 25, 25, 26, 40, 42, 45, 60	12
3·05	3·93	51·65	4, 9, 14, 21, 58	5
2·92	3·73	52·15	0, 0, 0, 7, 12, 12, 13, 16, 58	9
2·00	2·26	59·05	8, 9, 11, 17, 21, 23, 25, 32, 47, 51, 61, 83	12
2·28	2·55	59·56	2, 5, 7, 9, 14, 15, 16, 21, 25	9
1·74	1·88	61·55	3, 47, 52, 75, 88	5
1·51	1·61	62·56	0, 9, 16, 19, 30, 40, 45, 65	8
3·33	3·25	64·85	0, 2, 5, 6, 8, 12, 21, 21, 25, 26, 29, 51, 69	13
3·22	3·30	65·01	0, 3, 9, 11, 11, 20, 59, 90	8
2·88	3·34	67·38	3, 4, 10, 11, 15, 24, 42, 47, 55, 77	10
2·39	2·28	69·94	1, 3, 8, 9, 14, 15, 17, 26, 40, 46, 60, 83	12
2·76	2·45	75·18	2, 2, 6, 6, 11, 12, 13, 19, 39, 71, 80	11

Appendix 2—*Summary of the information derived from the reconstructions of the sulphite fibre networks of the break-zone samples*

		Raw data			Reconstruction with sulphite	
1	2	3	4	5	6	7
Sample No.	Tensile strength, kg/15 mm	Grammage, g/m²	Sample weight × 10⁶, g	Number actually in sample No.	Total fibre length, mm	Crossovers No.
1	1·92	35·32	18·7	12	10·23	32·66
2	1·51	35·84	14·1	9	6·47	18·66
3	1·05	47·00	30·2	7	5·55	10·00
4	0·70	47·74	26·1	8	5·97	14·66
5	2·72	33·44	23·4	11	8·48	32·66
6	2·11	39·85	25·6	7	5·16	14·00
7	2·07	41·11	31·6	10	7·66	16·66
8	1·94	42·51	23·9	7	5·20	11·33
9	1·97	42·92	22·9	6	5·07	9·00
10	1·63	49·06	31·2	5	3·20	4·66
11	2·84	37·31	24·1	9	7·52	20·00
12	2·65	41·18	20·3	12	9·60	27·33
13	2·68	42·08	23·3	15	10·76	57·33
14	2·53	43·21	32·8	7	6·55	9·00
15	2·29	44·72	31·0	10	8·46	24·33
16	2·67	44·96	35·1	10	8·83	27·00
17	2·73	45·30	29·6	11	9·46	34·00
18	2·06	46·17	29·2	10	7·20	23·33
19	2·03	48·07	23·9	9	8·10	15·00
20	2·48	48·07	29·8	14	10·39	45·33
21	2·17	48·64	24·2	11	7·81	27·66
22	1·99	49·02	24·5	8	4·98	10·66
23	1·91	49·02	19·5	13	9·87	41·00
24	2·52	50·41	29·1	9	7·07	21·66
25	2·18	50·56	26·4	11	8·71	19·66
26	1·93	52·83	27·0	8	5·96	13·66
27	1·71	53·05	37·6	7	5·30	9·66
28	1·62	53·96	33·8	8	6·63	17·66
29	1·51	55·74	24·7	13	9·25	44·33
30	1·46	57·06	28·1	6	4·00	7·66
31	0·31	69·17	44·8	10	6·16	22·66
32	3·04	48·98	52·8	12	9·17	30·66
33	3·05	51·65	30·4	5	4·10	4·66
34	2·92	52·15	30·5	9	8·22	16·00
35	2.00	59·05	34·1	12	8·28	28·66
36	2·28	59·56	40·0	9	7·95	13·66
37	1·74	61·55	30·7	5	3·23	5·66
38	1·51	62·56	24·9	8	6·62	17·00
39	3·33	64·85	39·9	13	11·05	41·66
40	3·22	65·01	55·4	8	6·96	15·00
41	2·88	67·38	47·3	10	7·49	25·66
42	2·39	69·94	47·6	12	9·69	35·33
43	2·79	75·18	31·9	11	9·35	31·66

fibres			*Calculated parameters*			
8	*9*	*10*	*11*	*12*	*13*	*14*
Crossover efficiency No.	*Crossovers per standard layer No.*	*Effectiveness of bonding No.*	*Equivalent standard layers No.*	*Equivalent effective crossovers (9×10×11) No.*	*Effective bonding per standard layer (9×10), $ML^{-1}T^{-2}$*	*Tensile per equivalent standard layer (2÷11), kg/15 mm*
0·495	16·5	1·23	5·36	109	20·3	0·36
0·519	24·6	1·17	3·41	98	28·8	0·44
0·476	18·1	1·03	8·57	160	18·6	0·12
0·524	22·8	1·05	7·28	174	23·9	0·10
0·594	24·8	1·11	6·69	182	27·2	0·41
0·667	29·8	1·04	7·02	218	31·0	0·30
0·371	15·3	1·06	9·28	151	16·2	0·22
0·540	24·1	1·05	6·47	164	25·3	0·30
0·600	35·3	1·05	6·12	227	37·1	0·32
0·466	28·3	1·01	8·62	246	28·6	0·19
0·556	19·0	1·09	6·81	141	20·7	0·42
0·414	15·7	1·18	5·76	107	18·5	0·46
0·546	25·9	1·17	6·94	210	30·3	0·39
0·429	11·5	1·04	9·54	114	12·0	0·26
0·541	18·1	1·07	9·18	178	19·4	0·25
0·600	18·5	1·06	10·58	207	19·6	0·25
0·618	20·1	1·09	8·85	194	21·9	0·31
0·519	24·6	1·06	8·45	220	26·1	0·24
0·417	12·3	1·10	6·82	92	13·5	0·30
0·498	22·3	1·11	9·03	224	24·8	0·28
0·503	24·6	1·09	6·88	184	26·8	0·32
0·381	24·7	1·04	6·64	171	25·7	0·30
0·526	22·3	1·20	5·59	150	26·8	0·34
0·602	23·4	1·06	8·39	208	24·8	0·30
0·358	13·9	1·10	7·71	118	15·3	0·28
0·488	21·2	1·05	7·57	169	22·3	0·26
0·460	19·5	1·02	10·98	218	19·9	0·16
0·631	22·1	1·04	9·89	227	23·0	0·16
0·568	27·8	1·12	7·22	225	31·1	0·21
0·511	28·1	1·02	7·70	221	28·7	0·19
0·503	32·6	1·02	13·44	447	33·3	0·02
0·465	19·7	1·03	16·42	333	20·3	0·19
0·466	16·8	1·02	8·45	145	17·1	0·36
0·445	12·8	1·07	8·99	123	13·7	0·33
0·434	16·9	1·06	10·18	182	17·9	0·20
0·380	11·7	1·04	12·08	147	12·2	0·19
0·566	33·3	1·01	8·45	284	33·6	0·21
0·608	21·3	1·07	6·96	159	22·8	0·22
0·534	17·8	1·07	12·42	237	19·0	0·27
0·536	17·0	1·02	17·01	295	17·3	0·19
0·570	24·8	1·03	14·41	368	25·5	0·20
0·536	19·8	1·04	14·78	304	20·6	0·16
0·576	19·2	1·08	9·59	199	20·7	0·29

Appendix 3

Definition of terms of reconstruction study

Standard layer—Layer of fibres having an aggregate length equal to 7·38 mm, which is the average sulphite fibre length as determined by all reconstructions.

Crossovers—Number of interfibre crossovers obtained in a given reconstruction.

Crossovers per standard layer—Number of interfibre crossovers that would be obtained in a standard layer of the same fibre orientation as the given reconstruction.

Crossover efficiency—Ratio of crossovers obtained in a given reconstruction to the maximum occurring when all fibres cross each other. For N fibres in a break-zone, the maximum crossovers are $0{\cdot}5N(N-1)$.

Effectiveness of bonding—Factor to account for the fact that newsprint is a mixture of sulphite and groundwood pulps, in which the sulphite bonds are stronger than those bonds involving groundwood. Bonds involving groundwood are assigned a strength equal to one. Sulphite bonds have been assigned a value of 1·71 (see explanation below).

Equivalent standard layer—Number of separate standard layers required to give the same bonding strength as the actual number of standard layers in the break-zone sample after allowing for interlayer bonding effects.

Equivalent effective crossovers—Crossovers per standard layer × number of equivalent standard layers × effectiveness of bonding.

Effective bonding per standard layer—Crossovers per standard layer × effectiveness of bonding.

Tensile strength per equivalent standard layer—Tensile strength of break-zone divided by the number of equivalent standard layers.

Definition of symbols

b	=	Weight of break-zone sample (g).
L	=	Total length of all sulphite fibres in a given break-zone reconstruction (mm).
L_{AVE}	=	Total length of sulphite fibre in all the break-zone reconstructions divided by the number of reconstructions. This is 7·38 mm and is the fibre length that constitutes a standard layer.
W	=	Weight per unit length of sulphite fibre (g/mm).
Y	=	Ratio of sulphite pulp yield to groundwood pulp yield.
N	=	Actual number of sulphite fibres in the break-zone.
n	=	Number of sulphite fibres in the standard layer.
α	=	Relative strength of the inter(sulphite)-fibre bond = 1·71.
β	=	Relative strength of all other bonds = 1·00.
E	=	Crossover efficiency.

Value of symbols

N, E, L, b were determined in the course of the experimental work or the reconstructions and $L_{\mathrm{AVE}} = 7{\cdot}38$ mm. Y, W and α/β are estimated as follows.

For the mill that made the newsprint tested, the yields of groundwood and sulphite pulp from wood are respectively 96 and 67·5 per cent. Therefore, $Y = 0{\cdot}675 \div 0{\cdot}96 = 0{\cdot}703$.

The average random sample weighed 30·0 micrograms; 26 per cent of this was sulphite fibre. The average number of sulphite fibres per random sample was 11·48. By reconstruction, the average break-zone sulphite fibre length was 0·778 mm. Hence—

$$W = \frac{30{\cdot}0 \times 10^{-6} \times 0{\cdot}26}{11{\cdot}48 \times 0{\cdot}778}$$
$$= 0{\cdot}873 \times 10^{-6} \text{ g/mm.}$$

Sulphite pulp handsheets have a breaking length of about 8 500 m, compared with about 3 500 m for groundwood. Allowing for the increased number of sulphite fibres, hence standard layers per unit grammage, the ratio of the bonding strengths—

$$\frac{\alpha}{\beta} \approx \frac{8\,500 \times 0{\cdot}703}{3\,500}$$
$$\approx 1{\cdot}71$$

It is assumed here that bonding strength substantially outweighs fibre strength as a factor in both breaking length values.

Calculation of crossovers per standard layer

$$n = N(L_{\text{AVE}}/L)$$
$$= 0{\cdot}5\ En(n-1)$$

Crossovers per standard layer

$$= 0{\cdot}5\ EN\frac{L_{\text{AVE}}}{L}\left(\frac{NL_{\text{AVE}}{}^{-1}}{L}\right)$$

$$= \frac{EN}{L}\left[27{\cdot}25\,\frac{N}{L} - 3{\cdot}69\right]$$

Calculation of effectiveness of bonding

The complex size distribution of the groundwood fibres has been conceptually aggregated into fibres having the same dimensions as the sulphite fibres. These 'conceptual' groundwood fibres are oriented in the same manner as the sulphite fibres. Then—

Number of reconstruction layers equivalent to break-zone weight

$$= Y\left(\frac{b}{WL} - 1\right) + 1$$

Fraction of sulphite fibres in break-zone

$$= \left[Y\left(\frac{b}{WL}-1\right)+1\right]^{-1}$$

Fraction of inter(sulphite)-fibre bonds in break-zone total

$$= \left[Y\left(\frac{b}{WL}-1\right)+1\right]^{-2}$$

Fraction of other interfibre bonds in break-zone total

$$= 1-\left[Y\left(\frac{b}{WL}\right)-1\right]^{-2}$$

Effectiveness of bonding

$$= \frac{1}{\beta}\left[\frac{\alpha}{\left[Y\left(\frac{b}{WL}-1\right)+1\right]^{2}}+\beta\left(1-\frac{1}{\left[Y\left(\frac{b}{WL}-1\right)+1\right]^{2}}\right)\right]$$

$$= 1+\left(\frac{\alpha}{\beta}-1\right)\times\frac{1}{\left[Y\left(\frac{b}{WL}-1\right)+1\right]^{2}}$$

$$= 1+0{\cdot}71\times0{\cdot}805\times10^{6}\,\frac{b}{L}+0{\cdot}297$$

$$= 0{\cdot}79+0{\cdot}57\times10^{6}\,\frac{b}{L}$$

Calculation of the equivalent standard layers

Number of reconstruction layers equivalent to break-zone weight

$$= Y\left(\frac{b}{WL}-1\right)+1$$

Number of standard layers equivalent to break-zone weight

$$= \frac{L}{L_{\mathrm{AVE}}}\left[Y\left(\frac{b}{WL}-1\right)+1\right]$$

Putting two standard layers together doubles the number of fibres and quadruples the number of crossovers; hence, if each layer has m crossovers, two layers together will have 4 m crossovers. The contribution of each interface between layers will thus be equivalent to two separate standard layers. The number of interfaces is one less than the number of standard layers equivalent to the break-zone weight. Thus, the number of equivalent standard layers

$$= 3 \text{ (standard layers equivalent to breakzone weight)} - 2$$

$$= 3 \frac{L}{L_{\text{AVE}}}\left[Y\left(\frac{b}{WL} - 1\right) + 1 \right] - 2$$

$$= 0{\cdot}328 \times 10^{6}\, b + 0{\cdot}1206 L - 2$$

Transcription of Discussion

Discussion

Mr D. Attwood It is quite true, Prof. Wahren, that a more comprehensive description of variations in the standard deviation is provided by the use of power spectra, but insufficient to use any mathematics based on scientific analysis. There is danger in a one-dimensional approach.

Prof. D. Wahren The kind of analysis that we have used required that one has a statistical process with approximately normal distribution on a sheet that is the result of such a process. Your instance applies to wire mark, for example, where a periodic function is superimposed on the process. To measure wire mark, we also use a line to scan the sample. We tilt the scanning line and, when it is parallel with the wire mark in the web, we get an intense periodic signal, which is a good indication of the degree of wire mark. It is further stated in our paper that anisotropic random sheets possess different spectra in different directions (see Fig. 9). Fig. 41 shows good correlation between the measured spectra of an anisotropic non-woven sample and the corresponding anisotropic random sheet.

Dr C. T. J. Dodson My observation relates to Mr Radvan's comment: you remember that he said you could detect the departure from randomness by counting the number of fibres intersecting with scan lines and Prof. Wahren replied that this gives you the integral of a curve. In fact, you can get the whole curve if you use different lengths of scan line.

Firstly, Dr Lyne, could you comment on the significance of the thirty fringes that occur in the observed regions and, secondly, can you make a guess—and I am sure you have thought about it long and hard—about the intervals of length on samples that correspond to your fringe intervals?

Dr M. B. Lyne There are 25–30 fringes on the paper samples shown in Fig. 2 and 3 and the sample is approximately 9 cm long, so the fringes were separated by about 3 mm. As mentioned in the addendum, the fringes represent, to a reasonable approximation, half λ displacements along the bisector of

Under the chairmanship of Dr H. Corte

the viewing and illuminating paths. Therefore, for simple motions, you could count the number of fringes between two points on the paper surface and multiply by half λ to get the displacement for the component along the bisector.

Dr D. Atack I was interested in seeing some of your holograms Dr Lyne taken more recently in Stockholm, but not reproduced in your paper. It is apparent that there is much more speckling on the holograms taken in the Swedish laboratory, which I suspect is due to a large in-plane component. The holograms presented in the paper contain, we believe, no in-plane component.

Dr Lyne Pictures of holograms can be made of a real or a conjugate virtual image. The microscopic study holograms were photographed by projecting the real image directly on to photographic film, whereas all the other holograms were photographed as virtual images. The magnification and means of projection in the microscopic study were the cause of greater speckle in those illustrations.

Dr K. Ebeling I would like to ask if you have considered the role of the liquid crystal coating on the temperature profile results. It seems to me that the coating can either share part of the load (that is, be under tension) or it can be passive during the straining experiment.

If the coating layer is under tension, then it will undergo thermal phenomena related to the Kelvin's thermoelastic effect. Depending on the nature of deformation (elastic or plastic), the sign of the heat phenomena can be positive or negative. The point I wanted to make is that, in such a case, the thermal phenomena of the coating will be superimposed on the thermal phenomena of the paper.

If the coating layer would be totally passive during the straining, the dynamic nature of the heat transfer is affected by the coating layer. During the elastic region of straining, paper tends to cool—that is, to absorb heat. This means that the heat generation associated with the apparent plastic deformation has to go on for some time before the heat absorption will be balanced out. Usually, this takes place at about 1 per cent elongation. Only after this elongation will the continuation of plastic straining generate heat in the specimen.

Dr Lyne The liquid crystal compound was a grease-like substance and had no discernable effect on the tensile strength. As mentioned in the paper, the thermal measurements (allowing a crude correction for the coating on the basis of relative weights of paper and coating) gave values that agreed closely with large area infra-red scan study. The temperature drop during initial elastic strain is negligible as measured by both techniques. I think a more definitive experiment, however, might be made using an infra-red microscope that is now commercially available.

Prof. L. Göttsching On the holographic method described, it surely needs more skill and effort compared with the moiré technique to evaluate the strain distribution of the paper assembled under stress, knowing that the application of this technique requires, for example, the printing of the paper investigated, which means a certain manipulation. What are the advantages of the holographic techniques in this special field of research?

Dr Lyne As mentioned in the paper, we tried moiré techniques first. We printed the finest grid possible on newsprint and used a suitable analyser plate over the top. We found that the technique had insufficient sensitivity to generate any useful information about the coefficient of variation of strain of the paper. The main advantage of the holographic method is that there is no interference whatsoever with the straining of the paper; it is a completely external sensing technique. It has very great sensitivity—down to the range of half λ displacements. That is certainly much greater than one could anticipate from the moiré techniques described in the text.

Dr J. A. Van den Akker Is it fair to say that, in holographic interferometry, we are dealing with a moiré effect in the diffraction pattern on the plate?

Dr Lyne There is a close analogy between moiré and holographic interferometry. I would direct your attention to two papers by my colleague Dr Nils Abramson of the Royal Institute of Technology in Stockholm [*Nature Physical Science*, 1971, **231** (20)] and reference 14 in the addendum.

The Chairman I would like to comment myself at this point. I understand Dr Lyne, that your coefficient of variation of the distribution of the local displacement is based on forty numbers and that the displacements refer to pairs of points that were originally separated by something like 3 or 4 mm, this order of magnitude. This would be the dimension of the areas of inspection, the small areas we are looking at. If one compares the local non-uniform extension of the sample with the mass that is present in the locality, then ideally one would like to compare areas of exactly the same size. The areas on which your coefficients of variations for the formation numbers are based are quite different and this rules out a direct comparison. The reason for making this point is this: Dr Dodson, in the paper he gives tomorrow, derived a very simple formula that relates the coefficient of variation for the extension (d) to the coefficient of variation for the grammage in the same areas (b)—

$$d = b/(1+b^2)$$

If b is 7 or 8 per cent, the square is small compared with unity and one would expect a linear relationship between the two coefficients of variation, as shown in your illustration. If the areas on which the coefficients of variation for the grammage are based are much smaller, however, the denominator will vary, because the variance of the grammage is (roughly speaking) inversely proportional to the area of inspection. One would not then expect a straight-line relationship between d and b of the type shown in your graph. This surprised me and I wonder if you have any comments to make.

Dr Lyne As I mentioned in the paper, we are dealing with a macroscopic fringe separation. Certainly, the formation inspection area is much smaller. I think it is an inherent problem in analysing fringe patterns that there will always be a macroscopic distance between the fringes. As the increment of strain between exposures of the hologram plate increases, the fringe order increases, but the fringe contrast decreases. In other words, there is a cross-over here of wanting a sufficient number of fringes to give some reasonable information about coefficient of variation, but not wanting so many fringes that they cannot be resolved.

Dr J. Mardon I would like to take issue with Prof. Wahren on his comments on two-wire forming at the end of his presentation. This is far too important a subject to be left with a misapprehension in the minds of the audience. It is not correct to deal with two-wire formers as one generic type. The four kinds of two-wire formers form three very clearly distinguishable types. Only one of these will produce paper better formed than on a properly operated flat wire machine. This one type is highly susceptible to wire mark. The other two types (which include three commercial designs) produce paper that is more badly formed than the common flat wire paper properly made, which will in fact print just as well.

Dr J. Grant I am reluctant to enter too deeply into the controversy between Prof. Wahren and Dr Mardon on the relative merits of two-wire newsprint machines, but I would refer to some rigidly controlled trials in which newsprint was run at high speed on Fourdrinier machines and on two entirely different two-wire machines. Apart from the shadowmarking, which Dr Mardon has already mentioned, there was really little difference in the essential physical properties of the papers made by the three different methods. There was, however, one outstanding difference, which I think is quite relevant and that was in the distribution of the loading between the two sides of the paper. With the Fourdrinier-made paper, there was a very marked difference between the two sides, giving rise to a pronounced two-sidedness; with both the two-wire machines, there was almost uniform distribution throughout the cross-section of the sheet as shown by splitting into four layers and analysing. I think this is quite an important matter when we are considering the structure of the sheet in relation to its properties.

Dr Mardon I have spent five years and a great proportion of my time thinking about this, because decisions of millions of dollars hang on it. Although Dr Grant is correct in his general statement, each of the two-wire former types have a completely different form of fibre distribution and a completely different form of fibre distribution if used on loaded sheets, so much so that, if we take a sheet of unknown origin and examine it simply by splitting it and looking at the drainage characteristics of the different layers, we can tell without any difficulty at all on which type of machine it has been made.

The Chairman You can make good and bad paper on any machine, I mean uniform or non-uniform paper.

Dr Dodson Whereas the fringes are not attached to real points in the paper, is it possible to make an analysis across the fringe pattern?

Dr Lyne I imagine this would be possible, although I have not done so.

Prof. D. R. Axelrad The slides to our contribution explain a lot, particularly in relation to this last question. An analysis across the fringe pattern can certainly be made. If you understand the fringe pattern in the proper manner and you know the interpretation required for this fringe pattern, it becomes very obvious when out-of-plane or in-plane motion has occurred. Normally, the out-of-plane motion is not difficult to observe, but rather difficult to measure.

Dr Lyne To the contribution by Dr Atack and Prof. Axelrad, I would like to comment briefly, especially that the addendum to the paper by Prof. Hazell and myself was intended to provide extra information about our experimental techniques and means of analysis, thus (I believe) it has answered most of the points raised in the contribution.

As my co-author, Prof. Hazell, is at present on sabbatical leave and could not attend the symposium, he has written to request that the following comment be made in response to point (*i*) of the contribution by Dr Atack and Prof. Axelrad—

> I have never suggested that 'lines of equal displacement occur in holographic interferometry only in the case of vibrating membranes', nor did I demonstrate this in their reference.[2] Fringes do represent lines of equal displacement, for example, in the case of rigid body rotation.

To the question of the contribution of possible out-of-place components, I would say that local components are probably present, because paper is a heterogeneous material, but I doubt the presence of macro-wrinkles.

There is a danger that the fringes in Fig. 2 & 3 will be interpreted as surface contour lines. A simple demonstration can be made to show that they are *not* contour lines. We altered the magnitude of the increment of strain applied between exposures of the holographic plate. If longitudinal wrinkles were present in the paper sample, their size would not change due to an alteration in the final strain increment (the webs were already prestrained to 90 per cent of their rupture extention). When the final strain increment was lessened, however, the deviations of each fringe from a straight line became progressively more coarse. This is expected by classical interferometry theory, but cannot be explained by longitudinal wrinkling.

Finally, to apply a perspective to this work, the first holographic interferometry was done in 1965 and we did more of these experiments in 1971. Analytical techniques are mushrooming in this field and it is to be expected that more sophisticated techniques such as the more recent multiple viewing angle approaches will be used in the future to separate and measure local in-plane and out-of-plane components.

I would like to thank Dr Bill Nixon of the Engineering Department at Cambridge for making possible the display of our interference holograms.

Mr B. Radvan I would like to ask Dr Lyne to speculate a little. He has quite properly disregarded boundary areas, but in many ways they may be interesting too. Your slides showed fringes near to the jaws: they are very straight, then become more and more curved, as one would intuitively expect; but it is not as simple as that. Obviously, we are dealing with a phenomenon of stress gradients spreading out. This could be a very important property in papermaking. In transmitting type impression, for instance, one does not want stress gradients to spread. I attempted to measure the distances between the fringes on your photographs without any special result, but I wonder if there are any results on long-fibred papers. Do you plan to do any?

Dr Lyne Boundary layers are quite interesting, of course, but their analysis is always more complex. We have looked at kraft softwood pulps in the edge tear configuration and in the study using a microscope objective. I would say that, for beaten kraft paper, the distribution of stresses about defects was over a broader area than in unbeaten kraft or newsprint.

Prof. P. Luner I would like to ask Dr Moffatt about changes in other properties on calendering besides breaking level. Have you looked at the tear or fold values on calendering newsprint and how these numbers change relative to the breaking level?

Dr J. M. Moffatt We did not really look at those other properties during the course of this study. We undertook these studies from the calendering end and have done a considerable amount of work in the field. When we managed to derive from the results this unique correlation between tensile and minimum caliper experienced during calendering, we did not really pursue the matter much further.

My original draft of this paper went into some of the implications of our work for developing realistic quality control tests for pressroom runnability. I hope it will be published somewhere else at a later date.

Dr Lyne I have a comment on Dr Moffatt's paper along the lines of Prof. Luner's question. In so far as the fracture line is concerned, there is an equating in the text of your paper of the break that occurs in a tensile fracture and the kind of rupture line that occurs in an in-plane tear. I disagree with that. I do not think that you can take your grammage results for a rupture line of a tensile specimen and merely equate it to the kind of ruptured line you would anticipate for an in-plane tear line. Specifically, in the paper that is quoted (your reference 7), we observed that the in-plane tear line deviated around high grammage points (or flocs) in the sheet (on calendered paper as well). I think tear and tensile lines might be different in this respect, because in-plane tear is primarily a matter of local rotation and opening of the web. It would seem logical that the tear line should follow zones that yield most readily—in other words, low grammage zones.

The Chairman What is the effect of the rate of loading?—your tests were presumably conducted in the normal standardised manner. If a fairly long strip of paper is loaded very rapidly, it can break into four or five pieces and I am just wondering along which lines these four or five fractures line would run, high spots or low spots. So far as I know, the theory for this effect—first observed in Stockholm a number of years ago, I think—has been that a standing wave moves through the paper between the two clamps. If the antinodes coincide with weak spots, the strip can break in different places. I wonder if you have given this dynamic fracture process any thought, because this is of course what newsprint is subjected to on the printing machine.

Dr Moffatt Were you using, Dr Lyne, actual newsprint or were you using handsheets? In the published work, if I remember correctly, you were using handsheets. How much calendering did you give the paper?

I expect our next published paper will answer the Chairman's question.

Dr Lyne We had studies in that paper on both TAPPI standard handsheets and on normal production newsprint. The handsheets were not calendered, but the newsprint underwent normal machine calendering. A ciné study of the in-plane tearing of this newsprint showed that the tear line avoided high mass points (or flocs) as it propagated across the web.

Dr A. de Ruvo In understanding formation testing and its relation to mechanical properties and the uniformity of mechanical properties, is it that the more uniform the sheet, the more uniform the mechanical properties? It is important to realise that you have other types of weak link in the structure—in the fibre itself. We need to distinguish when such weak links in the structure become more important than the improvement in formation. We should be provided with some means of measuring or distinguishing between weak links in the fibre material and those in the structure itself.

Dr D. H. Page I do not want to pre-empt what Prof. Axelrad might have to say, but I would like to comment on the interpretation of the interference pattern. It seems to me that the most likely interpretation of these wavy fringes in the middle of the sheet, in contrast to the rather straight fringes near the jaws, is that the sheet is going into longitudinal wrinkles while it is being strained and that these are out-of-plane displacements, which would of course be much larger than the in-plane displacements. If that is so, we would expect the extremely high coefficient of variation in the strain measured in this way, because it is not strictly the strain in the sheet that one is measuring, it is partly the out-of-plane displacement.

I do not know whether this is mentioned anywhere in anything that you have stated, because I have not read it all, but is that interpretation a valid one?

Dr Lyne I gather you have not read the addendum. A calculation of the relative sensitivity to the in-plane and out-of-plane motions with the various experimental set-ups appears in it. You certainly cannot eliminate the out-of-plane element in the procedure that we have used. You can only minimise its effect by choosing a minimum angle β, which we have done. In the experiment you are mentioning, there was a greater sensitivity to in-plane motion. We can say with certainty that the in-plane strain is being reflected in the fringe pattern, but the magnitude of the out-of-plane component is theoretically inestimable for the 10μ (or so) or in-plane strain induced between exposures of the hologram plate, since the paper was strained into the plastic region before the first exposure of the hologram. We have attempted to eliminate macro buckling from entering into our analysis by rejecting holograms that show gross fringe movement. Since we were looking for a general strength uniformity figure for a printing paper, it seemed satisfactory to us that *local* out-of-plane motion should be included in that figure.

Dr Mardon Dr Moffatt, whereas the grammage variations with time in the machine-direction would not have any effect on the significant discovery that you and Mr Beath have made, the grammage variations across the papermachine would certainly have the same effect as the smaller scale variations that you have been investigating. It seems to me—and I would like your comment—that you have in fact produced a very significant argument for automatic backtending.

Dr Moffatt I think I would be in favour of automatic backtending, because the unevenness that you have across the machine is a factor that is quite relevant to pressroom runnability.

In so far as automatic backtending can reduce or eliminate the measurement and integral lags associated with the manual process, the machine-direction variation in locally experienced compression should be attenuated. I would expect this is to be beneficial. Whether automatic backtending can pay for itself in terms of labour saving and reduced chemical pulp use is another problem.

Mr J. A. McLean Normally, with the sheet caliper of calendered newsprint reduced about 0·001 in by the breaker stack, the crushing action at the machine calender is less severe.