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THE BEHAVIOUR OF FIBRE-TO-FIBRE BONDS IN SHEETS UNDER DYNAMIC CONDITIONS

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BRITISH PAPER AND BOARD INDUSTRY RESEARCH ASSOCIATION, KENLEY

Synopsis

Using the techniques described in a previous paper, a study has been made of the breakage of fibre-to-fibre bonds in paper sheets under tensile strain. The frequent occurrence of partial separation in the areas of bonding and the relative rarity of total breakages are of particular interest. The way in which the bonded area loss is distributed between the bonds has been examined with particular reference to the effect of drying tension and beating. Both partial and total breakages are more common in freely dried sheets than in sheets dried under tension. Possible reasons for the occurrence of partial bond breakages are discussed.

Le comportement des liaisons entre fibres dans les feuilles dans les conditions dynamiques

Faisant usage des techniques décrites dans une précédente publication, une étude a été faite de la rupture des liaisons de fibre à fibre dans les feuilles de papier sous des conditions de déformation dynamique. La fréquente réalisation de séparations partielles dans les surfaces liées et la rareté rélative des ruptures totales sont d'intérêt particulier. La façon dont les pertes de surfaces liées sont réparties entre ces surfaces a été examinée, en tenant compte de l'effet de l'engraissement et des tensions au séchage. Les ruptures complètes et les ruptures partielles sont plus fréquentes dans les feuilles séchées librement que dans les feuilles séchées sous tension. Des causes possibles de ces ruptures partielles sont envisagées.

Das Verhalten von Zwischenfaserbindungen in Bahnen unter dynamischen Bedingungen

Mit Hilfe eines früher beschriebenen Verfahrens wurde die Zerstörung von Zwischenfaserbindungen in Bahnen unter Bruchdehnung beobachtet. Dabei erwiesen sich die Häufigkeit einer teilweisen Trennung der Bindungsflächen und die relative Seltenheit einer totalen Zerstörung von besonderem Interesse. Im Hinblick auf die Wirkung der Trocknungsspannung und der Mahlung wurde das Verhältnis der teilweisen zur vollständigen Trennung der Bindungsflächen untersucht. Dabei ergab sich, dass sowohl die teilweise wie die vollständige Zerstörung der Bindungsflächen in spannungslos getrockneten Blättern häufiger ist als in unter Spannung getrockneten Bahnen und es wurden mögliche Erklärungen für das Auftreten teilweiser Zerstörungen gegeben.

Introduction

THE work described in the earlier paper(1) has enabled us to adopt a more analytical approach to the subject of the physical properties of paper. We have been able to show that the fibre-to-fibre bonds that hold paper together are concentrated in discrete areas of optical contact between fibres and that the size, shape and distribution of these areas can be examined quantitatively. Clearly, these bonds play an important part in determining many of the physical properties of paper, in particular the mechanical properties; therefore, it is of considerable interest to determine their behaviour under dynamic conditions.

It has been believed for some time that, during the tensile straining of a paper sheet, bond breakage takes place. The work of Nordman (2) has clearly demonstrated that changes in opacity occur and that these changes are related to the irreversible energy loss during a straining/destraining cycle. However, there has been considerable controversy whether or not this opacity change is due to the breakage of bonds between fibres.

The advent of this new technique for the examination of individual bonds has made it possible to determine the extent to which this is the case and the work that will be described in this paper is devoted to the question of bond breakage in a sheet of paper under tensile conditions.

The finding that bonds (that is, areas of optical contact between fibres) break in paper sheets under tensile strain has already been described (3) and it was pointed out that, not only could there be a complete separation of the fibres with complete breakage of optical contact, but also that a partial loss of area of a bond could occur. It was decided, therefore, to carry out a quantitative examination of the loss in bonded area and the way in which paper-making variables influence it. The variables chosen for initial examination were beating and drying tension.

Experimental

APART from that used for the exploratory experiment, the paper chosen for this work was cut from handsheets of bleached spruce sulphite pulp beaten 20 min in the Valley beater and dried under three levels of tension in one direction, the paper being free to shrink in the transverse direction. For convenience, the direction of tension drying will hereafter be referred to as machine-direction (M.D.) and the free-to-shrink direction will be referred to as cross-direction (C.D.). Strips were strained to rupture and the fields (which were those selected for the work of the earlier paper) were rephotographed. The second photographs were then projected on to the drawings made from the first and changes in bonded area were recorded by drawing hatched regions. Owing to the difficulties of interpretation of the negatives, this often led to erroneous conclusions and it was necessary to check the results by comparison of enlarged prints.

It should be emphasised that the difficulties encountered in this examination were considerable. The microscopic image was rarely perfectly resolved owing to the fact that the bonds are observed by this technique through an optically imperfect fibre. An out-of-focus image could give a misleading appearance and the effect of changes in contrast, because of slightly different photographic conditions, could also be misleading. Moreover, the bonded area did not necessarily lie in a plane perpendicular to the microscope axis and, to ensure adequate coverage of the fields, it was often necessary to take several micrographs of each field. These considerations are particularly important because of the small bond breakages that often occur. Considerable care was taken, however, to ensure that the correct interpretation was made and it is considered that the results of this work are not in error to any significant degree from misinterpretations of the microscopic images. A selection of micrographs illustrating various degrees of bond breakage is shown in Fig. 1.

Results

THE exploratory work on bond breakage after tensile rupture (carried out on standard plate-dried sheets) revealed the way in which the loss of area is distributed between the bonds. For each bond, breakage can be expressed as

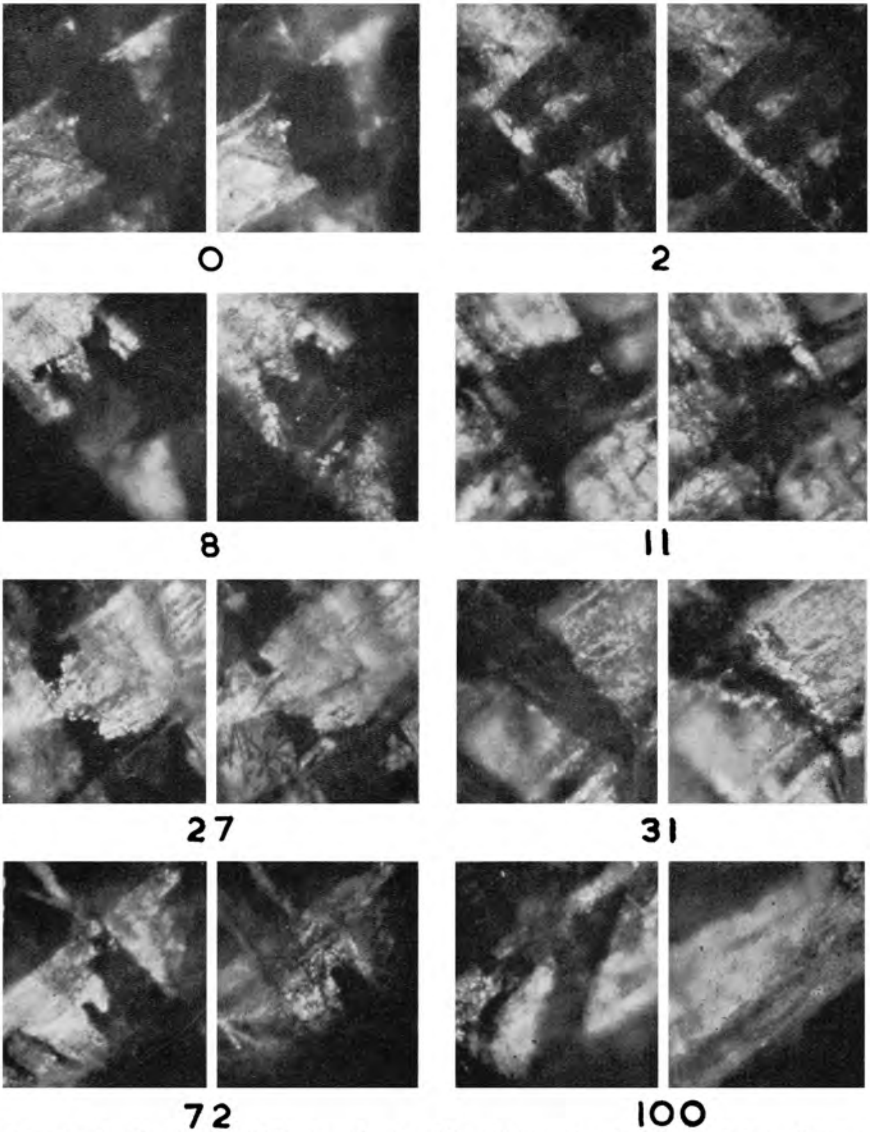

Fig. 1—A selection of fields showing bond breakage after tensile straining—figures indicate the percentage breakage

the percentage of its original area that has been lost and a histogram showing the frequency of occurrence of such percentage breakages has been plotted (Fig. 2). Almost half of the bonds remain unchanged, 6 per cent broke completely and the remainder (again almost half of the bonds) broke partially. Within the category of partial breakage, small degrees of breakage are most common. The histogram of Fig. 2 was compounded from results on three sheets of spruce sulphite beaten for 0, 10 and 30 min in the Valley beater, since in this brief exploratory work it was found that beating had no significant effect on the distribution. It was decided therefore that, in the planned experiment, it would be fruitful to investigate the effect of drying tension, in addition to the effect of beating, as it is known that drying tension affects the

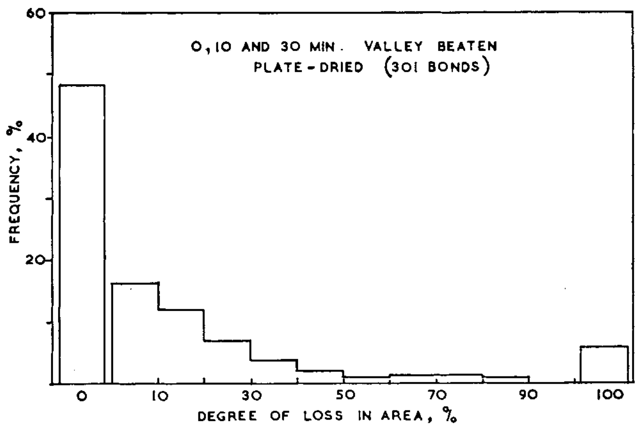

Fig. 2

opacity change on straining. All the results discussed hereafter refer to this major experiment.

In the analysis of the results, two aspects have been studied—the extent to which bond breakage is distributed between the bonds and the location at which each bond loses area (together with a consideration of the possible reasons for and implications of partial breakage). These aspects will now be considered separately.

Distribution of losses of bonded area

The frequency of occurrence of bonds showing a given percentage loss in area is plotted in the histograms of Fig. 3. Although it was originally hoped to detect differences between the sheets at three levels of drying tension, it is

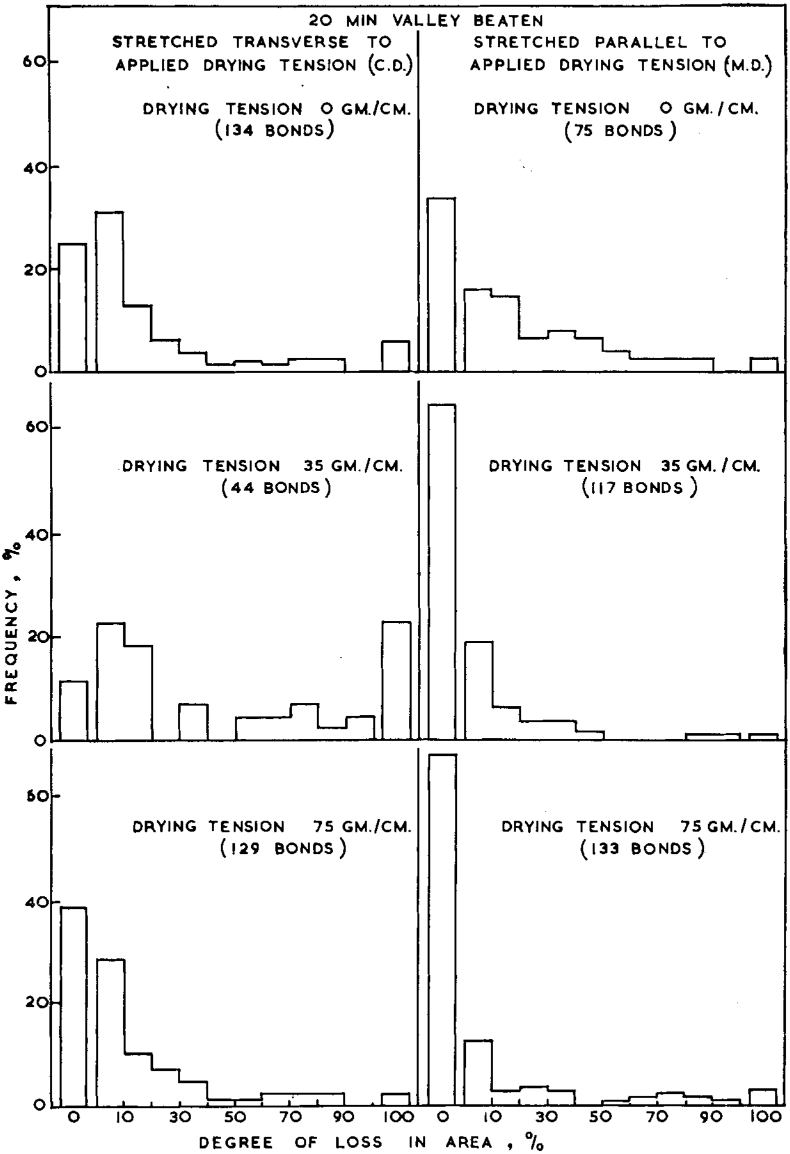
20 MIN VALLEY BEATEN
STRETCHED TRANSVERSE TO APPLIED DRYING TENSION (C.D.)
STRETCHED PARALLEL TO APPLIED DRYING TENSION (M.D.)
DRYING TENSION 0 GM./CM. (134 BONDS)
DRYING TENSION 0 GM./CM. (75 BONDS)
DRYING TENSION 35 GM./CM. (44 BONDS)
DRYING TENSION 35 GM./CM. (117 BONDS)
DRYING TENSION 75 GM./CM. (129 BONDS)
DRYING TENSION 75 GM./CM. (133 BONDS)
FREQUENCY, %
0
20
40
60
0
10
30
50
70
90
100
DEGREE OF LOSS IN AREA, %

Fig. 3

apparent that there is insufficient data for this. However, there is a significant and most interesting difference between the four sheets that have been strained in the direction of freely drying (0 g/cm M.D., 0 g/cm C.D., 35 g/cm C.D. and 75 g/cm C.D.) and the two that have been strained in the direction of an applied drying tension (35 g/cm M.D. and 75 g/cm M.D.). The results for these two groups have been compounded into a master histogram, Fig. 4. In the sheets strained in the free-to-shrink direction, about 30 per cent of bonds remain unchanged, 65 per cent break partially and 5½ per cent break completely. In the sheets strained in the direction of drying tension, 66 per cent of the bonds remain unchanged, 32 per cent break partially and 2 per cent break completely. The average percentage breakage is 21·5 per cent for the free-to-shrink direction and 9·0 per cent for the tension-dried direction.

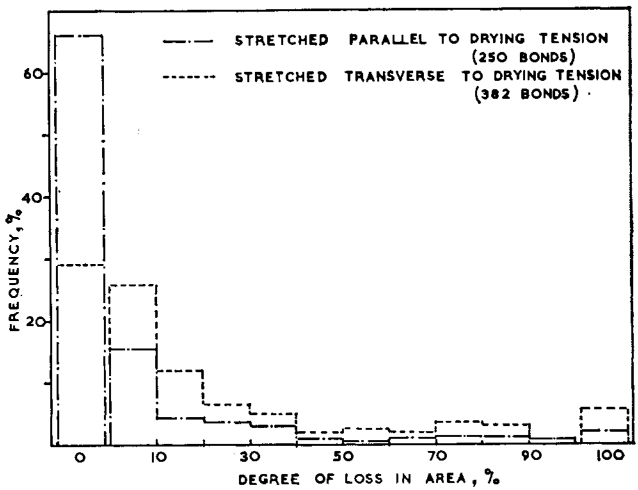

Fig. 4

It is also of interest to examine the contribution that each degree of bond breakage makes to the total area lost in the sheet. The loss in area within each percentage breakage category has been expressed as a percentage of the total area of the bonds and this loss has been plotted for each category in Fig. 5. The loss in area appears to be fairly equally distributed amongst the partial breakage categories, the large number of small breakages contributing approximately the same area change as the smaller number of large breakages. The effect of drying under tension is to reduce the actual number of bonds showing breakage, hence to reduce the total area loss, but it does not significantly affect the distribution of loss of area by partial breakage.

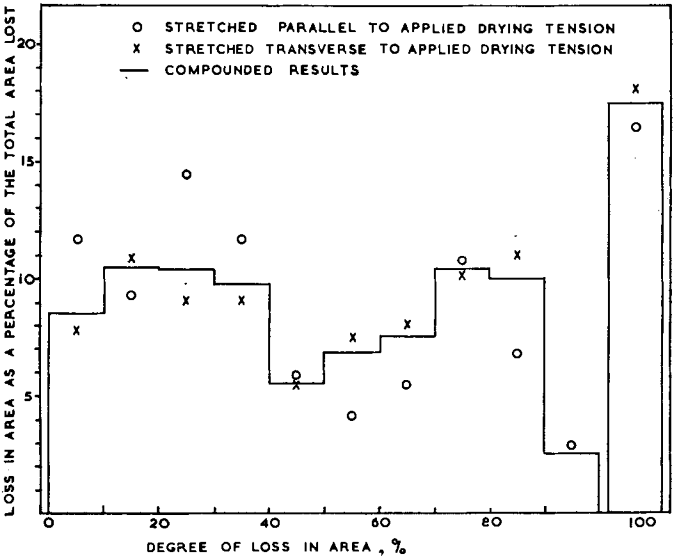

Fig. 5—Area loss as percentage of total initial area

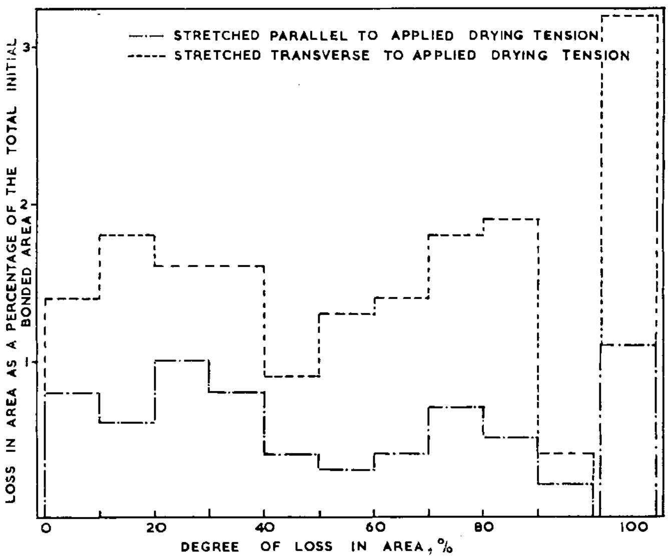

Fig. 6

A further conclusion can be drawn that is better appreciated from a different plot of these results. In Fig. 6, the loss in area in each category has been expressed as a percentage of the total area that has been lost. The similarity between the tension-dried and freely dried directions indicates that, *when bond breakage occurs in a sheet, independent of the total area lost, the distribution of that loss between the various degrees of bond breakage is the same.*

The occurrence of total breakage is of considerable importance to the theory relating paper structure and properties, since the presently accepted theory [4] incorporates complete fibre-to-fibre bond separation in the explanation of permanent set. In the work on the effect of drying tension, 21 bonds broke completely of the 382 examined in the free-to-shrink direction, whereas 5 out of 250 broke in the tension-dried direction. These values are only just significantly different at the 5 per cent level., thus it seems that, to obtain any detailed information on the effect of papermaking variables on total bond breakage, an impracticably large number of bonds would have to be examined. The change in bonded area arising from total bond breakage is seen to be in the region of 17 per cent of the area lost for both freely dried and tension-dried sheets. For convenience, some of the results are presented in Table 1.

TABLE 1—20 MIN VALLEY BEATEN SPRUCE SULPHITE HANDSHEETS

Value	*Stretched in free-to-shrink direction*	*Stretched in tension-dried direction*
Percentage of bonds unchanged	29·3	66·0
Percentage of bonds partially broken	65·2	32·0
Percentage of bonds completely broken	5·5	2·0
Loss in area as percentage of initial area	17·3	6·7
Loss in area due to 100% breakage as percentage of total area lost	18·2	16·6

The mean size of the completely broken bonds (510 μ^2) is lower than the mean size of all the bonds measured (930 μ^2), a difference that is significant at the 0·1 per cent level. It appears that the small mean area originates from both lower values of the upper and lower fibres (thus giving a lower area of crossing) and from the lower degree of bonding; however, these latter effects contribute more or less equally, thus individually they are not statistically highly significant.

Mode of bond breakage

It was pointed out earlier that, in addition to a consideration of the magnitude of the area lost, it would be of interest to consider the location within a bond site at which the loss occurred. This is clearly of importance in determining the mechanism of partial bond breakage.

A truly quantitative analysis of the loss of an irregularly shaped area from the original bond that itself is of irregular shape would be extremely difficult, even when, as is nearly always the case, the loss in area occurs at one discrete region at the periphery of the bonded area. The usual procedure under such circumstances is to attempt an arbitrary but sensible classification of a more qualitative nature and this course has been adopted. Bond breakages were classified initially into two modes. The first mode is that in which an increase of the length of the adjacent fibre segment occurs, thus relieving the stress applied to the bond via the segment. The second mode of partial breakage is that which does not appear to be directly relieving the stress in the associated fibre segment.

For the purpose of determining if a breakage were stress relieving (S.R.) or not, the criterion adopted was whether the breakage increased the projected interbond distance as defined in the earlier paper.[1] Breakages within this mode are illustrated in Fig. 7. Non-stress-relieving (N.S.R.) breakages are those that (it must be assumed) do not result in an increase in the effective or equivalent free fibre length of the associated fibre segment. These are principally re-entrants forming or enlarging within the bond area (*see* Fig. 7), although there were one or two cases of holes forming within the bond. It was found that some breakages, however, although they could not be strictly classified into the defined stress relieving mode, could conceivably increase the effective length of the fibre segment: thus, a third category had to be introduced designated *possible stress relieving.*

The number of incidences of the different modes of breakages have been assessed and tabulated in Table 2. The occurrence of non-stress-relieving breakage can be expressed simply by the number of occasions on which this type of breakage was observed and is given as a percentage of the total number of bonds examined.

The stress-relieving modes of breakage have been treated in a different way, since a single incidence of breakage can relieve stress in as many as four fibre segments (*see*, for example, Fig. 7). It was therefore decided to count the number of segments to which each bond breakage contributed stress relief.

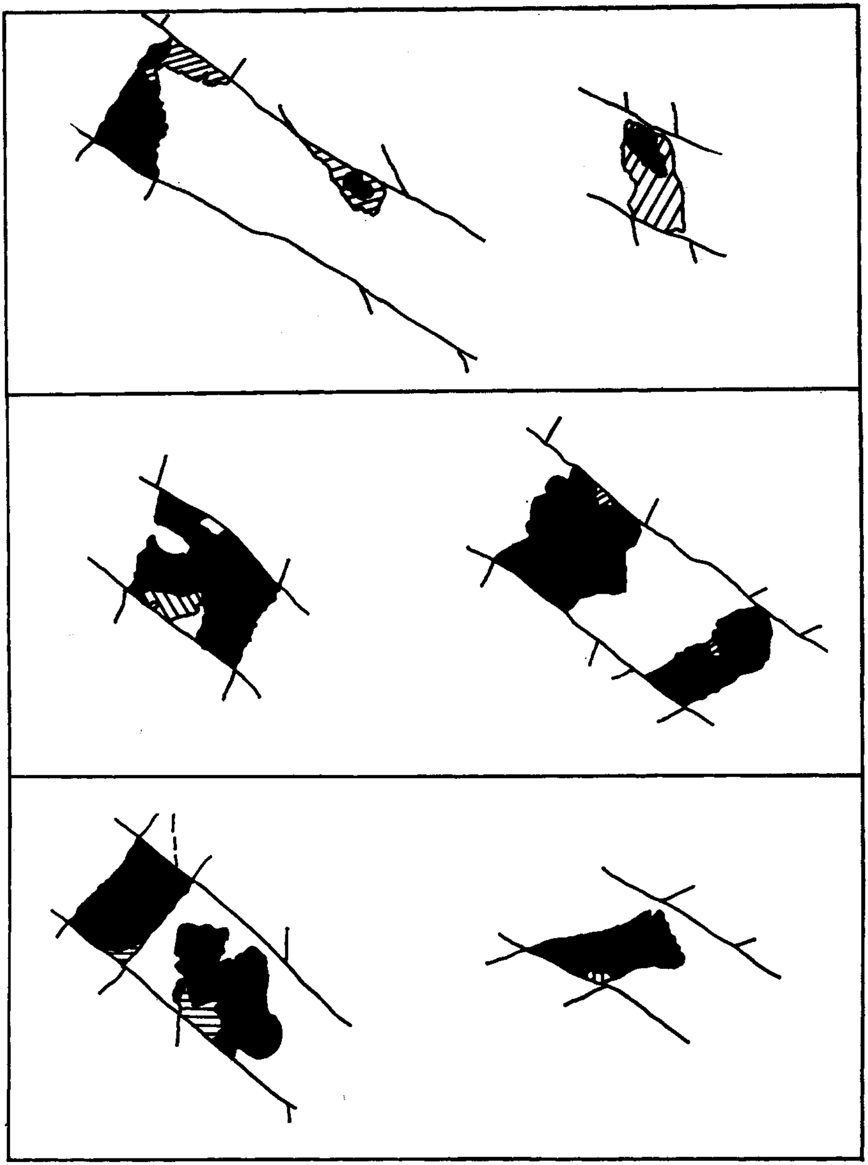

Fig. 7—Fields illustrating (*above*) stress-relieving, (*centre*) non-stress-relieving and (*below*) possible-stress-relieving bond breakage—the hatched regions indicate breakage, the black regions residual bond

This was done by an examination of each bond, with the result that some fibre segments are counted twice when stress-relieving breakage occurs at each end of the segment. Nevertheless, the results are perfectly satisfactory for comparison purposes.

In Table 2, the results have been compounded as before for the tension-dried and freely dried directions, since no differences were detected within these two groups. It appears that about 25 per cent of fibre segments have

TABLE 2

Value	*Stretched in freely dried direction*	*Stretched in tension-dried direction*
Number of bonds	382	250
Percentage of bonds showing N.S.R. breakages	24·7	11·6
Number of segments (4 × No. of bonds)	1 528	1 000
Percentage of segments that are stress relieved	25·2	11·3
Percentage of segments that are possibly stress relieved	9·9	4·6

stress relieved in them by bond breakage in the freely dried direction compared with 11 per cent in the tension-dried direction. The incidence of non-stress-relieving breakage in the freely dried direction (25 per cent) appears also to be greater than that in the tension-dried (12 per cent).

Discussion

THE work described in this paper shows beyond reasonable doubt that the change in light scattering coefficient resulting from tensile straining is largely due to the breakage of fibre-to-fibre bonds. The values obtained for the percentage loss in bonded area will be expected to give changes in the light scattering coefficient similar to those reported by Nordman. Moreover, the loss in bonded area of the cross-direction strips (17·3 per cent) was greater than that of the machine-direction strips (6·7 per cent), agreeing with Nordman's correlation between change in scattering coefficient and irreversible energy loss during straining. If our values of loss in bonded area are used to estimate the energy required for hydrogen bond breakage, however, it is found to be smaller than the energy loss on straining by many orders of magnitude and Nordman's results can be considered only as a correlation, not a cause and effect relationship.

A finding not in accord with previous thinking is that not only does the partial breakage of fibre-to-fibre bonds occur, but that this partial breakage accounts for a large proportion (over 80 per cent) of the loss in bonded area on straining. It is of interest therefore to discuss why bond breakage once started should not propagate to completion. There are a number of possible explanations—

(*a*) Bond breakage is time-dependent and the duration of the tensile test may be insufficient to permit complete bond failure in many cases. While this effect is undoubtedly present, it seems unlikely that many of the bonds showing small breakages would propagate to complete rupture within reasonable times.

(*b*) Partial bond breakage is halted, not by the duration of the test, but by local changes in structural conditions that relieve the stress on the bond.

(*c*) Bond breakage, by increasing the free length of the appropriate fibre segment, relieves the stress in the bond sufficiently to prevent further breakage. Although this concept was chosen as a basis of classification of bond breakage, it is difficult to assess the extent to which it occurs.

(*d*) Owing to the irregular shape of the bond (primarily in two dimensions, but possibly in three), high stress concentrations occur (for example, at an acute corner of the bond) and breakage continues until the stress concentration is reduced to the strength of the remaining bond.

(*e*) The distribution of adhesive strength within the area of optical contact is uneven and the regions that are weaker than the applied stress fail. This uneven bond strength arises from many factors, but the most important are probably the chemical nature of the original fibre surfaces, their topography and the effect of frozen-in stresses (because transverse shrinkage of the fibres and bond formation occur concurrently during drying).

It would seem likely that the majority of the large degrees of partial breakage occur due to the effects of (*a*), (*b*) and (*c*). The effects of (*d*) and (*e*) are almost certainly responsible for many of the small breakages. Losses of corners and small protrusions of the bonded area were common. The observation that re-entrants occur (*see*, for example, Fig. 7) is evidence of the effect of (*e*), since re-entrants often form at places corresponding to 'valleys' in the original surface topography of the fibres.

Several questions remain to be answered in connection with the phenomenon of partial bond breakage. The reason for its higher incidence in cross-direction than machine-direction strips is not known, although one can, of course, speculate on the possibilities. Van der Akker[5] has suggested that different stress distributions may be present in sheets dried under different tensions and this is a possible explanation of this phenomenon.

The distribution of percentage breakage within the partial breakage category and its apparent invariance not only with beating but also with drying tension is at present inexplicable and may remain so until further knowledge is gained of the nature of the stress distributions in paper sheets.

The very low incidence of the total separation of fibres after straining the sheet to failure is of considerable interest. One sixth of the change in bonded area is caused by total bond breakage, hence only one sixth of the light scattering coefficient change observed by Nordman can be attributed to the total separation of fibres. This change arises from 5 bonds out of 250 observed for the machine-direction strips and 21 out of the 382 observed in the cross-direction strips. This low incidence of the complete separation of previously bonded fibres is clearly of prime importance in the consideration of any theory that incorporates bond breakage as a central feature and this aspect will be considered in greater detail in a later paper.[6]

The observation that the mean size of the bonds that break completely is smaller than average implies that the smaller bonds are weaker and break preferentially. Thus, it appears that bond size is correlated with bond strength and bond strength is a major factor in governing complete bond breakage rather than local stress distribution.

In summary, it has been found that, on straining sheets to failure, bonds tend to break partially rather than completely and there is a much higher incidence of breakage in the cross-direction than in the machine-direction strips. Several reasons can be put forward for the phenomenon of partial breakage, although undoubtedly the distribution of intermolecular bond strength over the bond area and the relief of high stress concentrations at the bond site are important. The complete separation of previously bonded fibres is a relatively infrequent occurrence and when total bond breakage does occur it is confined to the smaller bonds.

It will be evident from this paper that, at the time of its submission, many of the experimental results—in particular, those relating to partial bond breakage—were not fully understood. A search for an explanation of these phenomena led to the formulation of a new theory of the structure and properties of paper, which was presented in a later paper at the conference.[6]

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Appendix

In addition to the work on bond breakage on sheets under tensile strain, a preliminary study was made of the behaviour of bonds during the folding of a sheet. Although only of an exploratory nature, the experiments yielded results that were of sufficient interest to be presented at the symposium and are therefore reported here.

Strips of standard handsheets (10 min Valley beaten spruce sulphite) were folded on a Schopper folding tester through 180° while under a tension of 1 kg. The fibre-to-fibre bonds in the surfaces of the sheets in the region of the fold were examined prior to folding and after the first, second and third folds, the fold being made in the same direction on each occasion. The degree of bond breakage was measured after each fold.

It was found that, in contrast to the case of tensile straining, the total failure of bonded crossings was a common occurrence. After one, two and three folds, 21 per cent, 34 per cent and 43 per cent, respectively, of the 250 bonds examined were found to have broken completely. The partial breakage of bonds, while present, was much less frequent than in the case of tensile straining. A further observation was that the surface on the outside of the fold appeared to show more breakage than the inside surface.

This exploratory work on fold indicates how the observational techniques can be applied to an investigation of bond behaviour, with a resulting elucidation of paper behaviour, under deformations other than tensile straining.

Transcription of Discussion

DISCUSSION

DR. H. CORTE: Stresses in the centre of the sheet are different from those in or near the surface. How far are the optical results representative of what happens inside the sheet?—or do they show merely edge effects?

MR. P. A. TYDEMAN: We think that qualitatively they are closely representative.

DR. CORTE: I can imagine that stresses in the sheet are higher. The fibres lying on top certainly have fewer bonds than those inside the sheet.

MR. D. H. PAGE: The change in optical contact area we get does correspond very well with the change in scattering coefficient that Nordman got and it indicates that there is the same area loss in the body of the sheet as there is on the surface. Furthermore, we must remember that, as we said, many of the fibres we observed are almost in the body of the sheet, in this sense, that we look at the surface and we examine only a small part of a fibre, the remainder of which may be completely covered by other fibres.

MR. J. MARDON: It would be interesting to know the rate at which you were straining. At, say, 2 in/sec, the actual breakage observed under normal light occurs at something less than 9 000 frames a second. On one frame you see nothing, on the next frame the paper will be broken.

Do you say that the work is carried out on bond breakage after tensile rupture? On rupture, surely all the bonds in the area of rupture must be broken, so we need to know the area you were investigating behind the rupture.

MR. TYDEMAN: We sampled bonds over the whole of the area of the tensile specimen as explained in the paper.

MR. MARDON: It would be interesting to know how the distribution of broken bonds varies on the specimen about the area of your rupture.

MR. TYDEMAN: We have been unable to detect any variation over the surface area of the specimen in terms of the total number of bonds on the surface. The samples are quite small.

MR. PAGE: I think we lean very heavily on Nordman's work here—and we are right to do so, because ours is a difficult technique and involves a tremendous amount of work, since we are looking each time at a single fibre-to-fibre bond. Therefore, we feel justified in using Nordman's observations on change in scattering coefficient to give a broader and more integrative picture. He showed quite conclusively that the scattering coefficient change occurs all over the sheet, not just in the region of the fracture. We must bear his very good work in mind when we are thinking of this.

DR. H. F. RANCE: On average, how many fibres thick were the sheets represented by these particular frequency distributions and does the frequency distribution vary according to the thickness of the sheet or according to how many fibres thick it is?

MR. TYDEMAN: I cannot say offhand how many fibres thick the sheets were, but they were 60 g/m^2 handsheets. We have not investigated whether or not there is any effect of thickness.

DR. RANCE: Would you not expect some variation quantitatively in the nature of these distributions with different thicknesses?

MR. TYDEMAN: No, not over the range of normal basis weights.

DR. J. A. VAN DEN AKKER: I wish to comment on the interesting experiments of Kallmes, McIntosh and Leopold. Mr. Truman raised a very interesting question in an earlier discussion. The matter of stress concentration involved in the discussion of his question would inevitably be involved here, but before mentioning this I would like to recall the classic work of deBruyne. He showed the importance of stress concentration in glued joints and the incorrectness of arriving at failing stress by taking the quotient of shear force and area of the joint. In experiments on fibre-to-fibre bond strength of the kind we have just heard about, one would expect severe stress concentration. Accordingly, the apparent shear strength of the bond would be much too low—possibly by a large factor.

MR. PAGE: I would like to follow on from there, if I may. I think there is even more to it than this, particularly when we start considering materials like cellulose film, because the stress concentration is then not only dependent on the fibre, but on the elasticity and thickness of the material to which it is bonded. If we change the thickness of the cellulose film, we might get different results for the force required to break this bond, owing to the change in stress concentration. We did this experiment ourselves (I think I mentioned yesterday), using glass as a substrate—which obviously is extremely inextensible—and we have tended to get lower values of the force required to remove the fibre in shear, because of the very high stress concentration that occurs here. If we make the glass thinner or use something less rigid than glass, we could get higher values. This whole question of the shear strength of bonds is extremely complicated and needs to be looked into in rather more detail.

MR. P. E. WRIST: Van den Akker's point is well taken and must be considered when attempting to explain the differences between the fibre-cellulose film and fibre-fibre bundle strength results. The same uncertainties of geometry during tensioning that cloud the interpretation of these experiments must occur also during actual straining of fibrous webs, therefore we feel there may still be value in the results. To me, of more significance than the difference between the two methods is the consistent and highly significant difference between the bond strength per unit optical bonded area for springwood and summerwood. We had expected that a difference would occur, but had guessed that the greater conformability of the springwood fibres would have made them the stronger bond formers. This was not so.

DR. L. NORDMAN: Have any tests been carried out in which the loading has been less than that required to produce rupture and, in that case, was it observed that the frequency of occurrence of 100 per cent bond breakage increased with increased straining?

MR. TYDEMAN: We have not carried out the exact experiment described in this question, but we have done a similar test. One tensile specimen was strained in successive cycles that, in most cases, progressively increased in magnitude. The first cycle consisted of straining the specimen by an amount slightly less than that corresponding to the yield point, then releasing it and examining the behaviour of the bonds. Only one out of the fifty seven examined showed any loss of area, its degree of breakage being 23 per cent. Successive cycles were carried out on the same specimen and the bond breakage after each cycle was determined and is summarised in the table below.

Thus, even after the sixth cycle, still only 5 per cent of the bonds had completely broken. Each cycle did produce further bond breakage, sometimes by the partial breakage of previously intact bonds, sometimes by an increase of the breakage during a previous cycle. Eventually, this recycling

10 min Valley beaten spruce sulphite handsheet

Cycle No.	Total strain of specimen after each cycle, %	Number of bonds		
		Unbroken	Partially broken	Completely broken
1	0·4	56	1	0
2	0·6	54	3	0
3	0·7	29	28	0
4	0·6	25	31	1
5	1·5	17	37	3
6	2·6	8	46	3

produced more total loss in bonded area than results from a single straining to rupture; moreover, the breakage is still mostly in the form of partial loss in the area of the bonds. After the sixth cycle, only 14 per cent of the bonds had not suffered some degree of loss. It should finally be pointed out that, although these figures were the result of a single experiment, they are considered to have considerable qualitative value.

MR. MARDON: I wish to draw attention to one thing that is relevant to picking at the printing press. Without going into any details, the mathematics of peeling are entirely different from the mathematics of direct separation.

PROF. G. JAYME: On the very interesting results obtained by McIntosh and Leopold on the strength of individual bonds between early and late wood fibres, I would refer to my slides shown yesterday, especially the cross-section of sheets made from pure early and late wood pulps. There can be no doubt that the former form a denser sheet, with higher figures for tensile, burst and fold, but a lower tear value. It is difficult to reconcile this well-known fact with the data of McIntosh and Leopold. One explanation may be of course that the total bonded area is greater in early wood pulp, even if the bonds themselves should be weaker. In addition, the fibres' own strength has to be taken into consideration and the packing density of the cell wall is greater in the late wood fibres as we have proved by staining and other techniques. This should explain the higher value for tearing strength obtained with late wood pulp, together with the fact that the total bonded area in late wood pulp sheets is smaller.

MR. WRIST: There is not necessarily any difficulty of reconciliation between the facts as stated by Prof. Jayme and the results of Leopold and

McIntosh. The latter have shown that individual summerwood fibres have a greater strength per unit cross-section than springwood and that summerwood fibres form stronger bond densities with one another than springwood fibres do. They have shown, moreover, that summerwood sheets are weaker than springwood sheets (in agreement with Jayme) and we must therefore conclude that this is explained by the differences in packing density and by a lower total bonded area in the summerwood fibre sheets. The figures of bonded area reported by Leopold relate only to the bonds they formed and broke experimentally and bear no connection to the number or to the average area of bonds that would be formed within a sheet.

DR. CORTE: At what approximate stresses (as percentage of the breaking stress) did areas of optical contact begin to disappear and at what stresses did the first 'optical bonds' disappear completely?

MR. PAGE: This is a question you should ask Dr. Nordman. We are looking at only a small sample of the bonds; he has looked at the whole lot at once.

Written contributions

DR. O. J. KALLMES (*for C. Mayhood, O. J. Kallmes and M. M. Cauley*): In the film just shown, we demonstrated the quantitative shear rupture of a single fibre-fibre contact. The shear forces on four softwood pulps were about the same, about 30 000 g/cm^2 per unit area of *optical* contact. This finding indirectly emphasises that optical contact is somehow linearly related to bonded area, but so long as we talk in terms of shear forces per unit optical contact area, this relationship is irrelevant *for now*.

MR. A. W. O'SULLIVAN: Some work that may be of help in a discussion on the differences in behaviour between handsheets dried (*a*) under tension and (*b*) free to shrink is being carried out at the present.

Using the optical method and a modification of Ingmanson and Thode's extrapolation technique (Young's modulus instead of breaking length)* on similar handsheets dried (*a*) and (*b*), results have shown that, in the case of (*b*), increased beating (Lampén mill) was followed by increased shrinkage on drying and decreased dried fibre surface area when compared with that of (*a*). Values of percentage bonded area (percentage of the total fibre surface) at any given freeness were about the same for the two cases: but, since the

* Ingmanson, W. L. and Thode, E. F., *Tappi*, 1959, **42** (1), 74–83; 83–93

surface area of (*b*) was less than that of (*a*), it follows that fewer optical bonds were present in (*b*).