Preferred citation: M.B. Lyne, M. Jackson, A.E. Ranger and A.R.V. Trigg. Evaluation and optimisation of the in-plane tearing strength of paper. In **The Fundamental Properties of Paper Related to its Uses**, *Trans. of the Vth Fund. Res. Symp. Cambridge, 1973*, (F. Bolam, ed.), pp 269–298, FRC, Manchester, 2018. DOI: 10.15376/frc.1973.1.269.

EVALUATION AND OPTIMISATION OF THE IN-PLANE TEARING STRENGTH OF PAPER

M. B. LYNE,* M. JACKSON, A. E. RANGER and A. R. V. TRIGG, MacMillan Bloedel Research Ltd., Vancouver, B.C., Canada

---

Synopsis Web failure in the papermaking and printing operations is considered as an in-plane tearing mechanism and two aspects of this—in-plane edge tear and in-plane started tear—are discussed.

A technique is proposed for the measurement of in-plane edge tearing strength and this is used to assess disc slitter performance and the potential of new approaches to slitting. It is shown that water jet slitting offers a possible alternative to conventional disc slitting, yielding edges with higher and more uniform edge tearing strength than those obtained from conventional disc slitting. The technique is used also to evaluate the influence of various edge defects on edge tearing strength. It is found that, whereas shives have no significant effect on the edge tearing strength of newsprint evaluated in this investigation, short edge cuts cause significant reductions in edge tearing strength. The strain concentration about web defects is examined using laser holographic interferometry and the observations are in qualitative agreement with those obtained with the edge tear tester.

Whereas the edge tearing strength is a measure of the force required to initiate a tear in the edge of a paper web, the in-plane started tearing strength is an energy measure of the flaw-carrying ability of the web. A pendulum tester, designed to evaluate this parameter, is used to determine how the degree of bleaching, the extent of beating and the drying history of chemical pulp in conjunction with the drainage characteristics of groundwood affect the in-plane started tear characteristics of paper. The relationship between Elmendorf and in-plane started tear is also discussed.

Introduction

THE significance of the in-plane tearing strength of paper in relation to its runnability performance during the dry stages of the papermaking process and in subsequent web printing operations has been discussed in an earlier publication.[1] Although that work was largely concerned with the assessment

* Present address—Swedish Forest Products Research Laboratory, Stockholm

Under the chairmanship of Prof. H. W. Giertz of the in-plane started tearing strength and its relationship to Elmendorf tearing strength, the distinction was made between the in-plane edge tearing strength and the started in-plane tearing strength. The former is a measure of the force required to initiate a tear in the edge of a web; the latter is a measure of the energy consumed in propagating a started tear.

In this present work, the in-plane edge test has been used to assess the influence of various types of edge defect, as well as the influence of various alternative approaches to conventional web slitting on edge tearing strength. The in-plane started tear test has been used on the other hand to determine the influence of various chemical and groundwood pulp parameters on the tearing response of paper.

Edge tearing strength of paper

IN AN earlier publication,[1] an edge tear tester equipped with diverging bar clamps was proposed. As illustrated in Fig. 1, this device causes a high stress concentration at the edge of the test specimen on the convergent side of the nips. By making the stress on this edge much greater than that in the remainder of the specimen, the total load at failure strongly depends on the force required to break the edge and thereby initiate tearing.

Skew tensions are caused in printing presses by built-in differences in web tension, faulty reel build or improper press adjustment. Pressroom tears, whether they start at a web defect or not, are often triggered off by a differential stress and are thus caused by skew tension. Consequently, the edge tear tester gives an accurate and realistic evaluation of edge strength. A technical description of this tester, together with an evaluation of its performance, is given in appendix 1.

The weakening effect of web defects and the resistance of slit edges to the initiation of tearing are critical factors in the running performance of newsprint. The edge tear test has therefore been used to measure the strength of newsprint edges containing shives, bark cell clusters, nicks, overcalendering marks and slime hole peripheries. The strain patterns caused by these defects during edge tear tests have been made visible through the use of laser interference holography. In this technique, holograms of a specimen at two levels of strain are superimposed to give a picture of the relative micro-displacements over the entire test surface.

The nature of the slitting mechanism employed and the uniformity of slitting quality also largely determine the minimum edge tearing strength or the point at which the web is most likely to rupture.

A disc and its complementary bed knife slit mainly by a mechanical shearing action. As shown in Fig. 2, a photomicrograph of a disc slit edge, the shearing action of the disc slitter causes a general displacement of the web

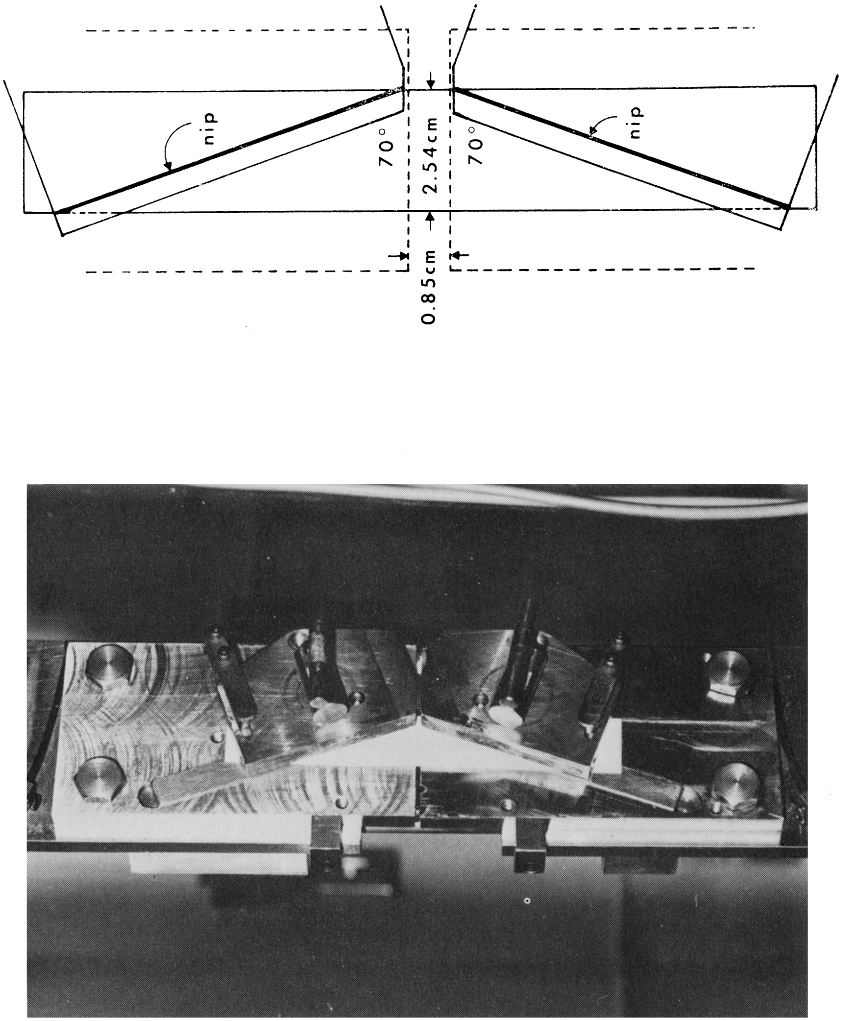


Fig. 1—Photograph and schematic diagram of the edge tear tester

structure, which manifests itself as a foldover of fibres at the edge. The result is a probable loss of bonded area in the zone adjacent to the edge that, in turn, can cause reductions in edge tearing strength. This effect is aggravated when slitter blades become dull and is compounded when the blades are burred or nicked, since periodic cuts in the edge of the web can occur.

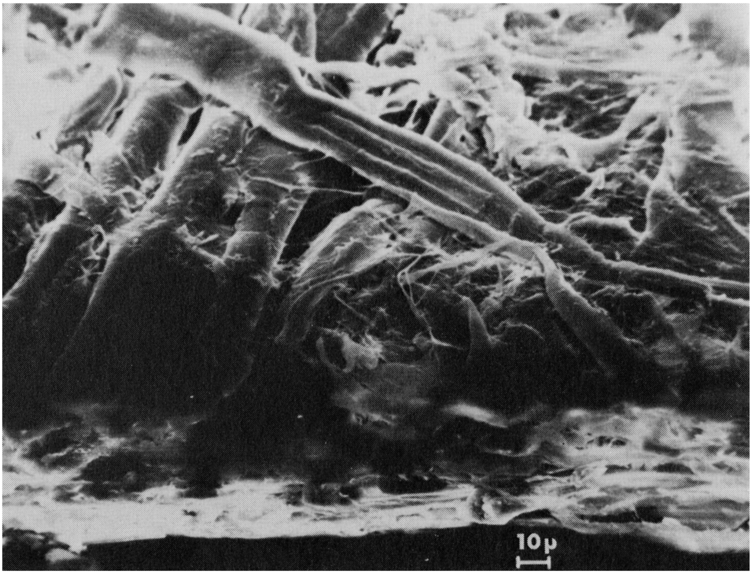


Fig. 2—Photomicrograph of a disc slit edge

In the mill, slitter blades are either sharpened or replaced when they become so dull that unsatisfactorily rough edges are created on rolls. This practice involves the loss of culled paper, as well as the cost of slitter maintenance.

Disc slitters also liberate lignocellulose debris from the edges of the web and scatter it over the web. Consequently, slitter dust can be a contributing factor to lint accumulation on printing plates and blankets. In offset lithography, linting severely limits the number of copies that can be printed before a wash-up is required and thus restricts the process as a high speed, high volume means of printing.

As an alternative to disc slitting, laser beam and high velocity water jet slitting offer potential means of producing dust-free uniform edges and an evaluation has been made of the relative edge tearing strength of laser, high velocity water jet and disc slit newsprint.

Experimental

Edge defects

OVERCALENDERING marks, shives and bark cell clusters were sampled from one roll of western Canadian newsprint. All samples were cut in the machine-direction with the defect positioned at the edge of each test specimen between the nips on the convergent side. Large slime holes were sampled from another newsprint machine and cut with their machine-direction edges aligned to constitute the test edges on the convergent side of the nips. In this way, the resistance of the edge of slime holes to the initiation of tearing was assessed, regardless of their original position in the web.

TABLE 1—THE EFFECT OF DEFECTS ON THE EDGE TEARING STRENGTH OF NEWSPRINT

Defect	*Edge tearing strength of*		*Failure at defect, per cent*
	*Edge with defect, kg**	*Adjacent good edge, kg**	
Shives	4·08±0·23	4·14±0·17	39
Bark	4·23±0·23	4·34±0·18	7
Overcalendering mark	4·67±0·23	4·26±0·22	†
1·5 mm cut	3·83±0·18	4·27±0·22	100
Slime hole edge	4·08±0·20	4·58±0·20	†

* Mean strength and error at 95 per cent confidence, sample size = 18
† Defects extend across entire test edge

Results shown in Table 1 for specimens with defects are compared with samples taken from an adjacent strip (along the edge) in order to minimise the effects of variation in grammage and web composition.

Laser and high velocity water jet slitting

It has been previously shown[1] that basic web properties such as degree of bonding can influence the edge tearing strength. Therefore, it is not surprising that edge tearing strength, as tested on a guillotine-cut edge, varies from one specimen of newsprint to another. In order to separate the effect of slitting quality on the edge tearing strength from the effects of roll to roll and within roll variations, each slit edge tested has been compared with a guillotine-cut edge from an adjacent portion of the web.

An index of slitter quality can then be derived from the ratio of the mean edge tearing strength of the slit edge to the mean edge tearing strength of the adjacent guillotine-cut edge. In addition, an appreciation of slitting uniformity can be obtained from the coefficients of variation of the edge tearing strengths of the various slitters evaluated.

High velocity water jet cutting devices consist of a pneumatically or hydraulically driven pump capable of generating high water pressures (typically in the range 20 000–100 000 lb/in^2) used in conjunction with the fine orifices or nozzles from which the water jets issue. Harris & Brierley[2] investigated the slitting of newsprint using a volume-limited pneumatic water pump. They used fine nozzles (0·05–0·1 mm in diameter) and pressures in the range 20½ k–25½ k lb/in². Franz[3] used a hydraulic pumping system capable of generating 50½ k lb/in² while supplying several nozzles to explore the slitting of corrugated board.

Since a mill application of water jet slitting would require that several nozzles be run simultaneously to satisfy the needs of one papermachine, experiments conducted by MacMillan Bloedel Research have continued to utilise a hydraulic pumping system similar to that used by Franz. Two trials have been made on newsprint at the laboratories of McCartney Manufacturing Co. Inc. of Baxter Springs, Kansas. In the first trial, the newsprint was fed into a nip roller system at 2 000 ft/min and slit with a 0·1 mm diameter nozzle at various pressures in the range 20½ k–35½ k lb/in². The same paper as that used in this trial was also slit at 5 000 ft/min, using a 400 W carbon dioxide laser developed by the Rice Barton Corporation of Worcester, Mass. The edge tearing strength data pertaining to laser, water jet and disc slit edges are shown in Table 2.

TABLE 2—THE EDGE TEARING STRENGTH OF DISC, WATER JET AND LASER SLIT NEWSPRINT

Slitter type	*Edge tearing strength* *Failure load, kg*			*Coefficient of variation, per cent*			*Edge tearing strength ratio*	
	Guillotine	*Disc*	*Water jet*	*Guillotine*	*Disc*	*Water jet*	*Disc guillotine*	*Water jet guillotine*
Water jet (2 000 ft/min)								
20½ k lb/in²	5·19	4·73	4·99	7·9	8·2	6·2	0·91	0·96
25½ k lb/in²	4·99	4·77	4·88	7·4	5·5	8·1	0·95	0·98
35½ k lb/in²	4·72	4·56	4·77	6·8	8·5	7·5	0·97	1·01
	Guillotine	*Disc*	*Laser*	*Guillotine*	*Disc*	*Laser*	*Disc: G*	*Laser: G*
Laser (5 000 ft/min)	4·88	4·85	4·79	5·9	4·7	8·6	0·99	0·98

In a second water jet slitting trial, the paper was fed through the unit at 5 200 ft/min and at various pressures in the range 30½ k–45½ k lb/in². The flow rate in both trials was approximately 0·1 (U.S.) gal/min of water per nozzle with 0·25 per cent of a long chain polymer added to the water supply to maintain collimation of the jet at 0·1 mm diameter at distances of 2–4 cm from the nozzle. The data from this second trial are shown in Table 3.

TABLE 3—THE EDGE TEARING STRENGTH OF WATER JET SLIT NEWSPRINT

Slitting conditions	*Edge tearing strength* *Failure load, kg* *Guillotine*	*Water jet*	*Coefficient of variation, per cent* *Guillotine*	*Water jet*	*Edge tearing strength ratio* *Water jet/guillotine*
Water jet (5 200 ft/min)					
$30\frac{1}{2}$ k lb/in^2	3·60	3·24	11·1	16·2	0·90
$35\frac{1}{2}$ k lb/in^2	3·48	3·22	11·5	7·7	0·93
$40\frac{1}{2}$k lb/in^2	3·07	3·14	11·3	8·6	1·02
$45\frac{1}{2}$k lb/in^2	2·77	2·77	10·8	10·1	1·00

Results

Influence of nicks, shives, bark, overcalender marks and slime holes on edge tearing strength

As SHOWN in Table 1, shives, bark and overcalender marks, as sampled, do not have a statistically significant effect on edge tearing strength. Yet, if a 1·5 mm long cut is made in the edge of the same paper to simulate the average length of the larger shives found in newsprint, the edge tearing strength is significantly reduced over that of the unnicked edge. As mentioned in the study of the effects of cuts in appendix 1, small decreases in strength are important, since an equivalently narrowed specimen would have resulted in an increased edge strength.

Although several authors[4–6] claim that shives are almost invariably found in induced web breaks, it would appear from this study that only those shives that are sufficiently thick to cause calender cuts or to be removed from the web by a disc slitter have any influence on tearing strength. It should be noted that failure at the nick occurred in all edge tear tests where cuts were made in the test edges. This was also the case in a previous study described in appendix 1, where the nick was as small as 0·5 mm. Since all of the edge tear tests propagated tears in the cross-direction, the shives had various orientations with respect to the test edge. Therefore, that web failures should intercept the shives 39 per cent of the time is largely a matter of statistical probability (the test zone being 0·85 cm in length).

The results shown in Table 1 also indicate that slime holes not only cause strain concentration owing to their disruption of the web structure, but also exhibit edges that are less resistant to tearing than are normal slit edges.

In an attempt to carry out an analysis of the strain occurring about the types of web defect mentioned here, laser holographic interferometry was used. The process by which the holographic images were formed is discussed in appendix 2.

If a holographic film plate is double exposed and the subject moved less than 100 μ between exposures, the two resulting reconstructed images will

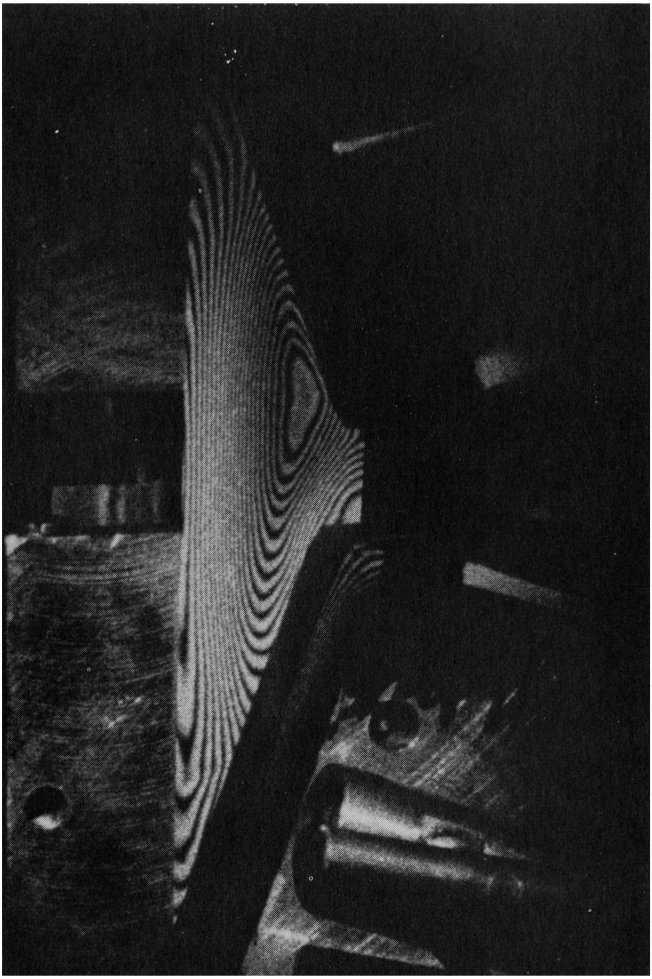


Fig. 3—Strain distribution in a newsprint sample in the edge tear tester

interfere to produce a fringe pattern in the area of movement.[7] Fig. 3 shows the resulting strain pattern in a standard newsprint strip, subject to a total strain of 1 per cent in the edge tear tester when a small additional increment of strain is applied between exposures. The jaws of the tester have been moved a small increment by an appropriately placed micrometer. Areas of strain concentration are indicated by a congestion of finer fringes, since the fringes represent lines of equal displacement.

Samples containing shives, bark cell clusters and overcalender marks situated at the edge were placed, as previously described, in the edge tear tester. No difference could be detected in the concentration of strain over that of the specimen containing no defect. When a 1·5 mm nick was introduced in the test edge, however, strain concentration was apparent at the apex of the tear as can be seen from Fig. 4.

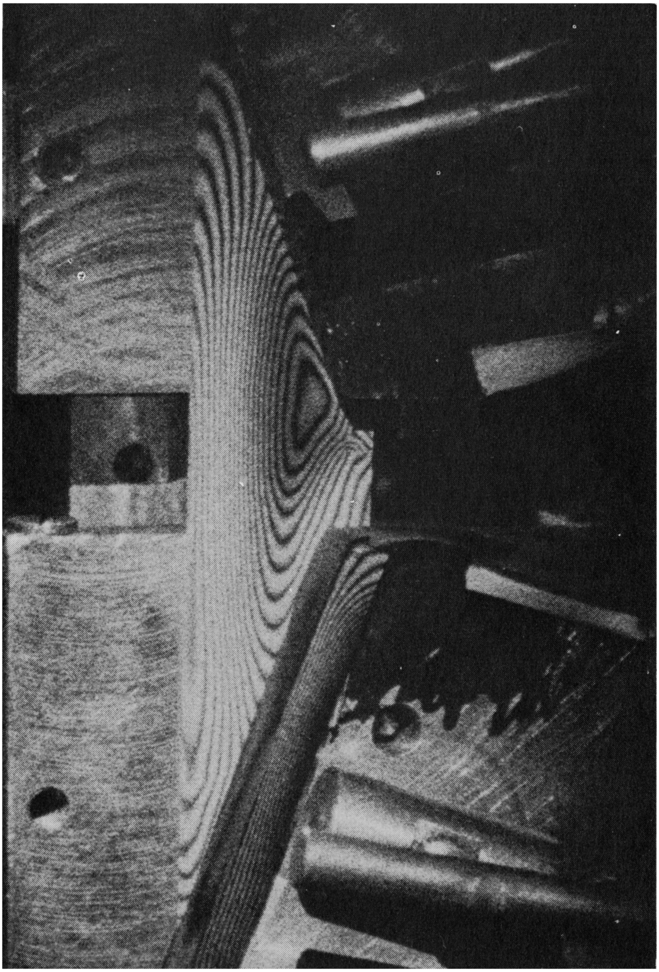


Fig. 4—Strain distribution about an edge cut in a newsprint sample in the edge tear tester

In an effort to analyse the factors controlling the concentration of strain at the apex of tears (that is, cuts in this test), two semi-bleached kraft specimens were tested as above. The beaten kraft specimen (500° CSF, 0·670 g/cm^3 density) shown in Fig. 5 demonstrated a considerable dissipation of the strain concentration at the tear apex. The corresponding nicked unbeaten kraft specimen (720° CSF, 0·500 g/cm^3 density) resembled the nicked newsprint sample, in which the fringe pattern was undisturbed beyond the apex of the

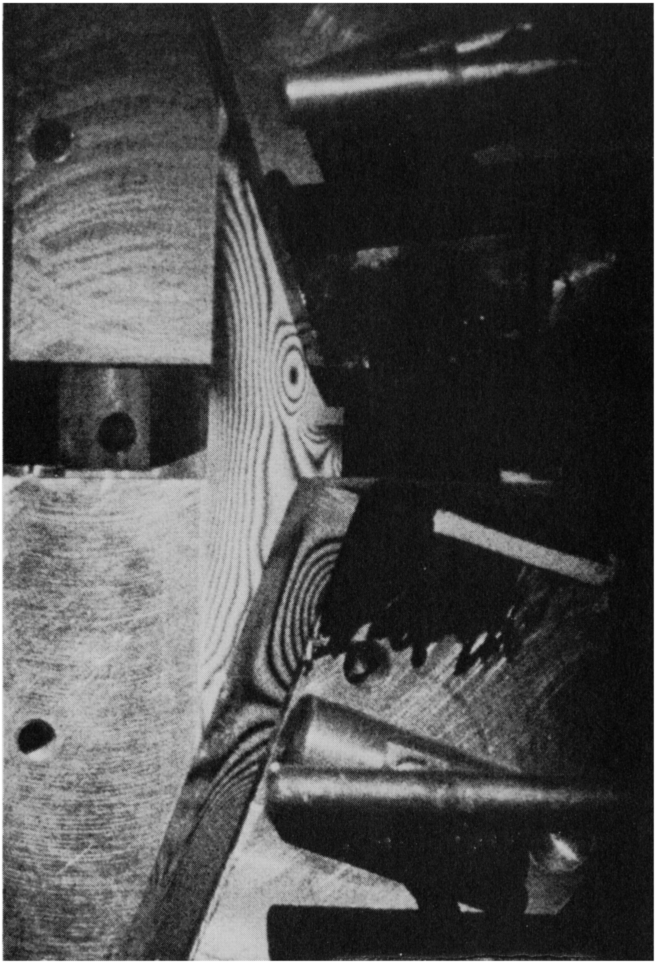


Fig. 5—Strain distribution about an edge cut in a beaten kraft sample in the edge tear tester

nick, indicating severe strain concentration at the apex. As previously theorised,[1] strain concentration about the apex of in-plane tears is lessened as beating progresses. This factor, at least in part, accounts for the more gradual post-maximum decline of in-plane tearing strength compared with Elmendorf tearing strength as beating progresses.

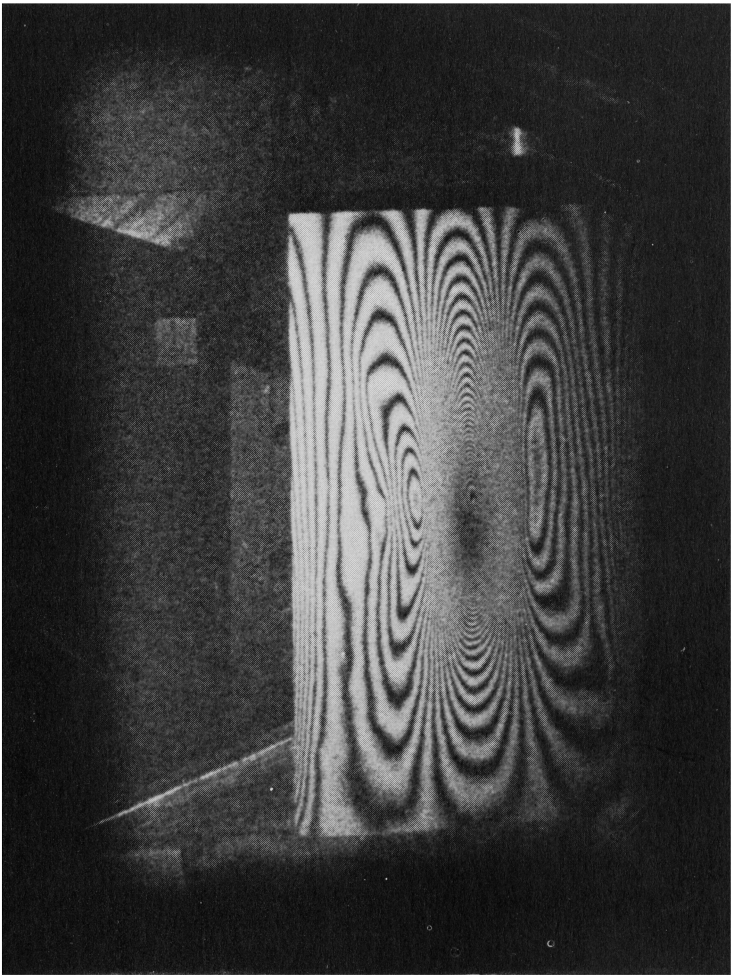


Fig. 6—Influence of a centre cut on the strain distribution in a newsprint sample under tension

The implications of cuts, for newsprint runnability, can be further appreciated by examining Fig. 6. The paper has been strained in ordinary tension after a 2 mm × 2 mm cross has been cut in its centre. The extent to which this synthesised web defect affects strain uniformity is evidenced by a broad disruption of the fringe pattern normally associated with webs under tensile strain. A detailed description of tensile strain patterns in paper webs can be found in the paper by Lyne & Hazell also given at this symposium.

Relative edge tearing strengths of disc slit, high velocity water jet slit and laser slit newsprint

Since the inception of tears presumably occurs at the point of minimum edge tearing strength, a low coefficient of variation is as critical as a high mean strength to good edge performance.

The data recorded in Table 2 indicate that in the pressure range $20\frac{1}{2}$ k–$35\frac{1}{2}$ k lb/in^2 increased jet pressures yield stronger edges than do conventional disc slitting as assessed by the edge tearing strength ratios. Not only is the failure load greater in the case of water jet slitting, but the coefficients of variation also appear to be generally lower. The results of the laser slitting are recorded in this table, too, where it is seen that the ratio between the laser slit and guillotine-cut edge tearing strength is similar to the corresponding ratio achieved with the water jet at high pressure. The coefficient of variation however is greater than for the corresponding disc slit edge.

Somewhat makeshift roll handling equipment was used in the initial trial in which the slitting was conducted at 2 000 ft/min. The data from the second trial, which was run at 5 200 ft/min are shown in Table 3. In this case, comparative disc slit edges were not available. The edge tearing strength ratio between the water jet and the guillotine-cut edge, however, is optimised at $40\frac{1}{2}$ k lb/in^2 and this is accompanied by a low coefficient of variation.

Discussion

Web defects

PRESENT shive removal techniques in western Canada appear to be effective in removing thicker shives, which could cause calender cuts. Since close examination over the entire surface of 100 ft of the worst roll of newsprint found in this study yielded no shives of sufficient dimension to cause an edge tearing strength reduction, the possibility of a shive of critical dimensions occurring at the edge is thus exceedingly low. Yet, at the present pressroom break frequency in the range 2–3 breaks per 100 rolls (one break per 150 miles of paper), even low probability events can be significant.

Nicks (or cuts) whether they occur within the web or in the edge of the sheet are potential tear sites. General runnability could be improved by a reduction in damage to the ends of newsprint rolls. Every effort should be made to protect the edges of newsprint rolls from marking in transit and during handling.

Slitting

As shown in Fig. 7, water jet slitting effectively combs the web apart. It may be that this combing action produces a stronger and more uniform edge that with disc slitting, because less disruption is caused in the adjacent web structure. The energy required for slitting is supplied solely by the high velocity water jet, thus no strain concentration is caused at the point of separation of the web. To a reasonable approximation, the water jet is a point with zero dimension in cross-section. Therefore, no wrinkles are created in the web as with conventional disc slitting when the web is forced to separate about the rotating blade. Also, winder breaks due to disc misalignment and lateral movement of the web across the slitter nip would be eliminated.

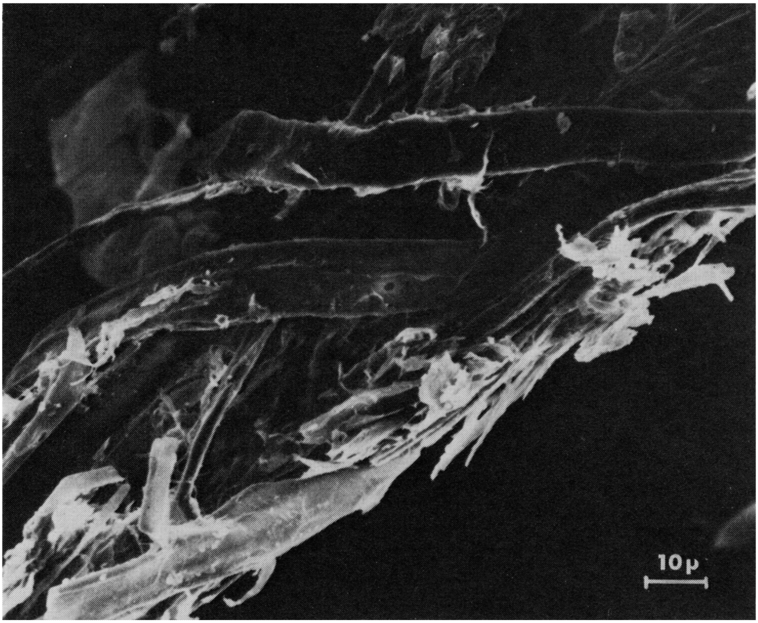


Fig. 7—Photomicrograph of a high pressure water jet slit edge

Any debris that might be liberated from the slitting zone is carried with the water jet down a drain pipe on the opposite side of the web. An examination of 50 ft of the edge of water jet slit newsprint revealed that all of the shives protruding into the edge were cut off. No evidence was found to suggest that larger shives had been knocked out of the edge as may occur in conventional disc slitting.

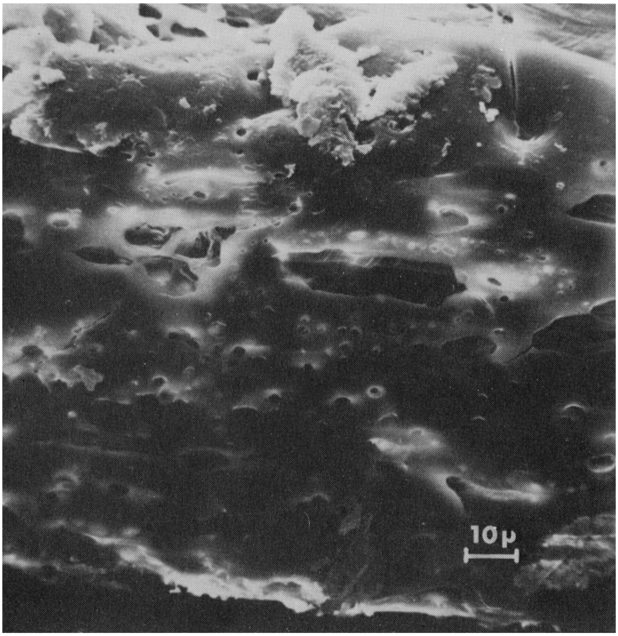


Fig. 8—Photomicrograph of a laser slit edge

The somewhat lower and non-uniform strengths observed with laser-slit newsprint may be explained by examining electron photomicrographs (Fig. 8). The laser fuses the cellulose material in the web, producing a cracked and probably brittle structure. Photomicrographs also show a deposition of fused particulate matter on the surface of the web adjacent to the slit edge. Since it is highly unlikely that this material is bonded to the web, this deposit may contribute to linting in the offset process.

The safety aspects can never be overemphasised when any form of slitting operation is under discussion or evaluation and each technique will have its own set of regulations regarding safe operation. The high velocity water jet slitter envisaged for a papermachine (Fig. 9) will employ guard saucers around each nozzle. A fixed gap of 1 cm between the saucer and drain trough is planned to ensure that the operator's hand cannot be inserted into the jet.

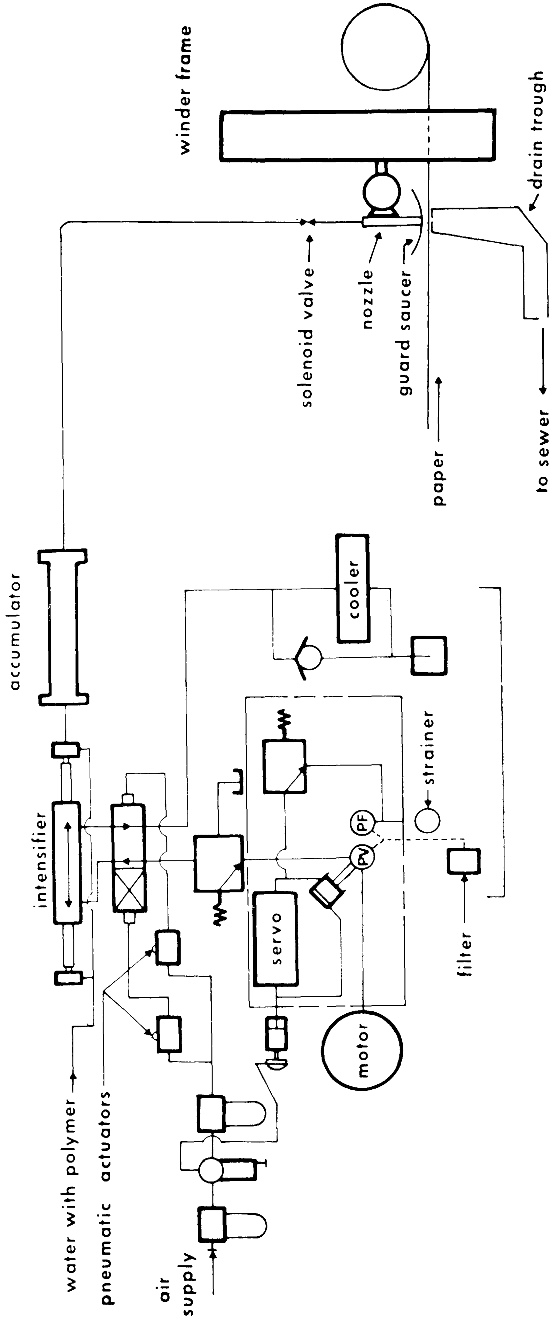


Fig. 9—Schematic diagram of a high velocity water jet slitting arrangement

Air-driven solenoid valves will be used to shut off the jet during the threading of the winder. Since the jet pressure is generated by a direct-acting hydraulic ram (no stored energy from compressed air) of fixed capacity, no danger will ensue in the event that a water line is ruptured.

In-plane started tearing strength of paper

SINCE it is highly unlikely that web defects in paper can be eliminated on a commercial scale, it is important for the improvement of web runnability that the ability of a web to sustain an existing flaw or defect be optimised. Earlier published work by the authors[1] has indicated that in-plane tearing corresponds more directly with the mode of breakdown of a web in the paper-making and printing operations than does the better known Elmendorf form of tearing, in which the tearing force is approximately normal to the plane of the web. This work discussed the influence of beating on the Elmendorf and in-plane tear test and demonstrated logical response to paper formation, flexural stiffness, mean fibre length and degree of bonding.

The initial work on in-plane tearing strength was carried out using an attachment originally developed by Van den Akker[8] for use with the Instron stress/strain instrument. The practicality of measuring the in-plane tearing strength of paper has been enhanced by the commercialisation of a pendulum instrument whose prototype was previously described.[1]

The degree of bleaching, the extent of beating and the drying history of chemical pulp in conjunction with the drainage characteristics of groundwood pulp are all factors that can be used to optimise in-plane tearing strength. This work is concerned with the effects of these various pulp parameters and paper formation on the relationship between Elmendorf and in-plane tearing strength.

The anomaly of increasing Elmendorf tearing strength with deteriorating formation was further evident in machine-made kraft papers, in which the sole variable was a 2·5-fold increase in the forming consistency. Whereas Elmendorf tear could rise by 20 per cent under these conditions, in-plane tear remained relatively constant or experienced a mild decline.

Fig. 10 shows the relationship between the Elmendorf and in-plane tearing energy as a function of sheet density achieved by beating in a PFI mill for mill unbleached never-dried pulp (60:40 western hemlock:Douglas fir), as well as for this same pulp semi-bleached (CEH) both in the mill and in the laboratory. It is evident that the effect of bleaching is to advance the pulp along the tear/density curve. Mechanical work done on the fibre by the mill stock pumping system may explain the difference between the unbeaten in-plane tearing strengths of the same pulp bleached in the mill and bleached in the laboratory by identical chemical treatments. The inverse relationship between Elmendorf tear and in-plane tear (at least in the earlier stages of beating) is also confirmed in Fig. 10. Full bleaching (CEHDED) was found to cause a further advancement of Elmendorf and in-plane tear.

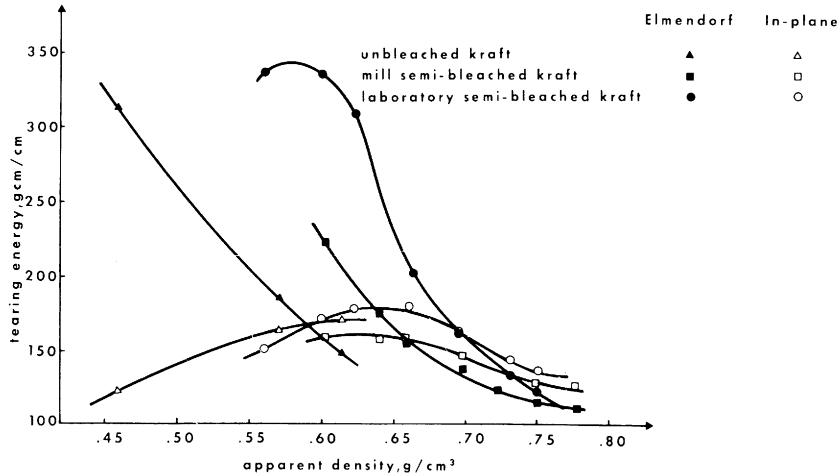


Fig. 10—The influence of beating on the Elmendorf and in-plane tear characteristics of never-dried kraft pulp (60 per cent Western Hemlock: 40 per cent Douglas fir)

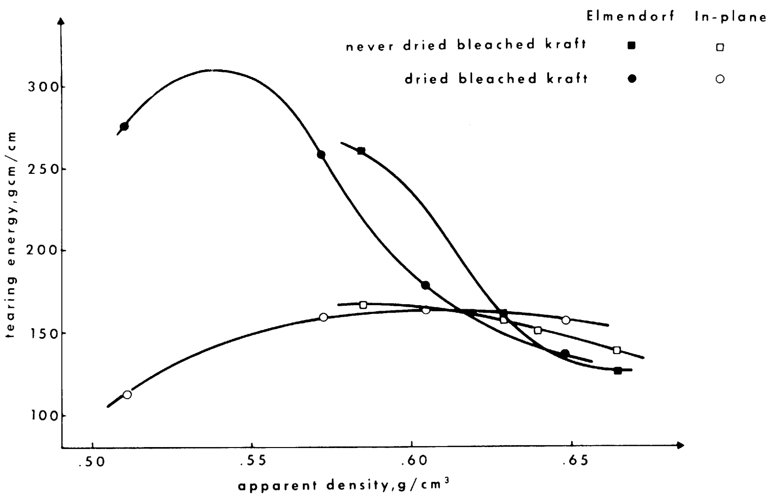


Fig. 11—The influence of beating on the Elmendorf and in-plane tear characteristics of dried and never-dried bleached kraft pulp (100 per cent Western Hemlock)

Fig. 11 illustrates the influence of beating on the Elmendorf and in-plane tear characteristics of dried and never-dried kraft pulp (100 per cent western hemlock). In this figure, never-dried kraft pulp is compared with dried kraft pulp and a pronounced reduction in bonding is evident as a result of pulp drying. Dried pulps generally exhibit higher Elmendorf tear characteristics than never-dried pulps, at least in the early stages of beating, yet drying is generally detrimental for unbeaten in-plane tearing strength. The point at which a never-dried pulp becomes a dried pulp is ill-defined and involves a gradual change in physical properties rather than a step change. Fig. 12 shows how the tearing strength of semi-bleached kraft pulp changes as a function of the pulp dryness before handsheet preparation. The data indicates clearly that drying causes an onset of debonding in the region of 45–55 per cent solids content. Once again, it is evident that, whereas drying improves Elmendorf tearing strength, it tends to cause a reduction in in-plane tearing strength.

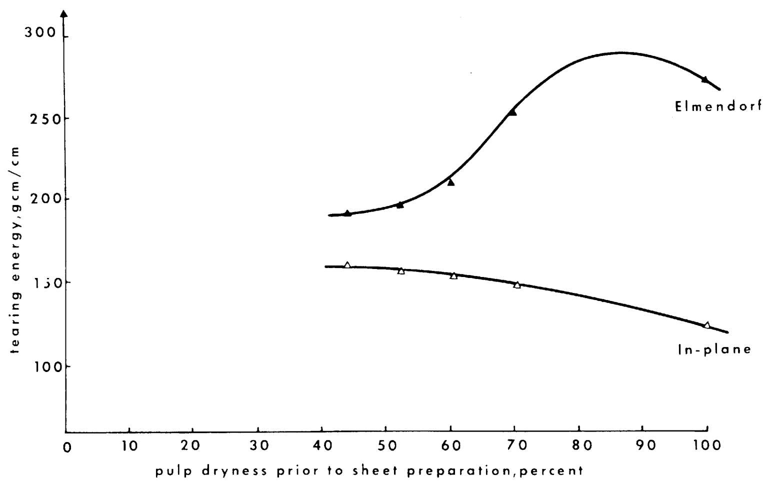


Fig. 12—The influence of pulp dryness on the Elmendorf and in-plane tear characteristcs of mill semi-bleached kraft pulp (60 per cent Western Hemlock: 40 per cent Douglas fir)

For never-dried kraft pulp, the non-linear nature of the relationship between Elmendorf tear and in-plane tear is shown for unbleached, semi-bleached and fully bleached kraft pulp in Fig. 13. The difference in the nature of the curve between the unbleached and bleached forms of the same kraft pulp is evident.

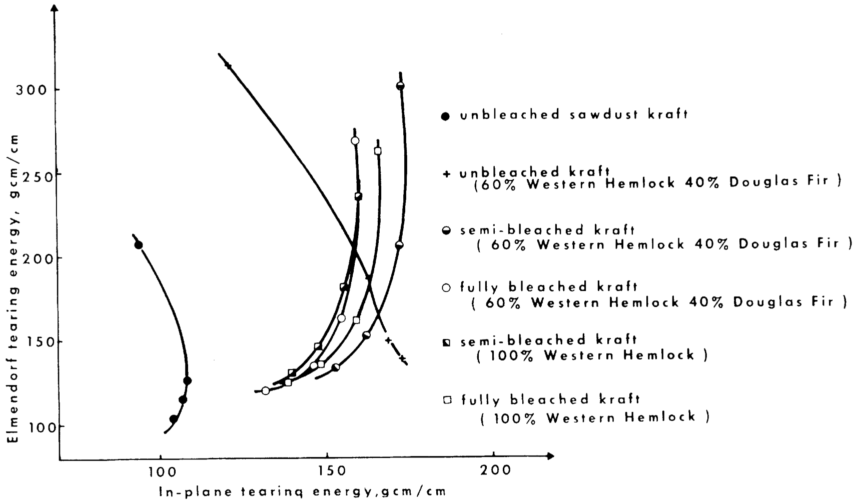


Fig. 13—The relationship between the Elmendorf and in-plane tear characteristics of never-dried kraft pulps

With semi-bleached and bleached dried kraft pulp, the relationship between the two types of tearing strength is shown in Fig. 14. In this case, it is evident that two Elmendorf tearing strength values are possible for a given level of in-plane tearing strength. This fact is related to the debonding effect of the drying process.

The relationship between the Elmendorf and in-plane tear characteristics of a series of eight groundwood pulps produced at different freeness levels on a single grinder is shown in Fig. 15, where it is seen that the correlation between the two forms of strength test is not high (simple correlation coefficient= 0·68). Data are included in this figure to show the influence of ozonation on two samples of chip refiner groundwood pulp. With the western hemlock pulp, ozonation resulted in improved in-plane tearing strength at the expense of Elmendorf tearing strength. On the other hand, ozonation of the spruce pulp caused a reduction in both Elmendorf and in-plane tearing strengths, thus suggesting that the increase in bonding achieved was sufficient to exceed the maximum in-plane tearing strength possible.

Fig. 16 shows the relationship between the two forms of tearing strength for stone groundwood pulp and semi-bleached kraft pulp separately and in admixture in the weight ratio 7:3 to approximate a newsprint furnish. Superimposed on this graph are four beater curves for different kraft pulps. It is evident that the correlation between Elmendorf and in-plane tear for newsprint can be high when the percentage content of kraft pulp is the only variable. Newsprint in-plane tearing strength may be optimised with respect to Elmendorf tearing strength in those cases when—

1. The bonding potential of the kraft component is improved through beating refining and/or the avoidance of predrying.
2. The groundwood freeness is changed to an appropriately lower level either as a result of operational manipulation in the groundwood mill or artificially by the introduction of the ozonation process.
3. The mass formation of the sheet is made as uniform as possible.

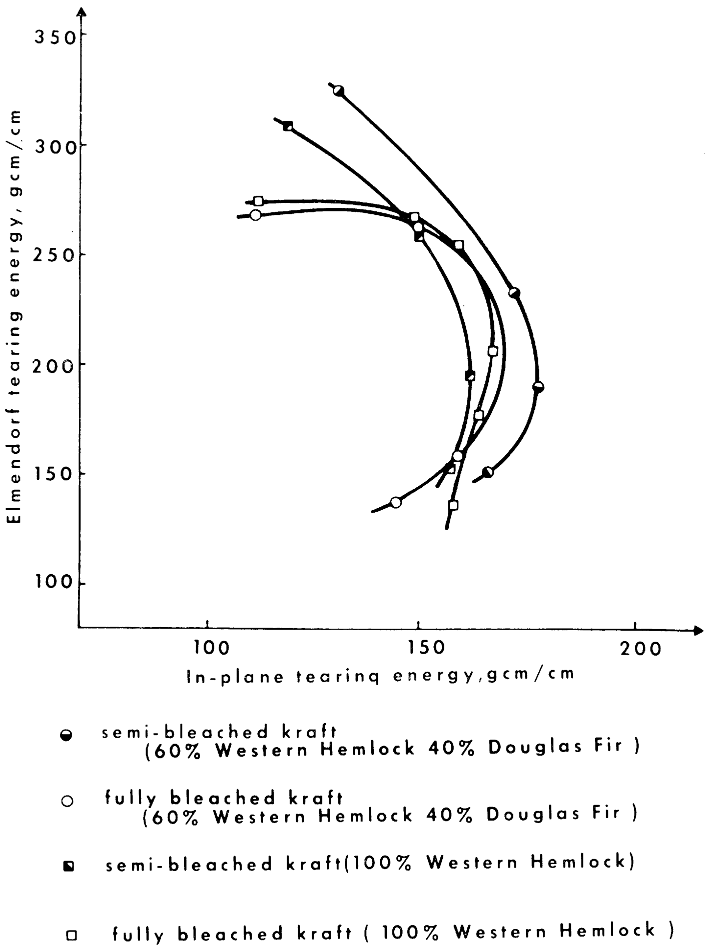
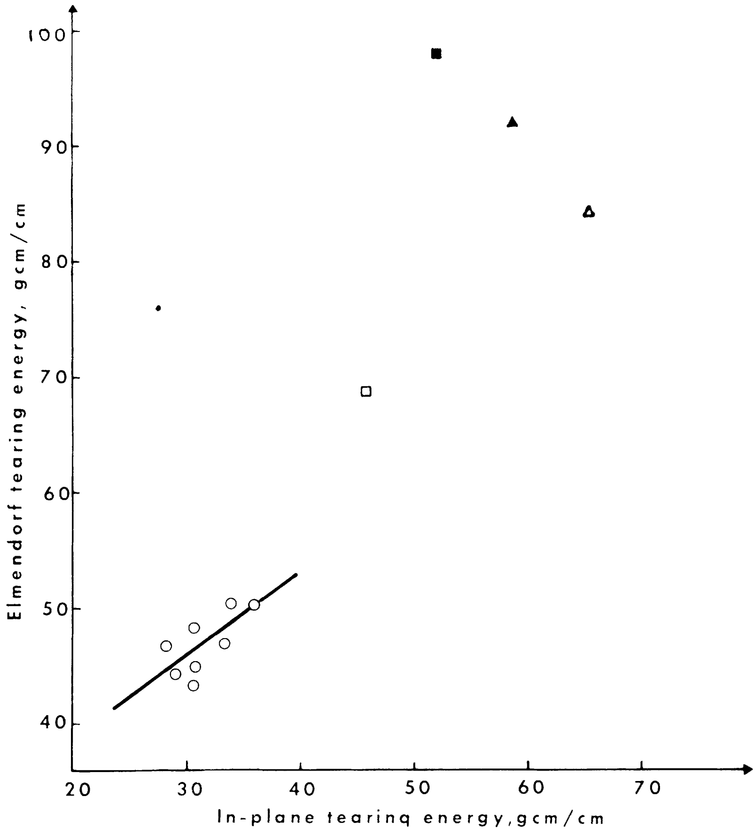


Fig. 14—The relationship between the Elmendorf and in-plane tear characteristics of dried kraft pulps



○ stone groundwood pulp

▲ chip refiner groundwood (100% Western Hemlock)

△ ozonated groundwood (100% Western Hemlock)

■ chip refiner groundwood (100% Eastern Spruce)

□ ozonated chip refiner groundwood

Fig. 15—The relationship between the Elmendorf and in-plane tear characteristics of groundwood pulps

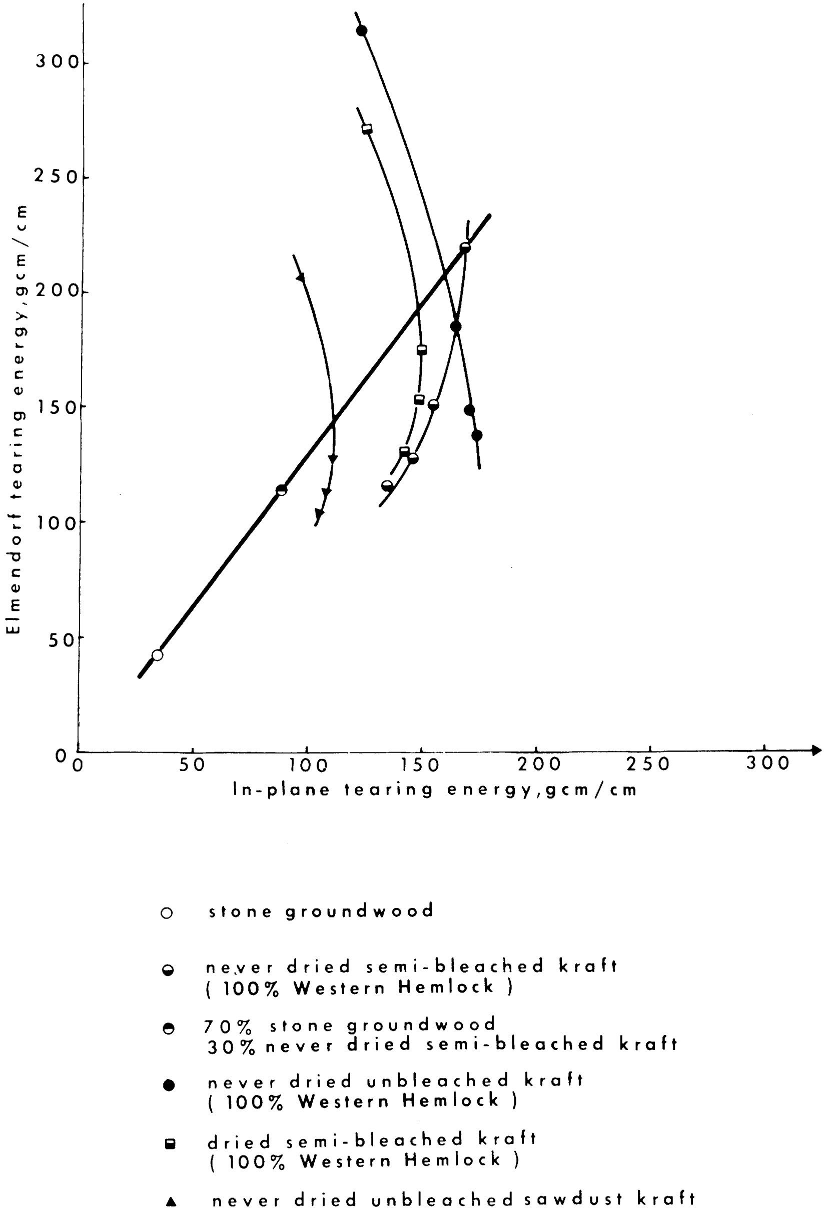


Fig. 16—Tearing strength relationships for kraft pulps and kraft/groundwood mixtures

Concluding remarks

WEB breakdown in the papermaking and printing operations is considered to occur according to an in-plane tearing mechanism and equipment suitable for the measurement of two important aspects of in-plane tearing strength has been discussed.

The in-plane edge tearing strength has been used to define slitter cut quality as well as to evaluate the influence of various defects situated at the edge of the sheet. The in-plane started tearing strength has been used on the other hand to assess the ability of a web to sustain a flaw and the nonequivalence of this parameter with the Elmendorf tear response has been discussed in some detail. It has been found that, whereas pulp drying exhibits a negative effect on the in-plane tearing strength, both bleaching and mild beating have a positive effect, the latter yielding optimum in-plane tearing strength at a significantly higher level of bonding than in the case of Elmendorf tearing strength.

Acknowledgement

The authors would like to thank MacMillan Bloedel Ltd. for permission to present this paper.

References

1. Lyne, M. B., Jackson, M. and Ranger, A. E., *Tappi*, 1972, **55** (6), 926
2. Harris, H. D. and Brierley, W. H., *Application of Water Jet Cutting*, First International Symposium on Jet Cutting Technology (Aptil 1972)
3. Franz, N. C., *Tappi*, 1970, **53** (6), 1 111
4. MacMillan, F. A., Farrell, W. R. and Booth, K. G., *Pulp & Paper Mag. Can.*, 1965, **66** (7), T361
5. Boadway, J. D., Murray, F. E., Cote, L. and Gray, J. T., *Pulp & Paper Mag. Can.*, 1963, **64** (C), T84
6. Sears, G. R., Tyler, R. F. and Denzer, C. W., *Pulp & Paper Mag. Can.*, 1965, **66** (7), T35
7. Beesley, M. J., *Lasers and their Applications* (Taylor & Francis, London, 1971)
8. Van den Akker, J. A., Wink, W. A. and Van Eperen, R. H., *Tappi*, 1967, **50** (9), 466
9. Leith, E. N. and Upatnieks, J., *J. Opt. Soc. Amer.*, 1964, **54** (11), 1 295
10. Leith, E. N. and Upatnieks, J., *Scientific American*, 1965, **212** (6), 24

***Appendix 1**—The MBR edge tear tester*

Technical description—As shown in Fig. 1, the test specimen is clamped in the edge tear tester between line contact jaws, one of which is mounted on guide rods to ensure parallel separation.

Essentially, the design variables in this divergent nip tester are specimen width, the total angle of divergence of the nips and test speed. Since it was desired to test specimens from standard handsheets as well as newsprint, the specimen size was limited to 2·54 cm in width and 15 cm in length. Using a gap at the convergent side of the nips of 0·85 cm, the total angle of divergence of the nips can be a maximum of approximately 140°.

Having fixed the geometry of the test as above, the effect of changing the starting gap at the convergent side of nips on the total load as measured on an Instron tensile tester was evaluated. Fig. 17 is a graph of these results showing that a significant tearing action begins to occur at a minimum span of 1·0 cm. Therefore, a minimum span of 0·85 cm was chosen, allowing a significant portion of the edge to be tested while ensuring that the stress concentration on the edge is sufficient to cause a tearing type of web failure.

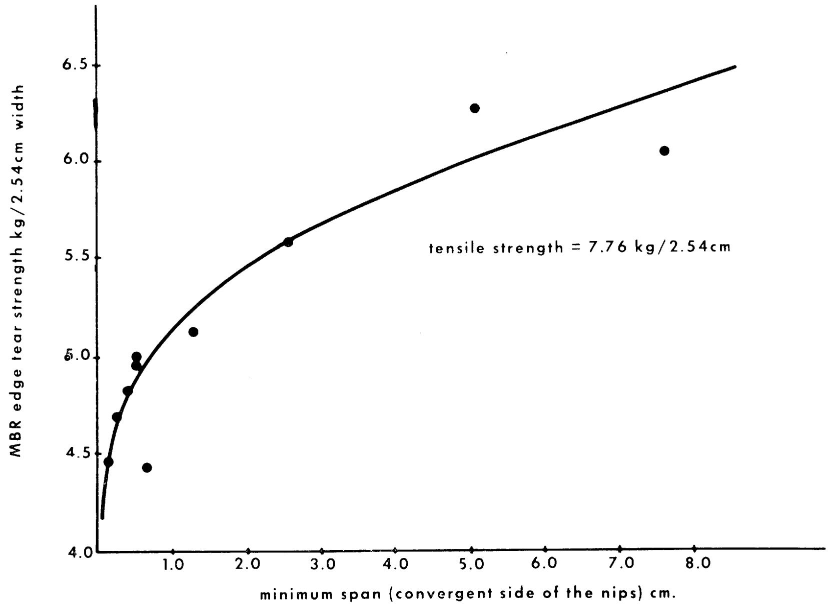


Fig. 17—Edge tearing strength as a function of minimum initial span

Fig. 18 demonstrates the effect of speed of separation of the jaws on the resulting edge tearing strength. The decline in strength with increased speed is a function of the response time of the Instron recording system and may also be a function of the decrease in time for stress relaxation in the specimen. In order to make comparisons

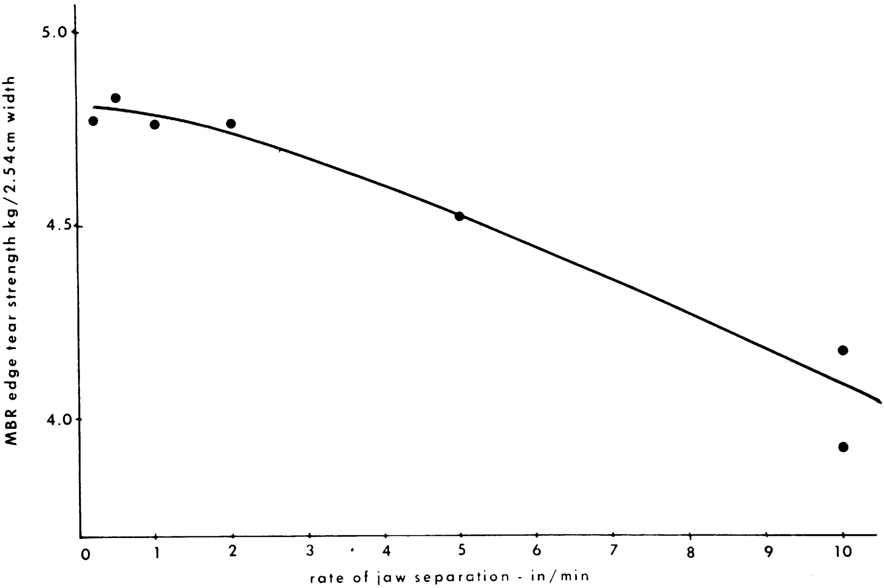


Fig. 18—Edge tearing strength as a function of the rate of jaw separation

between tensile strength and edge tearing strength and to ensure that the instrument response time would be adequate, a speed of 1 in (2·54 cm)/min was chosen.

The edge tearing strength of paper may therefore be defined as the total load at failure of a 2·54 cm wide strip held by line contact nips having an angle of divergence of 140° and constrained to separate at 1 in (2·54 cm)/min along a parallel path from an initial minimum separation of 0·85 cm.

Performance—The sensitivity of the edge tear test to defects or imperfections in the edge of the test specimen is critical to its effectiveness as a runnability indicator. Therefore, it was desired to compare the relative effects of putting a cut in the edge to be tested and reducing the specimen width by an equivalent amount. By using accurately machined templates as shown in Fig. 19, it was possible to match the length of nicks and cut-out portions of the specimens. The results of this study are shown in Fig. 20. Cuts cause a reduction in the edge tearing strength from 4·17 kg to 3·93 kg (approximately 6 per cent) for a 0·5 mm nick and a reduction from 4·75 kg to 3·62 kg (24 per cent) for a 2·5 mm nick, comparing narrowed and nicked specimen values, respectively.

The phenomenon of increasing edge tearing strength with decreasing specimen width is due to the reduction in stress concentration at the test edge. The length of the edge on the convergent side of the nips is effectively increased as the specimen is narrowed, thereby decreasing the severity of the strain ratio between elements on the short and long sides of the nips. This effect may be better appreciated through the theoretical approach pictured in Fig. 21.

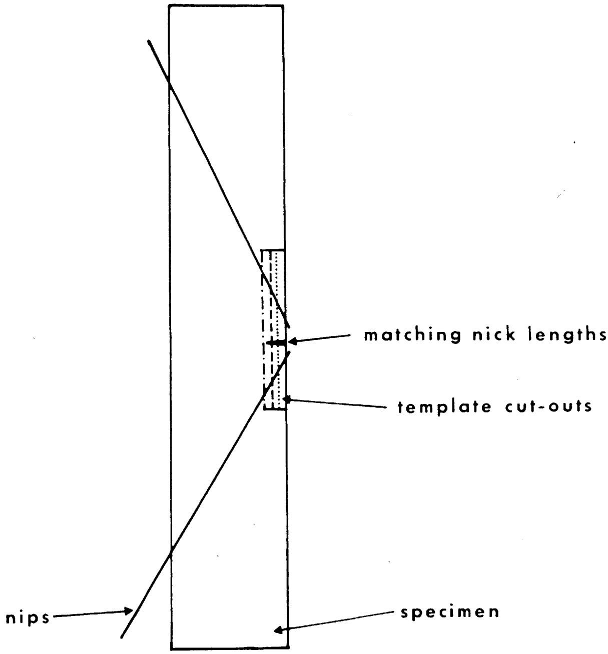


Fig. 19—Diagram of template cut-outs

Considering the shorter edge on the convergent side of the nips to be under the strain of tensile rupture, the strain across the test specimen can be accurately calculated from the geometry of the nips. Using the stress/strain relationship for a standard tensile test on newsprint, the above calculated strains may be converted into stresses. Each point in Fig. 21 represents the theoretical stress or load on a 1 mm wide longitudinal element. The stress distributions in specimens that have been reduced (as in Fig. 19) to 24·4, 23·4 and 22·4 mm from the original 25·4 mm width are plotted.

Relative to the stress in the rest of the web, the concentration of stress at the edge is decreased with a decrease in specimen width, but the area under the respective curves (the total load) increases.

The above curves fit the following simple equation to an index of determination better than 0·999.

$$\text{Local stress} = 1/(A-Bx)$$

where A, B are constants for each specimen width

x is the distance from the divergent edge of the test specimen.

Integration of this equation yields the theoretical total load at failure or the edge tearing strength for a specimen of width y—that is, $-1/\mathrm{B}\ \ln\ (A-By)$.

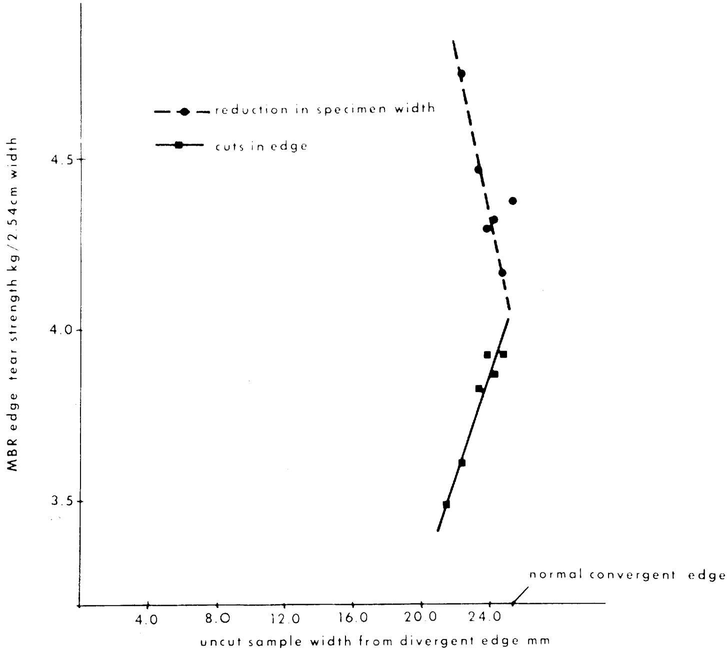


Fig. 20—Comparison of the effects of edge cuts and equivalent reductions in specimen width on edge tearing strength

The integrated values of edge tearing strength, uncorrected for specimen width, are shown in Fig. 22. Note the anticipated initial increase in edge tearing strength with decreasing specimen width, as found experimentally. Eventually, the reduction in load bearing width causes a net decrease in edge tearing strength.

Although the slope of the initial increase in edge tearing strength is the same as that measured in Fig. 20, it should be noted that the total theoretical loads are below those found experimentally for the same paper. No allowance has been made in this theoretical approach for the exaggerated Poisson effect (lateral shrinkage) that occurs in this test. Whereas the true strain pattern in this test is difficult to handle theoretically, it may be described by laser interference holography, as discussed in appendix 2. The guide bars for the upper clamp assembly tend to bend to accommodate the greater stress on the convergent side of the nips. The net effect is a reduction in stress concentration and a resultant higher integrated load. Non-parallel movement of the upper jaw could be corrected if a V-track and self-contained load cell were employed rather than the present guide bars and external Instron load cell.

It can be seen from the above analysis that the MBR edge tear tester is particularly sensitive to edge quality and, through the extreme concentration of stress on the test edge, it is capable of accurately gauging the resistance of edges to the initiation of tearing. It should be noted when evaluating the effect of web defects on edge

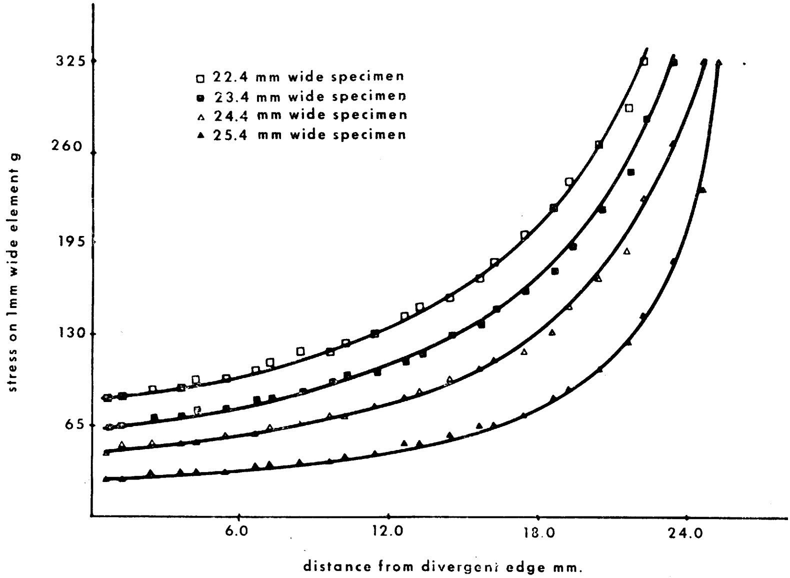


Fig. 21—Stress distribution across samples of various widths in the edge tear tester

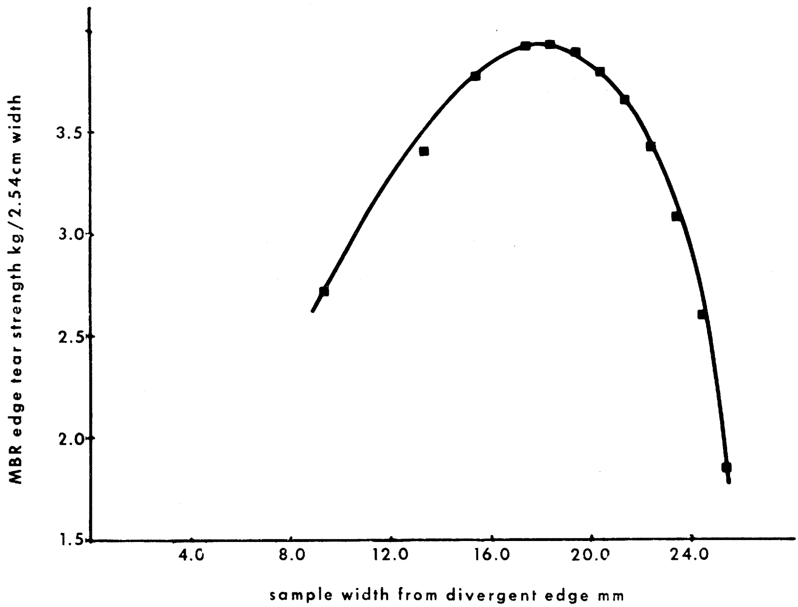


Fig. 22—Edge tearing strength as a function of specimen width

tear values that small reductions in strength may be significant, since the edge tearing strength would be increased for a specimen narrowed by the effective length of the defect.

***Appendix 2**—Image reconstruction by the holographic process*

Fig. 23 illustrates the set-up used in this strain analysis; one that is typical for the

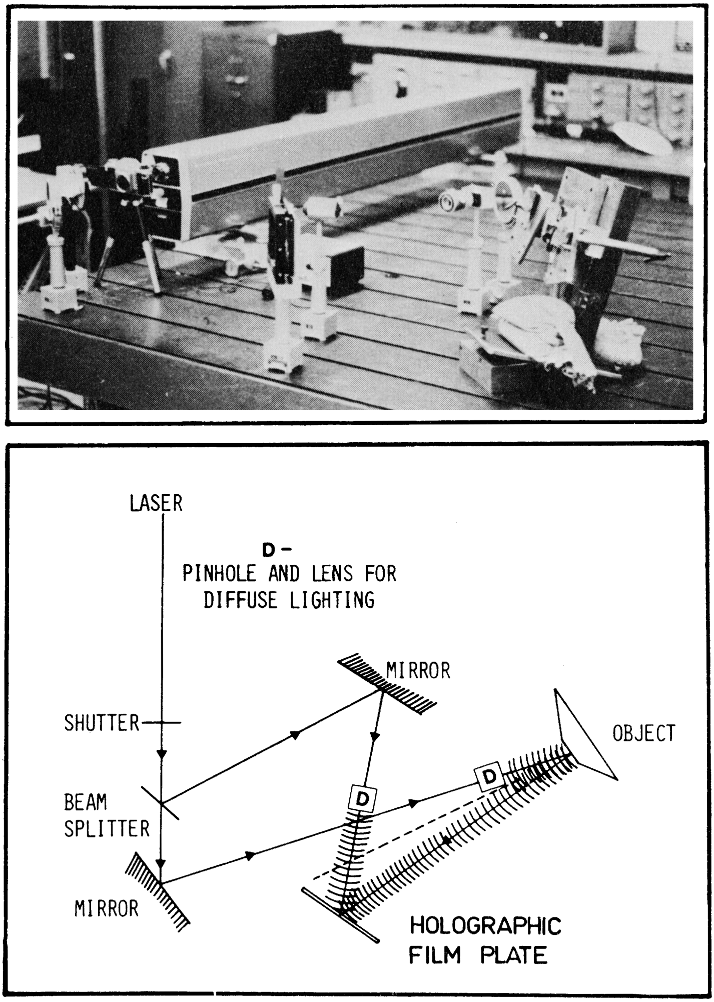


***Fig. 23**—Schematic diagram and photograph of the laser holographic interferometry apparatus*

holographic process. The laser produces a beam of light that is coherent or ordered so that all wave fronts are parallel rather than random as in ordinary illumination. By electrically exciting a gas mixture (helium and neon in this experiment) and resonating the light produced by electrons in the gas when they return to less excited states, a continuous, coherent and monochromatic light beam can be created.

The beam is split, as shown in Fig. 23, so that one beam path falls directly on a high resolution film plate and the other is reflected off the subject (for example, paper in the edge tear tester) back on to the same negative. The interference between the beams will appear as a complex diffraction pattern on the developed film plate.[9] When the developed film plate (hologram) is illuminated solely by the reference beam, a virtual three-dimensional image of the subject will be created in the subject's original location by the diffracted light waves.

Technically, the angle between the reference beam and light from an element of the subject will determine the spacing of lines in the hologram diffraction pattern and the relative intensities of light from various elements of the subject will determine the contrast of the lines in the diffraction pattern.[10] Thus, the phase and intensity of the coherent laser light reflected off the subject can be recorded as fineness and contrast in the hologram line structure. Since ordinary photography records only relative light intensity, an extra dimension of information is recorded in holography, which allows three-dimensional image reconstructions.

Transcription of Discussion

Discussion

Mr A. E. Ranger I would like to make two comments on Seth & Page's contribution *Fracture resistance*. Firstly, I think the suggestion that a tensile mode of failure should almost axiomatically be related to poor web runnability bears a little examination. The basic feature of the tensile mode of paper testing is that the stress distribution across the test piece is uniform (except for deliberately induced stress concentration). The failure of paper running through a press is a very rare event; if there is one thing that is probably even more rate, it is the situation in which the stress across the web is uniform and steady with time. Of course, this is a matter of speculation, but I am sure that everyone who has been paper running through a press will agree with me. Whether the pure tensile mode is used or whether the laws are inclined at some angle is a matter for speculation at this stage and certainly needs much further investigation.

My second point is perhaps more crucial to this problem. The first point was essentially concerned with the 'geometry' of simulation, but another aspect to simulation is of course strain rate. The strain rate used in a test for attempting to predict ultimate end use behaviour in such an instance is very important, since the ratio of the number of fibres broken to those pulled out at final fracture increases substantially with increase in strain rate. If one is using a low strain rate test to simulate a high strain rate end use situation, therefore, the very different proportion of fibres broken to those pulled out from the surrounding matrix can produce misleading results. This may explain why the tearing test has had some success in predicting press room runnability in spite of its defects. For any very small area of paper, the strain rate that it sees as the crack advances to it and then ruptures it is very high indeed. To match this strain rate with a tensile mode of testing would require expensive and sophisticated equipment.

This study of the relative number of fibres broken compared with those pulled out and its dependence on the strain rate is one that we have only relatively recently started, but we are already convinced of its vital importance.

With the Chairman's indulgence, may I say how disappointed I was after

Under the chairmanship of Prof. H. W. Giertz

Dr Goring's paper that no one saw fit to congratulate him on an excellent presentation, one that I thoroughly enjoyed. Having lived through (perhaps the word is survived) the last two or three years in the pulp and paper industry, I was comforted to hear David's belief that there will still be paper physicists and chemists around in the year 2001. I was a little disturbed at his suggestion, however, that they might be met on the street and I wondered what they were doing there.