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# FORMATION TESTING AS A MEANS OF MONITORING STRENGTH UNIFORMITY

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***Synopsis*** In any attempt to predict the durability or runnability of paper in its end uses, a means must be sought that is capable of measuring minimum strengths. Through the use of double exposure interference holography, an analysis is made of the strain variation of newsprint webs under critical tensile loading conditions. The coefficient of variation of strain is compared with formation values, which ideally should be measures of mass distribution. The QNSM, MK Systems and STFI formation testing instruments were used for this purpose and it was found that, in the case of the latter instrument, the index of determination of strain variation could reach 0·81. An assessment of the thermal uniformity of paper webs during tensile straining is facilitated by a liquid crystal thermal analysis and it is found that paper exhibits a particularly uniform distribution of temperature suggesting a constant work field model. While the influence of web defects on strength uniformity is briefly examined in this work, reference is made to a more detailed study to be found in another contribution to this symposium.

### *Introduction*

PREDICTION of the durability or runnability of paper in its end uses is highly dependent upon assessment of the minimum relevant strengths. Since the failure of paper webs is generally in the realm of statistically rare events, evaluation of the local variation about mean critical web strengths is important.

In this study, the uniformity of strain is examined in paper webs under near rupture tensile loads and means are sought to explain the source of this strain variation. It is logical to assume that the mass distribution (or variation of grammage) is a key factor controlling strain variation. Therefore, three optical formation testers have been compared for their abilities to measure grammage variation. Formation values supplied by these instruments are then correlated

*Under the chairmanship of Dr H. Corte*

with the coefficient of variation of strain as measured by a holographic interferometric analysis.

From the perspective of paper as a bonded fibre network, local strain may be viewed as the strain of fibre elements and the loss or partial loss of bonds. Both these processes are exothermic in the plastic prerupture zone of the tensile strain of paper, since (by definition) plastic flow implies an irreversible heat loss. Therefore, a further understanding of the sources of strain variation can be had by examining the thermal uniformity of paper during tensile straining. For this purpose, liquid crystals that exhibit a suitable narrow thermal spectrum of colour have been applied to paper webs.

### Results

THE formation values given by the STFI, QNSM and MK Systems formation testers for newsprint of various types are listed in Table 1. These values are graphically compared in Fig. 1 in order better to appreciate the discrepancies. Non-standard samples are numerically identified as in Table 1.

TABLE 1—FORMATION INDICES OF NEWSPRINT SAMPLES

| *Samples No.* | *Description* | *STFI formation M–D scan*[1] | *QNSM formation M–D scan*[2] | *MK Systems formation spiral scan*[3] |
|---|---|---|---|---|
| 1 | Standard newsprint, 52 g/m² | 8·67 | 61·5 | 2·1 |
| 2 | Standard newsprint, 52 g/m² | 8·14 | 57·0 | 2·0 |
| 3 | Standard newsprint, 52 g/m² | 10·2 | 73·0 | 2·2 |
| 4 | Standard newsprint, 52 g/m² | 10·3 | 77·0 | 2·7 |
| 5 | Standard newsprint, 52 g/m² | 10·6 | 84·0 | 2·5 |
| 6 | Standard newsprint, 52 g/m² | 9·49 | 78·0 | 2·2 |
| 7 | Vertiform, 52 g/m² | 9·08 | 61·0 | 2·1 |
| 8 | Standard news, 4·5 cm streaks | 9·44 | 77·5 | 2·5 |
| 9 | Standard news, green colour | 9·81 | 100·0 | 3·0 |
| 10 | Vertiforma, 36 g/m² | 14·1 | 75·0 | 3·0 |

[1] Formation number [2] Lin C [3] Coefficient of variation of grammage

It can be seen that coloured sample No. 9 is given inappropriately high formation values by the QNSM and MK Systems instruments. In addition, lightweight sample No. 10 is assigned an incorrect low formation value by the QNSM instrument. Removal of the coloured paper from the group of ten samples causes the QNSM/STFI correlation to increase from 0·336 to 0·518 and the MK Systems/STFI correlation to increase from 0·720 to 0·879. If only the lightweight paper is removed, the QNSM/STFI correlation increases to 0.693. Watermark streaks used for export identification purposes appear to have a mild effect on relative placement of sample No. 8.

Interference holograms were made of newsprint samples No. 1, 2, 4, 7 and 10 at 90 per cent of their rupture extensions. The difference in strain variation between better and poorer formation newsprint can be appreciated by examining the two interference holograms shown in Fig. 2 & 3. Each fringe represents a line of equal displacement from the stationary jaw at the right of the figures.

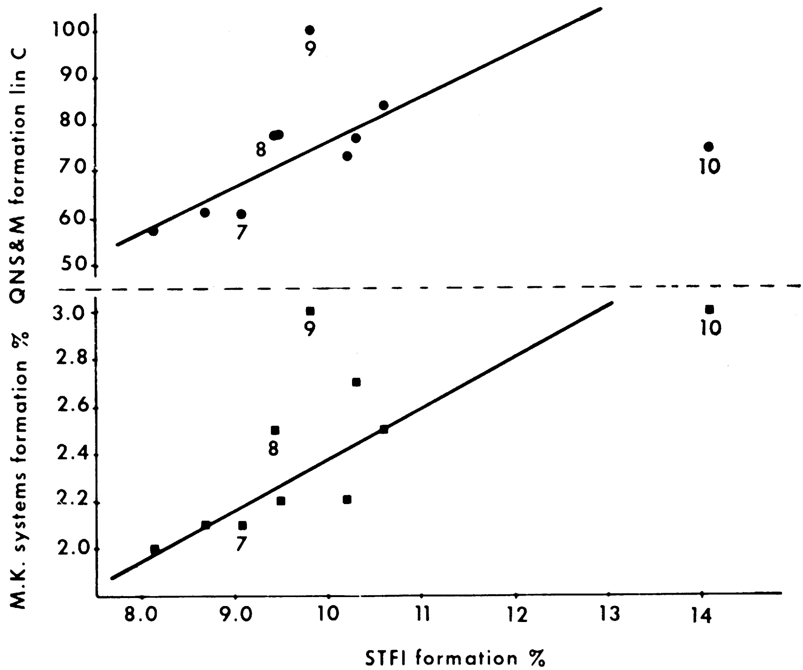



***Fig. 1***—Relationships among the STFI, MK Systems and QNSM formation values of newsprint samples

Coefficients of variation of strain obtained from the interference holograms of the above samples are plotted in Fig. 4 against the corresponding STFI, QNSM and MK Systems formation values. Generally, the correlation is close, reaching an index of determination of 0·81 in the case of STFI formation number.

The liquid crystal thermographs of these newsprint samples under strain to rupture were uniform to within the thermal resolution of the liquid crystal coating (that is, ±0·025° C). Since the total prerupture temperature change in the paper/liquid crystal system was in the order of 0·1° C, the technique cannot be considered definitive for assessment of thermal variation in newsprint. Yet lightly beaten (24° SR freeness) unbleached spruce kraft paper

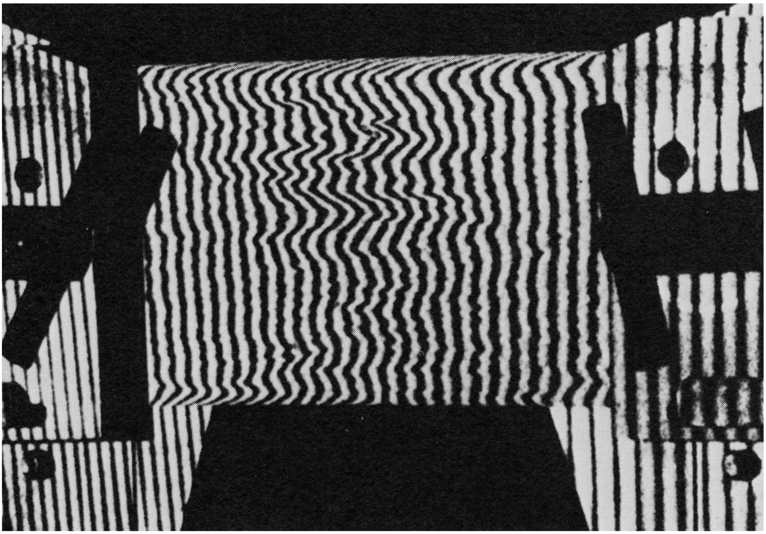


***Fig. 2***—Interference pattern formed on a newsprint sample having good formation

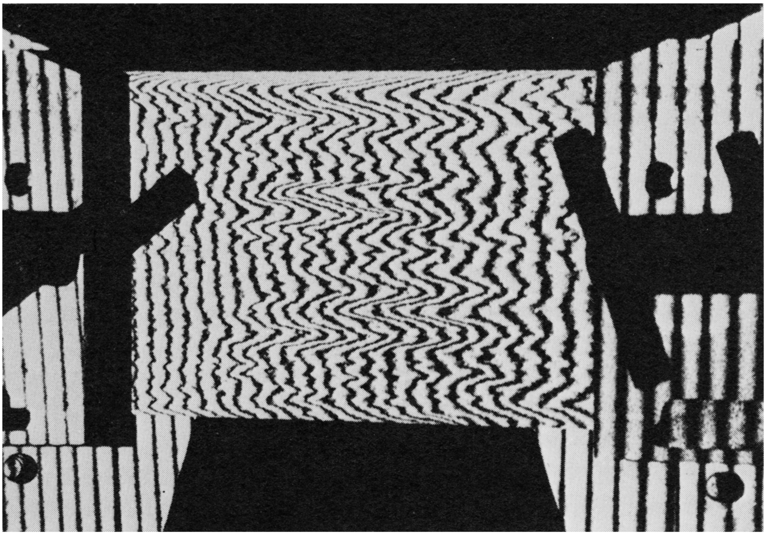


***Fig. 3***—Interference pattern formed on a newsprint sample having poorer formation

coated with liquid crystals exhibited a uniform 0·9° C temperature rise during prerupture straining.

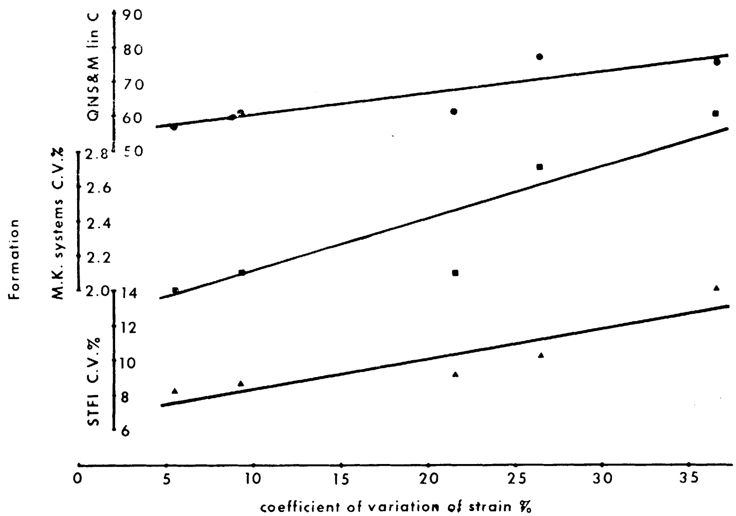



***Fig. 4***—Relationships among formation values and strain variation in newsprint samples

Further temperature rises of 0·1° C and 0·25° C for newsprint and kraft paper respectively occurred after rupture. Within 2·5 mm of either side of the rupture line, however, the post-rupture temperature increases were 0·15° C and 0·5° C for newsprint and kraft paper, respectively. The interpretation of the uniform colour change in liquid crystal coated newsprint and kraft papers during straining as a manifestation of a uniform thermal shift is supported by the observation of local colour change about rupture lines and about strain lines in tracing paper specimens.

The predominance of grammage distribution as a determining factor in web strain variation can be further appreciated by examining in Fig. 5 the rupture lines of poorer and better formation kraft paper and comparing them with adjacent beta-radiograph positives. Typically, the rupture lines follow lines of least grammage in the web. The complex rupture in the above poorer formation web has been preserved by the Instron break detection system. Both samples were uniformly coated with the black liquid crystal compound after the radiographs were taken.

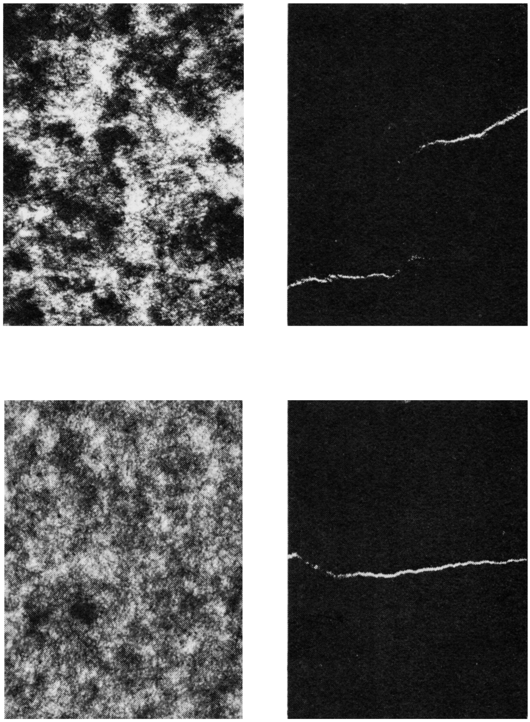


***Fig. 5***—Beta-radiograph positives and corresponding liquid crystal coated unbleached kraft paper specimens (24° SR freeness) that have undergone tensile rupture

### *Experimental*

#### *Measurement of formation*

THE ten newsprint samples listed in Table 1 were standard production from mills in British Columbia having kraft contents of $25\pm2$ per cent and, with the exception of lightweight sample No. 10, they had standard grammages of $52\pm2$ g/m$^2$.

Specimens for the three formation testers were cut as adjacent squares along the machine-direction to minimise formation differences. All specimens were aged before testing until brightness was relatively stable in a dark and constant humidity environment. They were then shipped in sealed black plastic bags and all of the formation tests done within one week.

Specimens tested for QNSM formation were then used as subjects for strain analysis, since their handling was at a minimum and known.

Formation indices, as shown in Table 1 for the ten newsprint samples, are reported in units that the inventors claim are appropriate for their instruments.

*STFI formation tester*

The rotating scanning cylinder around which the test specimen is held is made of diffusing teflon having approximately the same reflectance as that of newsprint. Light transmission is measured through a diffusing mat placed over the test specimen. Illumination is provided through the teflon cylinder by a scanning light and lens assembly that moves in conjunction with a reading photocell system. A 0·1 mm diameter measuring area is used, allowing a wavelength or floc size spectrum to be made from 0·1 mm to 40 mm. The output of each analysing filter is normalised about integral wavelengths, affording a rational scale of spectral density.

The read-out from the tester is shown in Fig. 6. The densities of various size flocs may be directly compared on the spectral density graph. Their relative contributions to the formation can be found on the formation graph, which is an integration of the spectral density over the above wavelength range. The value obtained by integration over the entire wavelength spectrum is designated the *formation number* and is theoretically equal to the coefficient of variation of the grammage expressed in per cent.[1]

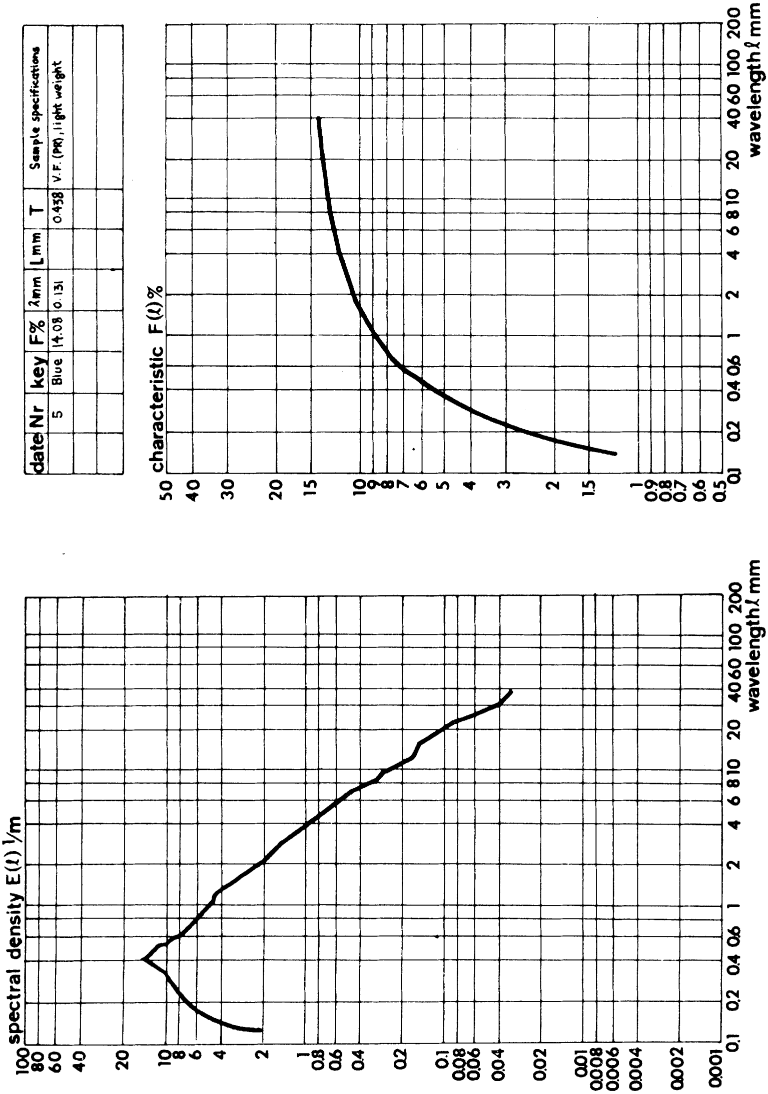
Sample size is variable with maximum dimensions of 30 cm by 21 cm.

*QNSM formation tester*

The paper sample is placed within a clear plastic cylinder and is held in place by centrifugal force. The illumination and scanning assemblies are similar to those of the STFI instrument except that the illumination is undiffused and the photocell reads directly without an intervening diffusing layer.

The RMS value of the output of the scanning photocell (or Lin C) is taken as a formation index.[2] Since the mean of this output is preset for each sample, the Lin C represents the coefficient of variation of the light intensity detected through a 0·15 mm diameter viewing aperture.

As shown in Fig. 7, the QNSM tester also divides the floc spectrum using one third octave band pass filters and displays the outputs against their corresponding centre frequencies or wavelengths (from 0·4 mm to 10 cm). The filter outputs are not normalised about their centre frequencies, resulting in filter outputs that are skewed towards the shorter wavelengths (a one third octave band pass representing a wider band width at higher frequency). Interpretation of the relative contributions of various floc sizes to the total formation (Lin C) must therefore be made on a non-rational scale.




| date | Nr | key | F% | λmm | Lmm | T | Sample specifications |
|---|---|---|---|---|---|---|---|
| | 5 | Blue | 14.08 | 0.131 | | 0.438 | V.F. (PR), light weight |

*Fig. 6*—STFI spectral density and formation characteristic graphs

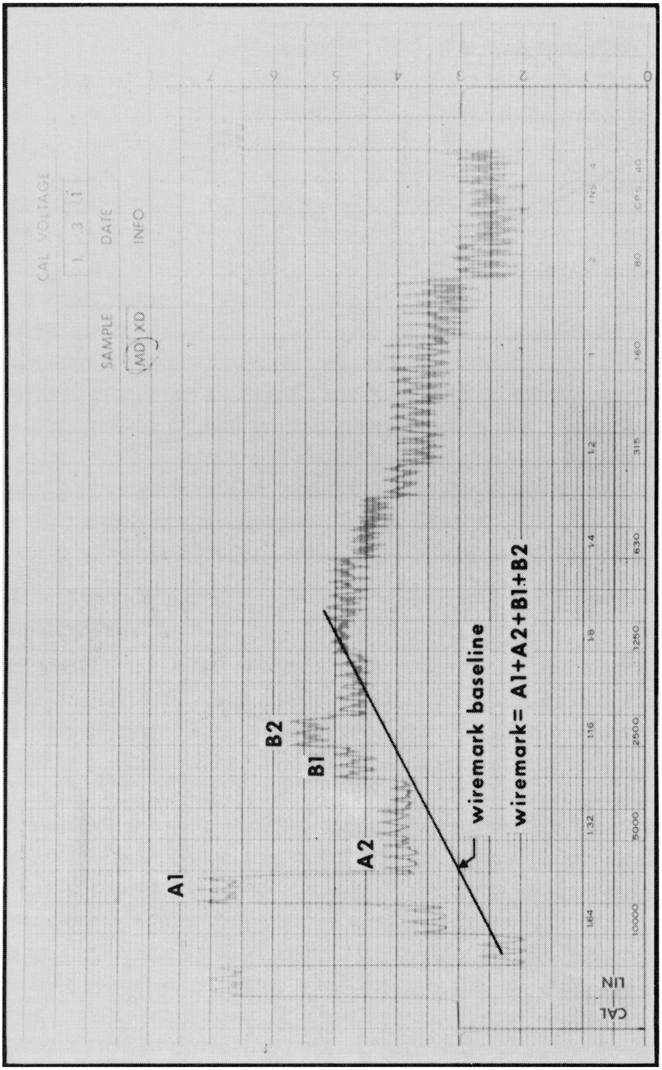



***Fig. 7***—QNSM wavelength spectrum and wiremark value

Wiremark values (which are frequently reported as the linear sum of the outputs of the four most related filters taken from a subjective baseline) are similarly skewed, owing to the differing bandwidths of the filters concerned. Sample size is 11 in by 11 in and the scanning area is fixed at 7·5 in by 11 in.

*MK Systems formation tester*

Paper is placed on a turntable rotating at 100 rev/min and scanned spirally outwards. The mean and RMS values of the light transmission during a scan are determined and combined to produce the coefficient of variation of the transmission. This value is then reported directly as the coefficient of variation of the grammage in per cent.[3] Illumination is provided by a collimated light source, which moves radially with a direct reading photocell assembly. The scanning area is 0·2 mm in diameter and, at the time of these tests, the sample size was a 1 in diameter disc. The tester features a magnified map of the optically determined grammage, using five classes of optical density as shown in Fig. 8.

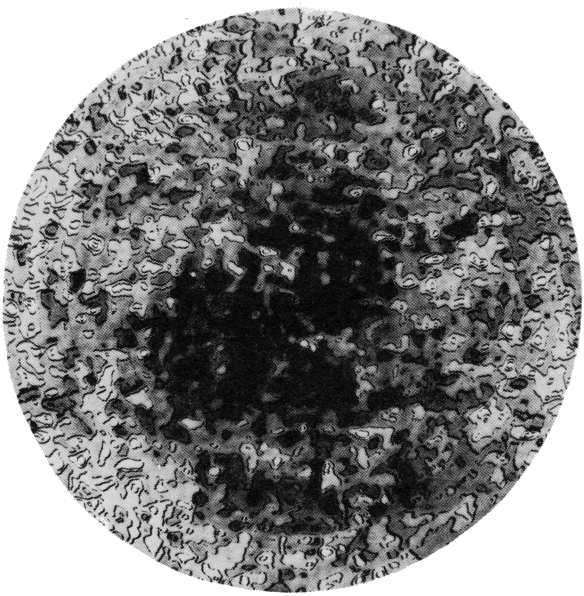


***Fig. 8***—MK Systems magnified map of optically determined grammage

*Measurement of strain variation*

The jaws used to strain the newsprint specimens were of the line contact type with a ball and socket hinge and differential screw arrangement to allow high and even nip loading. The jaws were mounted on tight fitting ways and a micrometer mounted between them so that strains applied to the moving jaw could be measured.

Extension at rupture was measured on all samples in this study before strain analysis. Specimens, measuring 7 cm wide and 9·25 cm between the jaws, were strained to 90 per cent of their rupture extension, before the initial exposure of the holographic film. After the first exposure, a small additional strain was imparted using a fine differential screw (30 and 32 threads per inch). The second exposure was then taken and the film developed. Details of the laser holographic interferometry technique appear in the appendix.

The fringes, which represent lines of equal displacement, are relatively straight on the paper in the vicinity of the jaws, indicating that jaw slippage has not occurred. A boundary effect was observed in the edge zones of all specimens. Fringe patterns in these zones indicate that strain variation is more severe near the edges. Therefore, these zones have been omitted from strain analysis.

Samples 1, 2, 4, 7 and 10 were submitted to strain analysis, since the fringes that formed on their holographic reconstructions were free of out-of-plane effects (see appendix). The separation of the fringes along a line between the jaws (perpendicular to the fringes) was measured. Since only one jaw is moved between exposures of the holographic film, a gradient in fringe separation exists between the jaws. Individual values of fringe separation were proportionally corrected to a zero gradient and the coefficient of variation of these corrected values reported directly as the coefficient of variation of strain in each specimen.

*Measurement of thermal variation*

Specimens of 65 g/m$^2$, 24° SR freeness, unbleached, machine-made kraft paper and specimens of newsprint from the above collection of samples were prepared having a width of 5 cm and an effective length of 6·5 cm.

A special narrow spectrum liquid crystal compound consisting of cholesteryls and powdered carbon was supplied by the Pressure Chemical Co. of Pittsburgh. Using chloroform as a viscosity-controlling solvent, it was possible to apply a uniform 50 g/m$^2$ coating to the paper specimens with a laboratory airknife coater. Unlike blade coaters, which tend to fill in depressions in the web surface, the airknife coater applies an equal weight of coating over the entire area of the specimen. This was verified by an examination of the optical density of the specimens when coated with the carbon-filled liquid crystal compound. After the chloroform had evaporated, the coating weight was 50 g/m$^2$. This was sufficient to impregnate the webs and leave a glossy liquid crystal surface.

The liquid crystal compound is a grease-like substance and was found to have no significant effect on tensile strength values. The thermal spectrum of this compound was chosen to be centred on the 20° C temperature of the conditioning room in which the tensile tests were conducted. An Instron tensile tester was employed, using a straining rate of approximately 15 per cent/min.

The liquid crystals employed exhibit a cholesteric-ordered structure and, because the degree of order changes in the material with temperature, the shorter wavelengths of light are scattered at lower temperatures. Scattered light is only a small portion of the incident light so that colour discrimination is best observed against a black background. Powdered carbon is a particularly good light absorber and has been mixed into the compound for this purpose. This liquid crystal compound exhibits a four-colour (six if black is counted at both extremes) continuous thermal spectrum. Mid-red to mid-blue in the spectrum represents a 0·8° C change in temperature.

All specimens were photographically recorded during straining from a position perpendicular to specimen surface.

### *Technical analysis and discussions*

THE resolution of the strain, grammage and thermal distribution sensing techniques used here are of considerable importance to any discussion of their relationship.

Häglund, Norman & Wahren[4] have shown that a resolution in the order of the fibre diameter is necessary to record all the variation in a paper web's grammage. Taking the scanning diameters of the MK Systems, QNSM and STFI formation instruments as used in this study, it can be shown theoretically that the fraction of the variation in grammage recorded must lie between 0·30 and 0·45 for these instruments.

Since there are no optics between the specimen and the holographic film in the holographic process, the sensitivity to strain is in the order of the resolution of the holographic film or the wavelength of light. Therefore, all the strain variation in the paper webs induced between exposures of the holographic film is recorded in the resulting interference fringe pattern. Since the interference fringes have finite widths, however, they must represent an integration of the strains of all the fibre elements that lie beneath them. The separation of the fringe centres has been used for the calculation of strain variation; thus, the effective resolution of strain in this analysis is of the order of the ability to discern the fringe centres (approximately 0·2 mm).

Information about the variation in strain of elements finer than 0·2 mm may be obtainable if an analysis of the uniformity of the fringe front is made, although laser speckle mitigates against this. Holographic interference microscopy may be the solution for finer resolution strain studies.

Whether grammage variation is actually being resolved by the STFI, QNSM and MK Systems formation instruments is of concern, since they are optical devices. Visual formation of paper (or the distribution of optical opacity seen by the eye) is a function of the mass distribution and of the distribution of scattering surface throughout a paper web. Besides, papers having high brightness and low opacity appear to the eye to be more uniform, since contrast of points of low grammage and low scattering potential is lessened. Indeed, the distribution of scattering surface in a paper web may relate to the inverse of the grammage distribution in the web. This phenomenon is caused during wet pressing and calendering, in which high mass points are likely to be more compressed, thus enhancing local bonding. The local scattering surface is thereby reduced by the area taken up in bonding, since the separation of material that has been hydrogen bonded is less than that required to interrupt light transmission.

The Kubelka-Munk theory can be employed to describe the relative importance of scattering, brightness and grammage to the light absorbance of paper, provided two criteria are met—that a diffusely incident light source is used to illuminate the paper and that all the light transmitted through the paper is measured.[6] Furthermore, if the paper is illuminated through a diffusing material with the same reflectance as that of the paper, the Kubelka-Munk equation for light absorbance reduces to—

$$A = \ln\left[\sinh(bsw) + \cosh(bsw)\right] = bsw$$

where $A$ = absorbance, $\ln(I_0/I)$
$b$ = $(1/R_\infty - R_\infty)/2$
$R_\infty$ = brightness of the paper
$s$ = scattering coefficient of the paper
$w$ = grammage of the paper

Thus, the determining factor for the absorbance of paper is $bsw$. The optically determined portion $bs$ is only slightly influenced by local variation in the scattering coefficient, since $d(bs)/ds$ is approximately 25 per cent at newsprint brightness levels.[1]

Since brightness is virtually constant throughout a paper sample, it does not affect the coefficient of variation of the absorbance, $\sigma(A)/\bar{A}$. Therefore, to a close approximation, the coefficient of variation of the absorbance is proportional to the coefficient of variation of the grammage, $\sigma(w)/\bar{w}$, regardless of local variation in the scattering coefficient and changes in paper brightness.

The Kubelka-Munk theory cannot strictly be applied to the QNSM and MK Systems instruments, however, since their light sources are non-diffuse and their light sensing is directionally selective. The consequence is an undue sensitivity to the scattering properties of the surface of the web and is manifested by inappropriate correction for opacity and brightness.[5] This can be seen in the displacement of coloured sample No. 9 above the QNSM/STFI and MK Systems/STFI regression lines. Similarly, the surface layers of the web are a greater proportion of the thickness of lighter grammage papers, thereby masking the true change in light absorbance with grammage. Lightweight sample No. 10 is thus displaced below the regression lines.

Despite the above limitations, it would appear from the correlation between optically assessed formation and strain variation that formation testers can be used to monitor strength uniformity. This is especially true in view of the relationship between formation and the variation in tearing strengths.[7]

Since the object of attempting to monitor strain uniformity or tear strength uniformity is the improvement of critical minimum strength points in the web, the strength disruption caused by web defects cannot be overlooked. Fig. 9 shows a newsprint specimen at the centre of which a 2 mm by 2 mm cross has been cut before straining. The normal tensile interference fringe pattern has been completely disturbed in the specimen by the introduction of this synthesised flaw. Clearly, the avoidance of such flaws is as important as grammage uniformity to the economics of making runnable and durable papers. The trend towards the manufacture of lightweight grades will magnify these considerations, since the highest strain variation and the greatest effect of flaws were observed for lightweight papers. A discussion of the relative importance of various types of flaw to edge strength is given in the paper *The Evaluation and Optimisation of the In-plane Tearing Strength of Paper* (see pages 269–298).

The spatial resolution of the thermal distribution in paper during straining as measured in liquid crystal impregnated specimens depends partly on the thermal conductivity of the paper/liquid crystal system. Heat dispersion in the web during the tensile tests (of approximately 10 s duration) should not be greatly increased by filling the insulating voids in paper with liquid crystals that have a similar thermal conductivity [0·0003 cal/(cm) (s) (°C)] to that of paper. Heat losses by convection and moisture desorption during straining are probably considerably lessened by the permeation of the hydrophobic liquid crystal compound into the web. Conversely, radiative losses in the specimen are probably increased, since the liquid crystal compound is black. Radiative and convective heat losses are estimated to be of the order of 20 per cent of the heat generated during the straining of paper.[8]

By assuming the heat capacity of the liquid crystal compound to be the same as that for paper [approximately 0·35 cal/(g)(°C)], the temperature changes observed in the paper/liquid crystal system can be crudely converted

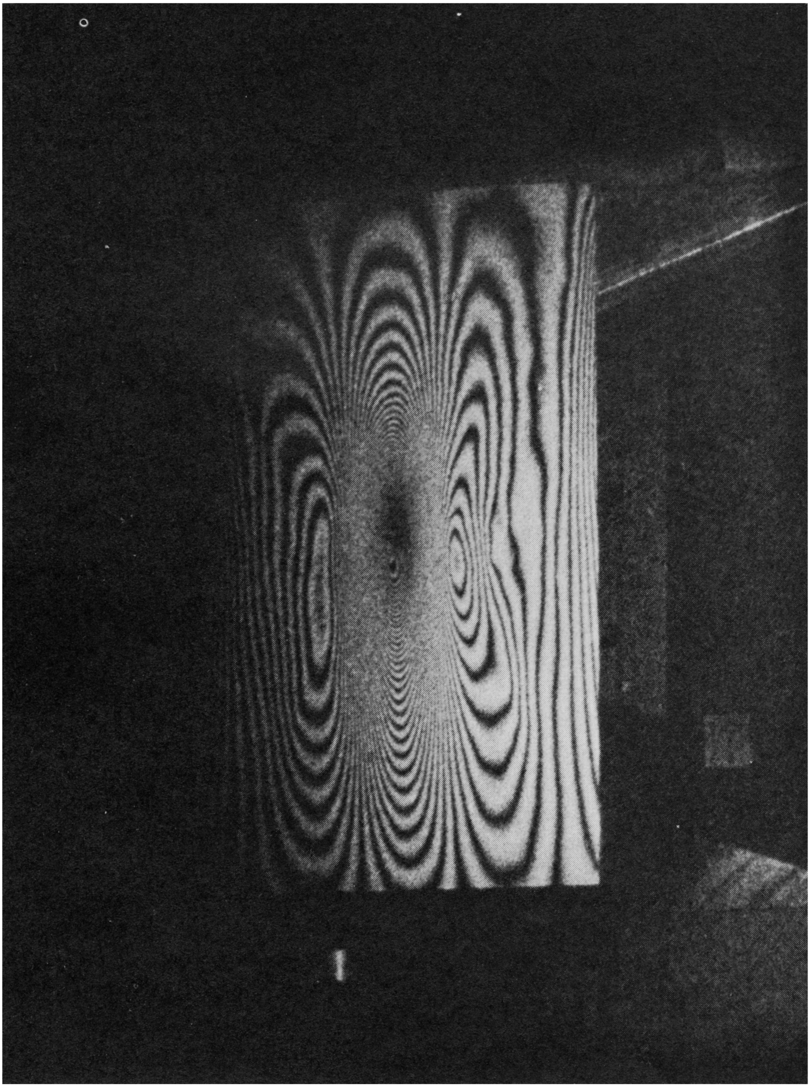


***Fig. 9***—Influence of a centre cut on the strain distribution in a newsprint sample under tension

on a weight basis to temperature changes for paper alone. The kraft paper alone would increase by 0·71° C during straining and would undergo a further post-rupture temperature increase of 0·25° C, except along the rupture line, when the temperature rise would be 0·88° C over the prerupture temperature. Similarly, the newsprint alone would increase by 0·2° C during straining and undergo a further 0·2° C rise after rupture, except along the rupture line, when the temperature would rise 0·3° C over the prerupture temperature.

These temperature changes are in general in agreement with those measured by an infra-red scanning camera, except that the slight initial temperature decrease during elastic straining observed by Dumbleton, Kringstad & Söremark was not seen.[8] Unfortunately the scanning spot size used by Dumbleton *et al.* was 6 mm in diameter, thereby eliminating the detection of over 95 per cent of the temperature variation. Although a general uniformity in prerupture strain temperature increases was observed by Dumbleton *et al.* and by the authors, a definitive experiment with an infra-red scanning spot of considerably reduced diameter would facilitate the construction of a thermodynamic model for paper strain.

If the uniformity in temperature during web straining is real, a constant work field model could be envisaged for paper. During tensile straining, areas of high grammage and compaction undergo high stress, but low strain; the converse is true for low grammage areas. Thus, the local work done per unit mass would be constant throughout the specimen, resulting in a uniform temperature increase. More simply, considering paper as a mass field, the work done would be uniform.

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The authors thank Dr Nils Abramson for revision of the addendum. Dr Abramson is director of the Laser Research Group at the Royal Institute of Technology in Stockholm and is the author of several papers on the fundamentals of holographic fringe analysis.

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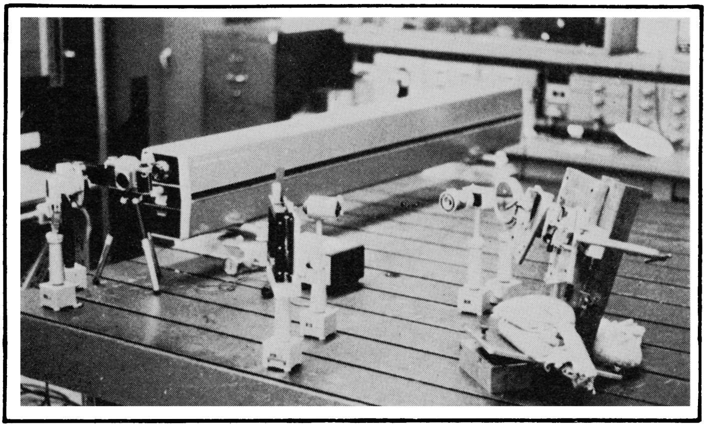
## Appendix

*Holographic image reconstruction*

FIG. 10 shows the typical set-up of a holographic optics table used in strain analysis. The laser produces a continuous beam of light that is coherent or ordered so that all wave fronts are parallel rather than of random orientation as in normal forms of illumination. Specifically, the argon laser used in these experiments relies on the spontaneous emission of light that occurs when electrically excited argon atoms return to lower states of ionisation. Various spectral lines are produced when this light is resonated between aligned mirrors, but the dominant wavelength is separated by a selecting prism.[9]

A monochromatic beam at 0·5145 μ of coherent light from the laser is split so that one beam path falls directly on the holographic film positive and the other is reflected off the subject (for example, a strained piece of paper) back on to the same film plate. The beams are diffused before falling on the subject and the film in order that they may interfere over the entire surface of the film.



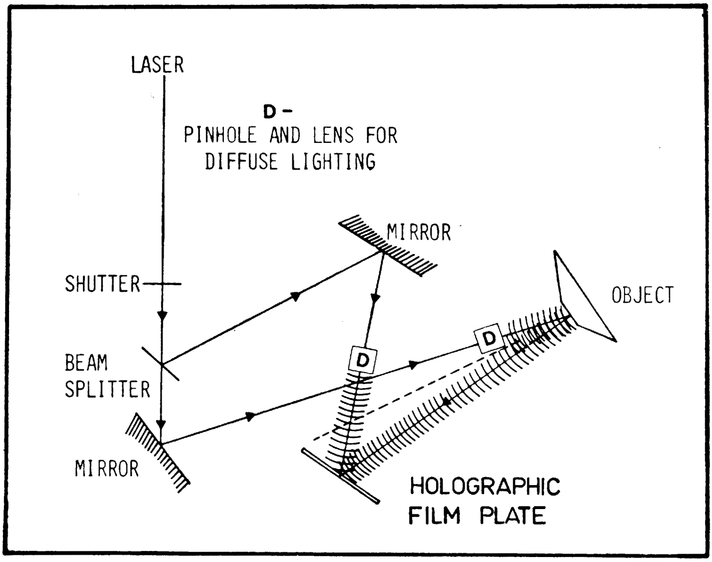



***Fig. 10***—Schematic diagram and photograph of the laser holographic interferometry apparatus

The resolution of the film used as a holographic plate is approximately 0·4 μ or in the order of the wavelength of the light used. Therefore, the phase relationship between the light from the reference beam and that from the subject is recorded on the film, as well as the relative light intensities. The interference between the beams is recorded as a fine diffraction pattern on the developed film plate or hologram.[10]

When the hologram is illuminated solely by the reference beam, a three-dimensional virtual image (or reconstruction) of the subject can be viewed in the original subject location. Spacing between the lines in the hologram diffraction pattern determines the angle between an element in the reconstructed subject and the reference beam. Contrast between lines in the diffraction pattern determines the relative intensities of the elements in the subject.[11] Therefore, a three-dimensional image is recorded in holography by employing phase information as well as relative light intensity as is done in photography.

*Holographic interferometry*

If the holographic film is double exposed and the subject is moved less than 100 $\mu$ between exposures, the two resulting reconstructed images will interfere and produce a fringe pattern in the area of movement. Fig. 2 & 3 in this study are photographs of double-exposed holograms in which subjects are paper specimens strained to near tensile rupture. Between exposures of the holograms, the jaws were further separated by less than 100 $\mu$ by employing a fine-pitched differential screw.

Each fringe represents a line of equal displacement, the movement between fringes being one half wavelength of light. Therefore, the coefficient of variation of the strain at critical near-rupture conditions can be found by assessing the mean and standard deviation of the separation of the fringes. Appropriate corrections must be made for the gradient in fringe separation that occurs because one jaw is moveable and the other stationary.

The geometry of the holographic set-up determines the proportion of the displacement in the plane of the paper that will be recorded in the resulting fringe pattern. This proportionality constant is cancelled out of the coefficient of variation of strain, but must be accommodated in calculations of absolute strain. For a homogeneous material, it would be possible to ascertain local strain by taking the derivative of the fringe order with respect to the distance from the stationary jaw and multiplying by the above proportional constant. Quantitative measurements of strain about defects, etc. might be made in this way (though it was not attempted in this work).

Out-of-plane motion and paper buckling cause fringes to form in space, rather than on the surface of the subject. Therefore, these spurious effects can be identified when viewing the hologram by examining the subject from different angles. If the fringes appear to move with respect to the subject, then out-of-plane motion has occurred. All samples used in this analysis are free of these effects.

It may be noted that parallel, straight fringe lines have formed on the jaws in

Fig. 2 & 3. When the differential screw is turned in order to impart a small additional strain between exposures of the hologram, the torque applied causes a minor rotation about a vertical axis (Fig. 2 & 3). The fringe pattern seen on the paper specimen is the modulation by strain in the specimen of the straight, parallel fringes caused by the mild rotation, though the coefficient of variation of the separation of the fringes is free of effects caused by rotation.

### *Discussion*

Other interference techniques were tried by the authors with varying success. Moiré fringes created by placing an analyser plate over a line grid printed on paper were found to be too insensitive to strain, given the practical resolution achievable with the printing process (namely, 200 lines/in).

When coherent laser light is reflected by a high surface area material such as paper, local constructive and destructive interference of the scattered light results in a phenomenon known as laser speckle. If two laser beams are used to illuminate a specimen from opposite sides, at shallow angles to the plane of the specimen, the resulting speckle pattern will be relatively insensitive to out-of-plane deformation of the specimen. If a photograph of the illuminated specimen is double exposed and an increment of strain is given to the specimen between exposures, the speckle patterns will interfere and cause fringes to be formed. Unfortunately, the relative insensitivity of this technique to out-of-plane motion is offset by inadequate fringe contrast when the paper is used as a specimen.

Real time holographic interference is a process in which specimen strain can be actively examined by observing through a developed hologram the interference of the specimen with its holographic image. Paper is not stable enough in the critical plastic strain region, however, to remain undeformed while the hologram is developed. Therefore, when the hologram is replaced after approximately 20 min development time, a complex of interference fringes is observed before any additional strain is applied. Even though this technique was inapplicable to the experimental conditions in this study, it presents a possibility for observing real time straining of paper at strain levels for which creep is less predominant.

Double exposure holographic interferometry was ultimately chosen for the analysis of strain variation in paper webs, because the time between exposures is less than 30 s. When the strain level was not altered between exposures of the holographic film, no interference fringes were formed.

Holographic interference is applicable to microscopic strain analysis and may be relevant for studies of single fibre straining and three-dimensional analyses of network strain at the interfibre level.

Fig. 11 shows a holographic interferometry apparatus of recent construction in which a microscope objective lens provides a magnified view of a piece of paper under strain. The initial strain level was set using a micrometer before the first exposure of the holographic film plate. The increment of strain between exposures was imparted with an adjustable pneumatic piston, thereby avoiding the rotational effects seen in Fig. 2 & 3. The circular viewing areas shown in Fig. 12–14 all represent 5 mm diameter areas of the strained web.

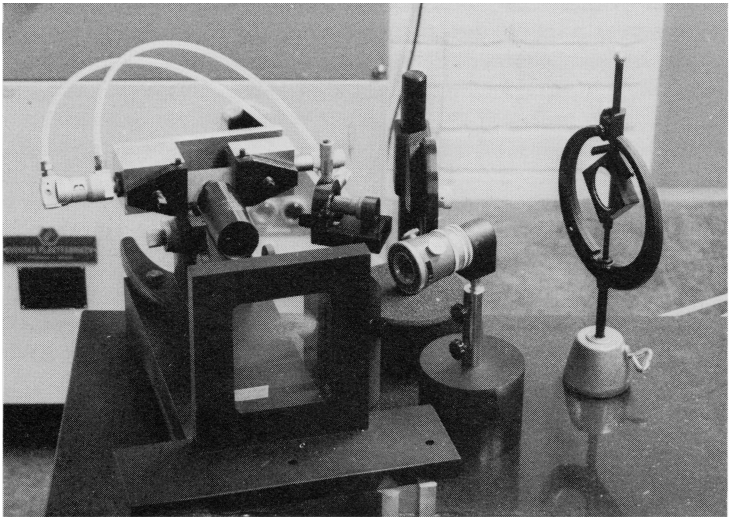


***Fig. 11***—Apparatus for holographic interferometry through a microscope

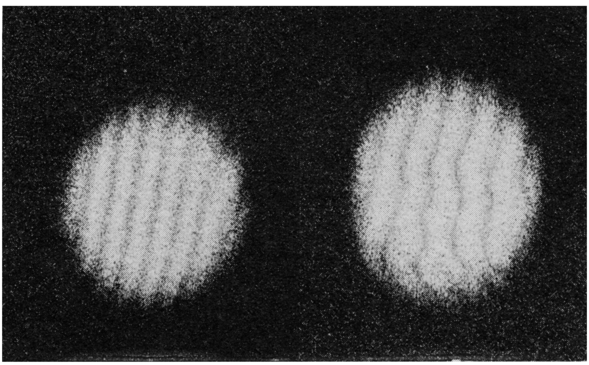


***Fig. 12***—Interference patterns formed on normal grammage zone (left) and low grammage zone (right)

Fig. 12 is a comparison between the interference pattern observed for a normal grammage area of a strained newsprint web having good formation and that associated with a low grammage area in an otherwise good formation newsprint web. The parallel straight lines on the normal grammage area are due solely to the uniform straining of the paper web, since no rotation has occurred between exposures of these hologram plates. The disruption of this pattern in the low grammage area illustrates the non-uniformity of displacement in low grammage zones.

Fig. 13 is a composite of four magnified areas of the same strained kraft paper web. The areas originally lay in the same geometric positions, but have been brought closer together in order to make a more compact figure. This web has very poor formation, with the result that the interference fringes undergo bending, convergence and divergence, indicating considerable non-uniformity in displacement.

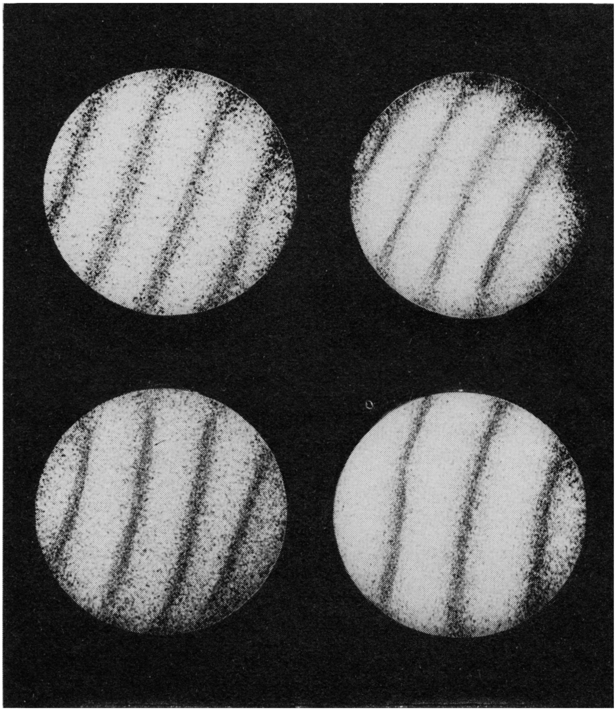


***Fig. 13***—Interference patterns on selected areas of paper having poor formation

Finally, Fig. 14 shows a similarly shrunk composite of four viewing areas in the vicinity of a 2 mm diameter hole in a strained kraft web. The hole is located just outside the viewing zone in the upper right corner of Fig. 14. The pronounced convergence of the fringe lines in the direction of the hole and the general deviation from straight, parallel fringe lines (associated with undamaged, good formation paper) illustrates the degree of non-linearity of displacement in these regions. This supports the contention that severe strain concentration exists about such defects in strained paper webs.

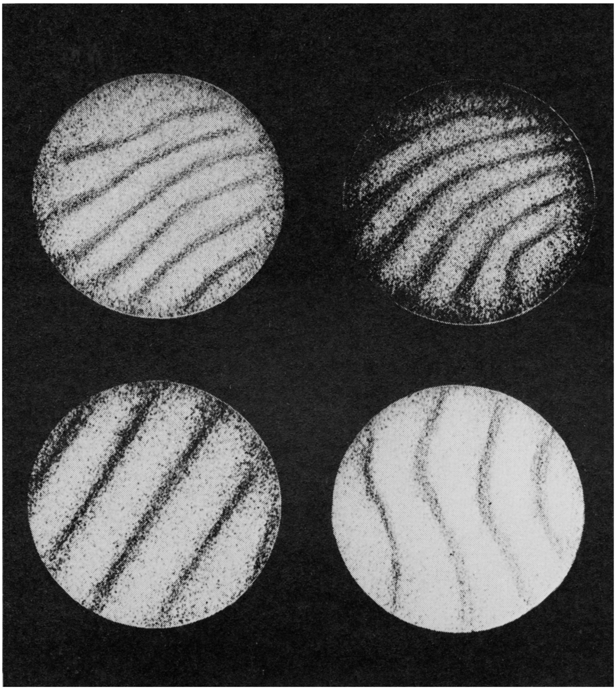


***Fig. 14***—Interference patterns on selected areas of paper about a 2 mm diameter hole

### *Addendum*

ADDITIONAL information is offered of the experimental set-ups used in the holographic interferometry study of strained paper webs. The description in the appendix of the method of analysing the coefficient of variation of strain in-plane stressed newsprint webs is amplified. An estimate of the relative sensitivity of this method to in-plane and out-of-plane motion is also given.

*Sensitivity to in-plane and out-of-plane displacement*

The geometry of the essential components of the experimental set-up for the study of strained paper webs is shown in Fig. 15.

The bisector of the angle between the path of the light beam that illuminates the paper web and the line of viewing a point on the paper surface makes an angle β with the plane of the paper web. It is important to know the angle β in any analysis of holographic interference fringes, since *the interference fringes represent lines of equal displacement for motion along this bisector.*[11, 12]

Therefore, in the case of displacement in the plane of the paper (Fig. 15) or in the case of out-of-plane motion (perpendicular to the plane of the paper web), the fringe lines represent only the components of displacements along the bisector. Therefore, in the case of an in-plane displacement $\Delta R$, the component $\Delta R \cos\beta$ is recorded in the fringe pattern. Similarly, in the case of out-of-plane displacement $\Delta D$, the component $\Delta D \sin\beta$ is recorded. The relative *sensitivity* to in-plane and out-of-plane displacements is thus—

$$\text{sensitivity}\ \frac{\text{in-plane}}{\text{out-of-plane}} = \frac{\cos\beta}{\sin\beta}$$

Furthermore, if the angle $\beta$ does not vary appreciably over the surface to be analysed, then the sensitivity to in-plane and out-of-plane displacement remains constant over the surface. Since the fringes were viewed (through the double-exposed holographic plate) at a distance of approximately one metre and since the area of examination on the paper webs was relatively small, the relative sensitivity can be considered constant over the area of examination. It should also be remembered that only the central portions of the plane-stressed webs were examined in the analysis of strain variation, thereby also avoiding undesirable boundary effects.

In double-exposure holography, the fringes represent lines of equal displacement along the bisector. The displacement or component of displacement along the bisector required to produce one fringe is $\lambda/2\cos\gamma$, where $\lambda$ is the wavelength of the laser light used (0·5145 $\mu$ for the argon laser and 0·6328 $\mu$ for the helium-neon laser) and $\gamma$ is the angle shown in Fig. 15. Since $\gamma$ is of the order of 10°, the displacement along the bisector required to produce one fringe, to a close approximation, equals $\lambda/2$.

Therefore, for the case of in-plane motion, each fringe represents a $\lambda/2\cos\beta$

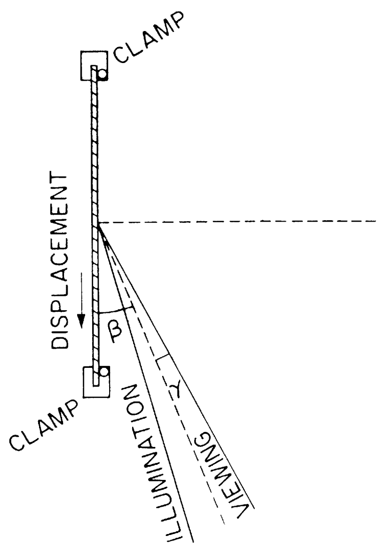



***Fig. 15***—Geometry of the holographic interferometry set-up

displacement in plane. Similarly, for the case of out-of-plane motion each fringe represents a $\lambda/2\sin\beta$ displacement out of plane.[13] For the general case of a displacement vector making an angle $\theta$ with the bisector, each fringe represents a displacement of $\lambda/2\cos\theta$ in the direction of the displacement vector.

Three experimental set-ups were employed for studying paper webs under various strain conditions. Fig. 9 in this paper and Fig. 3–6 in the paper *The Evaluation and Optimisation of the In-plane Tearing Strength of Paper* (pages 276–279) were produced with the holographic set-up pictured in Fig. 10 of this paper. The angle $\beta$ was 60° in those qualitative examinations, giving an in-plane/out-of-plane sensitivity ratio of 0·58.

In the analysis of the coefficient of variation of strain made for samples 1, 2, 4, 7 and 10 in this paper, the angle $\beta$ was 35°. The angle $\beta$ was minimised to the fullest extent possible given the physical size and geometry of the equipment used. The in-plane/out-of-plane sensitivity ratio was thus 1·4.

For holographic interferometry through a microscope objective, to be presented as part of this paper at the symposium, the angle $\beta$ was 55°. The sensitivity ratio was thus 0·70.

It is interesting to note the appearance of circular or closed fringes in the holographic interference patterns shown in Fig. 3–6 in the paper on in-plane tear and Fig. 9 in this paper. Out-of-plane effects were caused in these specimens by the placement of a cross cut in the centre of the sample in Fig. 9 (identical to Fig. 6) and by the severely skewed stress distributions imposed on the specimens in the edge tear tester (Fig. 3–5). Considering the higher angle $\beta$ for these experiments, out-of-plane motion could be expected to produce the closed fringes associated with the classic case for out-of-plane movement when $\beta = 90°$.[14]

For the normal newsprint webs strained between parallel jaws (samples 1, 2, 4, 7 and 10 in this paper), it is virtually impossible to calculate theoretically the possible local out-of-plane movement in the web during the addition of an increment of strain in the plastic strain region of newsprint. Sensitivity to local out-of-plane motion during the addition of the strain increment between exposures of the hologram has been minimised by the choice of a low angle $\beta$ (35°).

### *Elimination of spurious displacements in samples 1, 2, 4, 7 and 10*

The authors would like to distinguish two forms of displacement that may contribute to the fringe patterns observed in these experiments. Specifically for samples 1, 2, 4, 7 and 10, the authors have attempted to measure the coefficient of variation of *local* displacement. It was desirable therefore to eliminate movements of the straining apparatus (excluding proper displacement of the moveable jaw) that might be caused when the screw was moved to impart the increment of strain between exposures of the hologram. Similarly, movements of large portions of the paper web by jaw slippage were to be avoided. We shall call these forms of spurious movements *macro* displacement.

The technique used to eliminate these effects in samples 1, 2, 4, 7 and 10 has been to discard all holograms that exhibit gross fringe movements with respect to the surface of the paper webs when the fringe pattern is viewed from slightly different angles. This technique may be explained by following the basic paper on fringe localisation by Aleksandrov & Bonch-Bruevich.[14]

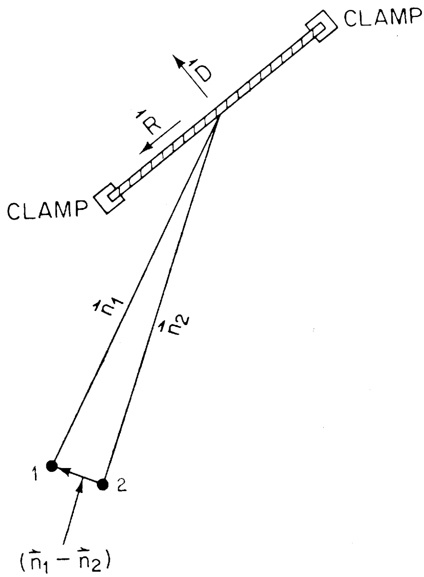



***Fig. 16***—Fringe localisation diagram

Given a macro in-plane or out-of-plane displacement of the surface to be analysed (the whole surface or a large part thereof), as represented in Fig. 16 by the vectors *R* and *D*, respectively, the movement of fringes seen by viewing a point on the surface along two different paths (in the directions of unit vectors $n_1$ and $n_2$) may be described by—

in-plane $$K\lambda = \vec{R} \cdot (\vec{n_1} - \vec{n_2})$$

out-of-plane $$K\lambda = \vec{D} \cdot (\vec{n_1} - \vec{n_2})$$

where *K* equals the number of fringes that move past the point on the paper surface as the view is shifted from location 1 to 2. The number *K* can be zero (no gross fringe movement) in the trivial case when a motion occurs perpendicular to the difference vector $n_1 - n_2$ or *when no macro displacement R* or *D* occurs. This may be extended to the case of any macro movement.

Since the above trivial solution would produce a ring-like interference pattern, such motion could be easily identified.* Therefore, the observation of no gross

* In the simplified case when $\beta = 90°$, dicussed in many elementary texts, $K = 0$ is equivalent to no displacement in-plane

fringe movement ($K = 0$) is a good test for the avoidance of macro displacement. All the holograms used of samples 1, 2, 4, 7 and 10 were thus made free of macro in-plane and out-of-plane displacements.

*Measurement of the coefficient of strain*

By making a linear correction for the gradient in fringe separation that occurred between the stationary jaw and the moveable jaw, it is possible to calculate the coefficient of variation of fringe separation. This is directly equivalent to the coefficient of variation of strain along the bisector shown in Fig. 15 ($\beta = 35°$).

That the coefficient of variation of strain along this bisector should include possible out-of-plane components is viewed as satisfactory by the authors, since the stated aim of this study was to provide a measure of the strength uniformity of paper. That formation determines a substantial portion of the strength uniformity of newsprint paper has been demonstrated in this paper.

*General comment*

Although no attempt was made in this paper to measure local strains, it could be done for in-plane strain by differentiating the in-plane components with respect to the distance to the stationary jaw.[12] The measurement of three-dimensional strains is of course much more complex. There are several possible techniques that generally employ local component analysis based on multiple viewing angles.[12, 15]

# Transcription of Discussion

## *Discussion*

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*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 $\lambda$ 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 $\lambda$ 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 $\beta$, 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 $10\mu$ (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.