Full-field local displacement analysis of two-sided paperboard

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ABSTRACT

This report describes a method to examine full-field displacements of both sides of paperboard during tensile testing. Analysis showed out-of-plane shear behavior near the failures zones. The method was reliably used to examine out-of-plane shear in double notch shear specimens. Differences in shear behavior of machine direction and cross-machine direction specimens are described.

INTRODUCTION

The papermaking process produces paperboard whose mechanical properties vary through its thickness. For example, paperboard made on a single-wire fourdrinier machine tends to have more density on its wire side. Dual headboxes are often used to produce paperboard with improved optical and printing properties on one side. Cylinder board machines can produce paperboard with different furnishes in several strata within the sheet. The effect of different furnishes within the sheet can be macroscopically measured by conventional testing, but this testing only provides an average property for the entire construction.

This report describes a method to measure small-scale displacements on each side of a tensile paperboard specimen. Differential displacements between sides of a tensile specimen indicate local out-of-plane shear behavior and may be a failure precursor.

Micromechanical models for in-plane paperboard tensile strength usually incorporate bonding or z-toughness [1-3]. Importance of these properties is inferred due to their ability to predict tensile strength. Bonding and z-toughness properties are difficult to incorporate in models because property value, location, and distribution within the paperboard are important. Observation of shear behavior prior to tensile failure could facilitate future research efforts for accurate measurement.

EXPERIMENTAL PROCEDURE

The purpose of this work was to examine the two-sided failure region of paperboard in tension. Identical CCD cameras having spatial resolution of 1392 by 1040 pixels captured images of both sides of a tensile specimen. As shown in Figure 1, dual fiber optics from a single halogen source was used to illuminate each side of the specimen. Surface displacement measurements were enhanced by spraying a diffuse random pattern on each surface. A dedicated computer was used to simultaneously trigger each camera and capture force and grip displacement during tensile testing. All data, images, force, and displacement were captured at 6 Hz.

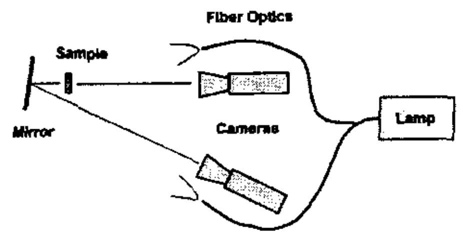

Figure 1. Top view of dual camera imaging system. Sample strain is out-of-plane.

While testing, a mask was used to prevent light illuminating one specimen surface from flooding the camera capturing images of the opposite surface. For this work, the mask reduced specimen width for the front image.

Two types of specimens were analyzed. Tensile specimens were 25 mm wide and 100 mm between grips. Grip displacement rate was 10 mm/min. Double-notch shear specimens, as described in [4], 25 mm wide and 100 mm long, were prepared with a 3.2-mm shear lap and were tested with a grip displacement rate of 1 mm/min. The shear lap was created by cutting approximately halfway through the thickness across the specimen width on the front side, then cutting halfway through the thickness on the back side, with the cuts offset by 3.2 mm. Both MD (machine direction) and CD (cross-machine direc-tion) orientations were tested.

DATA ANALYSIS

Digital image correlation (DIC) was performed using MatPIV1.6.1[5] within the Matlab® computing environment. Other researchers [6-9] have successfully used DIC to measure surface displacements of paper under stress and used the displacements to calculate local strain. In this work, two cameras captured images of both sides of a tensile specimen. Calibration images (Fig. 2) were used to (1) convert a pixel displacement to metric displacement and (2) map each camera to the other. Mapping is important to define a global coordinate system. Even though magnification and specimen location within each camera's pixel array was similar, mapping was necessary to compare displacements in the same location of the specimen. Mapping included adjustment scalars for translation, rotation, and magnification.

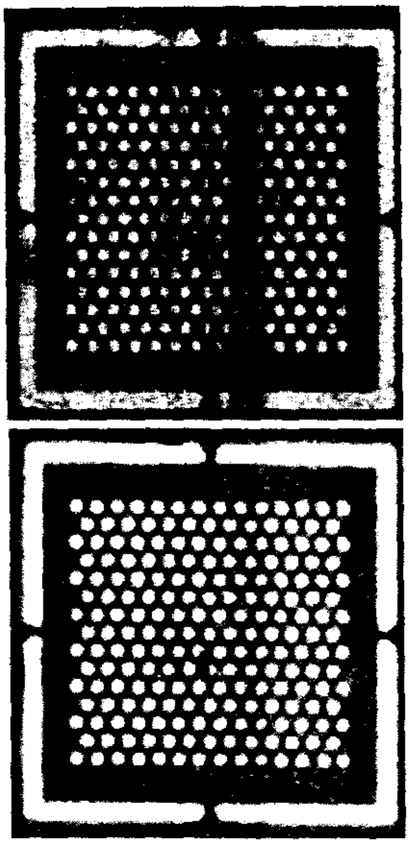

Figure 2. Calibration images for front camera (top) and rear camera (bottom). Bottom row of dots for each image represents 7.92 mm center-to-center. Left row of (staggered) dots for each image represents 7.40 mm center-to-center.

DIC analysis produced x and y location arrays and u and v displacement arrays, where u corresponded to x-displacement and v to y-displacement. Resulting location arrays for the front and rear of the specimen were not identical; i.e., u and v displacements were calculated for slightly different x and y locations for the front and rear images. A cubic spline interpolation was used to calculate u and v displacements for the rear image at the locations determined by analysis of the front image.

MATERIAL

Paperboard used in this work was a commercially made softwood kraft linerboard. Nominal grammage was 209 gm/m^2; nominal caliper was 0.3 mm.

RESULTS/DISCUSSION

Figure 3 compares calculated mean strain from front images with the mean strain calculated from rear images and with grip strain. Mean strain was calculated by averaging 594 regions for each image. Regions were approximately 1 mm by 1 mm. Strain as determined by DIC does not precisely agree with grip strain because the complete specimen area, for both front and rear, were not captured. High strain regions could be outside one image and within the other image and was caused, in this work, by masking one specimen surface. Specimen misalignment within grips can also produce mean strain differences. Region mapping was not performed for these data (as for two-sided DIC analysis) but demonstrated the importance of strain mapping. Region mapping was computer-intensive and was reserved for images near failure. Strain rate for front and rear images was similar.

Inherent with DIC research and current technology is a tradeoff between image frame rate and camera resolution. Previous work [9] showed rapid strain propagation through paper tensile specimens. In that work, images were captured at 120 Hz. Though not reported, an FFT analysis indicated that a comprehensive investigation of strain propagation would require an image capture speed of 800-900Hz. For analysis of paperboard failure zones, high resolution is critical, and our camera technology does not provide suitable resolution at > 800Hz image capture rate.

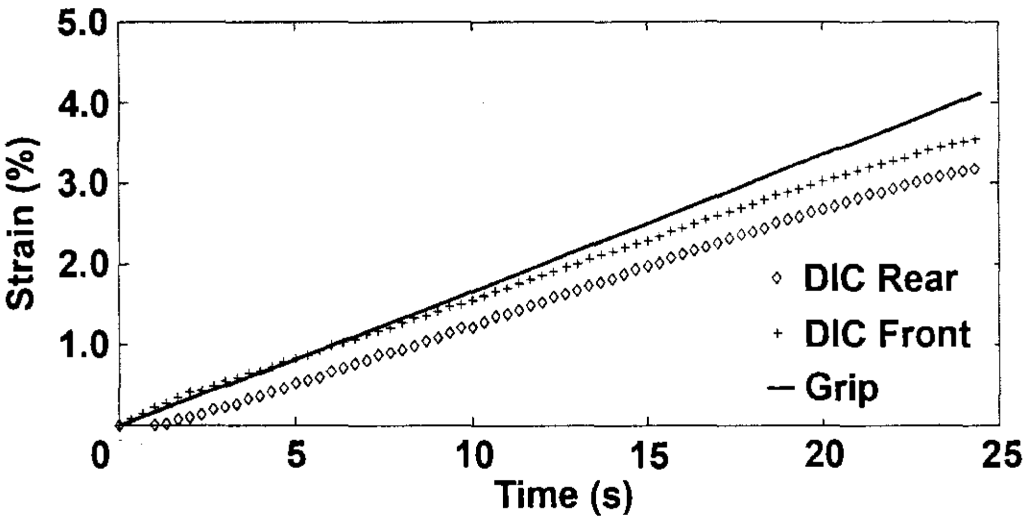

Figure 3. Comparison of strain as calculated by front and rear image digital image correlation (DIC) and grip strain. Data points are shown at 3 Hz instead of 6 Hz for clarity.

Pre- and post-failure rear camera images for a CD tensile specimen are shown in Figure 4. Images were separated by 0.17 seconds and indicated a 'brittle' failure. No gradual softening within the failure zone was apparent. The right image (b) in Figure 4 was designated as i_f, the left image (a) as i_{f-1}, and the specimen area was approximately 6 cm vertically and 1.6 cm horizontally.

DIC correlation of i_{f-2} with i_{f-3} and i_{f-1} with i_{f-2} gave more evidence of the nature of the failure and is shown in Figure 5 in a contour plot of u-displacement. At 0.33 s prior to failure u displacement, differences between the front and rear images were small and are shown on the left plot of Figure 5. However, at 0.17 s prior to failure, u displacement differences between front and rear images were large and are shown in the right plot of Figure 5. These contour plots were for the specimen shown in
Figure 3. Displacement differences were greatest above and below the failure zone and indicated large out-of-plane shear strains.

Results shown in Figure 5 were typical for CD tensile tests. Displacement differences between front and rear images were apparent only in analysis of an image immediately prior to failure. Out-of-plane shear strain was expected because many ductile materials, especially metals, fail in a shear plane through the tensile specimen thickness [10].

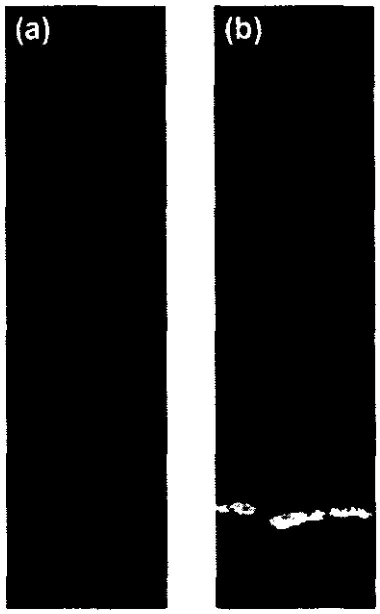

Figure 4. Consecutive pre- (a) and post-(b) failure images for a CD tensile specimen.

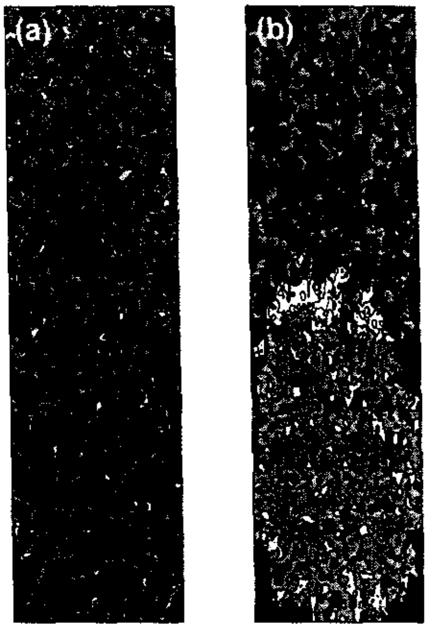

Figure 5. U-displacement differences between front and rear images of a CD tensile specimen shown in a contour plot. The left plot (a) is the difference mapping for i_{f-2} vs i_{f-3} and the right plot (b) for i_{f-1} vs i_{f-2}.

For this paperboard, MD analysis showed negligible differences between front and rear images prior to failure. MD failure may have been more 'brittle' than CD failure and occurred over a time frame too short to capture at 6 Hz.

Double-notch shear specimens were tested at a slower grip displacement rate of 1 mm/min to capture more failure behavior. Examination of double notch shear specimens was an obvious choice for a front/rear image analysis. Double notch shear specimens produce out-of-plane shear behavior because notches placed on each side of the specimen create different in-plane displacements on front and rear surfaces.

Contour plots of v-displacement differences between front and rear surfaces of a CD double-notch specimen are shown in Figure 6. Each contour plot represents approximately 6 cm vertically and 1.6 cm horizontally. Darker areas represent higher front-to-rear v-displacement. Displacement differences are evident in the t_{f-7} contour plot and intensify in the shear zone until failure. Variations in the average gray level of consecutive images indicated each surface did not experience increasing strain levels simultaneously. It is not clear whether the slower grip displacement rate for shear specimens increased the number of images with evidence of failure, but 7 images with shear displacements can improve shear strain calculation in future efforts. Analysis of other CD shear specimens had similar results, as the failure zone became apparent about 1 s prior to ultimate failure.

Figure 7 shows front and rear v-displacement difference contours for a double notch MD specimen. Contour plot areas are the same as for Figure 6, with 6 cm vertically and 1.6 cm horizontally. DIC for contour t_{f-1} is a comparison of the t_{f-1} image with the t_{f-6} image. A longer time gap between images was used, as compared to Figure 6, in response to more gradual failure. Each contour represents 1 s and 0.016 mm of grip displacement. Failure zone displacements became evident 3 s prior to failure as shown in the t_{f-18} v-displacement contour. However, the contour for t_{f-30} had a large gradient between top and bottom of the specimen that disappeared in the next contour, t_{f-24}. As shear strains become larger (darker images), relaxation within the failure zone could cause such a gradient. Results shown in Figure 7 were typical of MD double notch shear specimens.

CONCLUSIONS

A dual camera system was used to determine locations and magnitude of out-of-plane shear strains of tensile paperboard specimens. Analysis identified locations of out-of-plane shear strains in CD tensile and CD and MD double edge notch specimens, but not MD tensile specimens. Minor test modifications can improve measurement of out-of-plane strain in MD tensile specimens. This work will be expanded to examine other paperboards and develop a more thorough failure analysis.

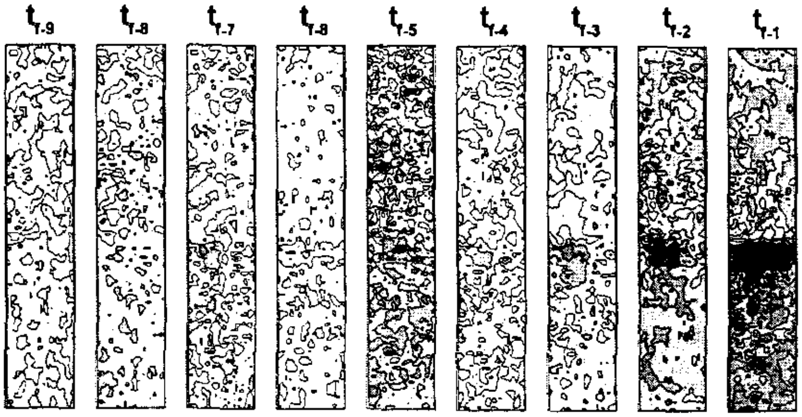

Figure 6. Contour plots of front/rear v-displacement difference of CD double edge notch specimen for several images prior to failure.

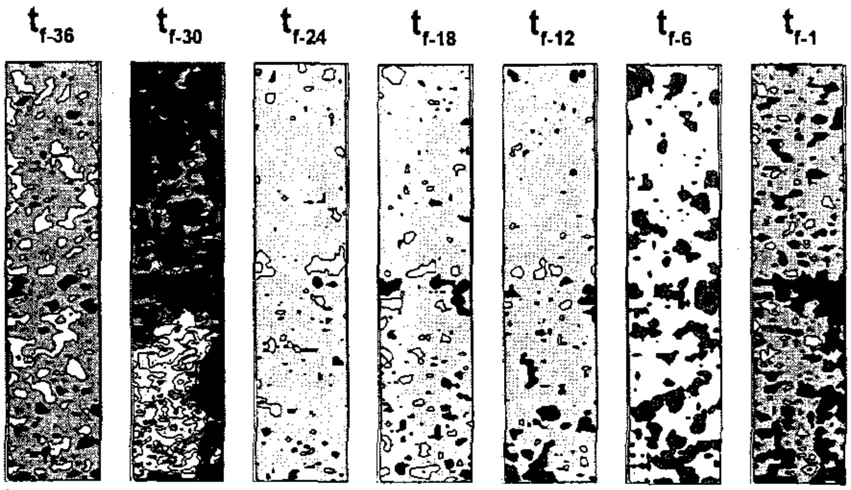

Figure 7. Contour plot of front/rear v-displacement difference of MD double edge notch specimen for several images prior to failure.

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