

Measurement of strains in a paper tensile specimen using computer vision and digital image correlation

Part 1: Data acquisition and image analysis system

Michael A. Sutton and Yuh J. Chao

Associate and assistant professors, Dept. of Mechanical Engineering, University of South Carolina, Columbia, S.C. 29208.

ABSTRACT *An automatic data acquisition and data analysis system for the study of surface deformation in paper specimens through image analysis has been developed. The measurement method is a noncontacting whole-field method that is insensitive to typical laboratory vibrations and which has variable sensitivity that can be modified during post-processing of the data. This range in sensitivity can include the localized variability in paper specimens, or it can be employed to average out such effects and obtain the macroscopic response.*

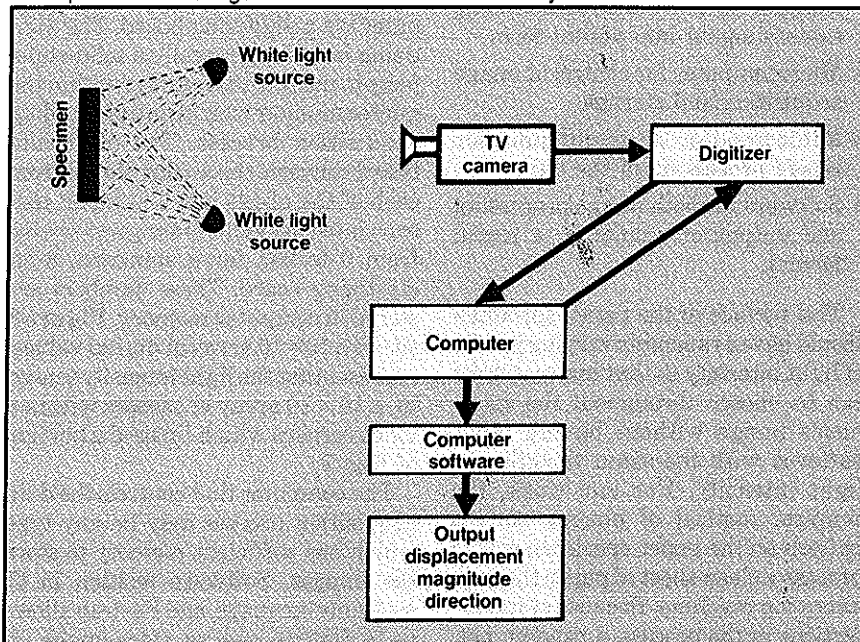
KEYWORDS

Analysis
Computers
Measurement
Mechanical properties
Instrumentation
Strain measurement

In recent years, several micromechanics and macromechanics models for paper have been developed (1-4). Such mathematical modeling, because of the complexity of the structure, requires that many assumptions be made to obtain a mathematically tractable formulation. The simplifying assumptions allow us to make continuum mechanics calculations in many cases. Hence, experiments must be carried out in the areas of mechanical deformation of paper for both the macroscale and microscale responses of the paper, so that a better understanding of the actual structure of paper can be obtained. With such understanding, improved models can be developed.

However, experiments such as these are difficult to perform for typical paper specimens. For example, the measurement of the in-plane strain field in a uniaxial test specimen is both difficult and time consuming. The difficulties involve the low elastic modulus and, hence, extreme flexibility of typically thin samples, as well as the inherent inaccuracies in the use of

1. Experimental configuration for the correlation analysis.



conventional strain gauges, linear variable displacement transducers (LVDTs), or extensometers. The time-consuming portion of the tests involves

the need for recording data on both the macroscale and microscale, so that the interrelationships of the micromechanics parameters and the global mea-

surements can be quantified.

Our work is aimed at the development of an automatic data acquisition and data analysis system for the study of surface deformation in paper specimens through image analysis. In Part 1, we propose such a system and discuss its individual components. The measurement method we propose is a non-contacting, whole-field method that is insensitive to typical laboratory vibrations and which has variable sensitivity that can be modified during post-processing of the data. The range in sensitivity of the method can include the localized variability present in paper specimens, or it can be employed to average out such effects and obtain the macroscopic response. In Part 2, we will show that this automated image-acquisition and analysis methodology can be used to quantify the displacement field present in a uniaxial test specimen.

Automated data acquisition process

Figure 1 shows a layout of the proposed data acquisition system (5-8). The system, as applied to the analysis of paper specimens, is composed of several parts:

- Specimen
- Specimen lighting
- Video camera for image acquisition
- Digitizer for conversion of the analog camera signal into digital form
- Microcomputer for control of image acquisition and storage
- Minicomputer or mainframe for image processing of the data
- Software for both image processing and output of results in a useful format.

The surface of the paper specimen should have a randomly varying profile of light intensity so that many subsets can be chosen throughout the specimen's image without having other patterns with the same variation in light intensity. For our work, the simplest method of placing such a pattern on the paper specimen was to process a clean sheet of paper through a copying machine. Because of imperfections in the process, a random pattern of small particles was deposited on the sheet. The pattern was then magnified several times in the copier to obtain an enlarged pattern. This pattern was photocopied onto the ten-

sile specimen of paper to obtain a pattern similar to the one shown in Fig. 2. This procedure worked well for paper specimens; however, it is not the only method available (5-8).

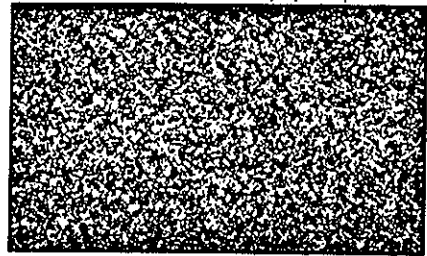
The specimen is usually illuminated with a standard white light source, and the illuminated surface is imaged by a video camera. The only requirement for the illumination is that the illumination be both reasonably uniform over the specimen's surface and also reasonably constant during the test. Small variations (5-10% variation over the entire image) in both uniformity and magnitude of the light intensity are accounted for when estimating the displacement.

For all of the work currently being done, the video camera is a charge-coupled device. These are solid-state cameras, with individual sensors, each of which is designated a "pixel" (short for picture element). The cameras have approximately 400×500 sensors in a two-dimensional array that is on the order of 12.7 mm by 12.7 mm in physical size. Each sensor averages the light intensity for 1/30th of a second and emits an analog signal. The magnitude of the analog signal output by each sensor is linearly proportional to the intensity of the illumination that was incident upon the surface of the sensor.

To convert the light intensity values sensed by each pixel into a number, the camera is interfaced with a computer via a digitizing board. The digitizing board is generally a solid-state, plug-in module that resides within the microcomputer which controls the data acquisition process. The digitizing board converts the analog signal from each of the pixels into a number, and each intensity value is assigned a value from 0 to 255 for a standard, 8-bit digitizing board. These numbers are stored in computer memory. Figure 3 shows a 10×10 array of digital values, representing the light intensity sensed by a 10×10 array of sensors within a video camera which imaged a portion of Fig. 2.

The computer that controls the data acquisition process may be any type which has sufficient memory to store the images. Software written in C, assembly language, and Fortran allows us to digitize images, store image intensity data, and eventually address portions of the images for image processing. Generally, the microcomputers are best suited for specific data acquisition tasks and are not as effi-

2. The randomly varying pattern of intensity on the surface of the paper specimen



cient for computation-bound operations. Hence, most of the actual image processing of the images was performed on a mainframe computer. This was accomplished by transferring the images from the microcomputer to the mainframe through a communications software package.

In summary, the data acquisition process would proceed as follows for a typical test of a paper specimen. For each loading level applied to the specimen, the specimen's surface is imaged by a fixed camera, digitized by the digitizing board, and stored either on floppy disk or in the memory of the microcomputer. Each image, then, represents the positions of points on the surface of the paper. These data are transferred to a mainframe computer for image processing.

Image analysis procedure

To compute the displacements of the individual points on the surface of the specimen, subsets are chosen from the undeformed configuration of the specimen (i.e., the unloaded or slightly preloaded specimen). For this work, we chose a subset of 20×20 pixels. Using digital correlation (7, 8), the location of the subset after each loading is computed by comparing the chosen subset from the undeformed image to subsets from each of the other images until the best "match" is obtained. The difference in the location of the subset before loading and after loading is the displacement vector V . Mathematically, one searches for the minimum in the normalized, cross-correlation function. The normalized cross-correlation function is defined by the equation:

$$C(V, \Delta V) = 1.0 - \frac{\int [I(X') I(X)] dA}{\left(\int [I(X')^2] dA \int [I(X)^2] dA \right)^{1/2}}$$

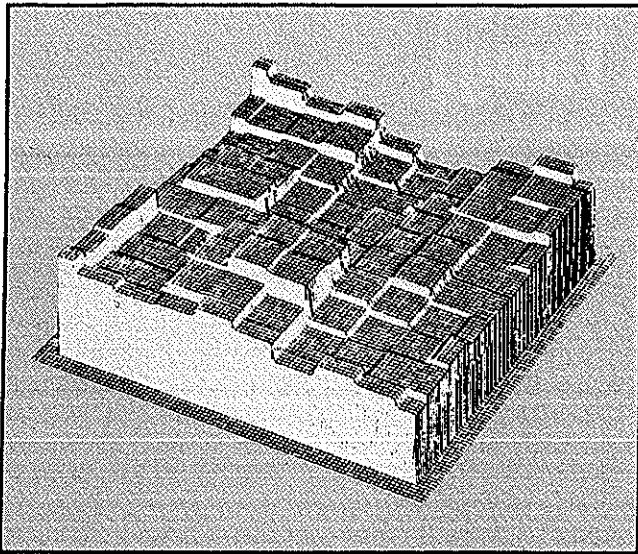
where

$$X' = X + V + \Delta V(dX) \quad (1)$$

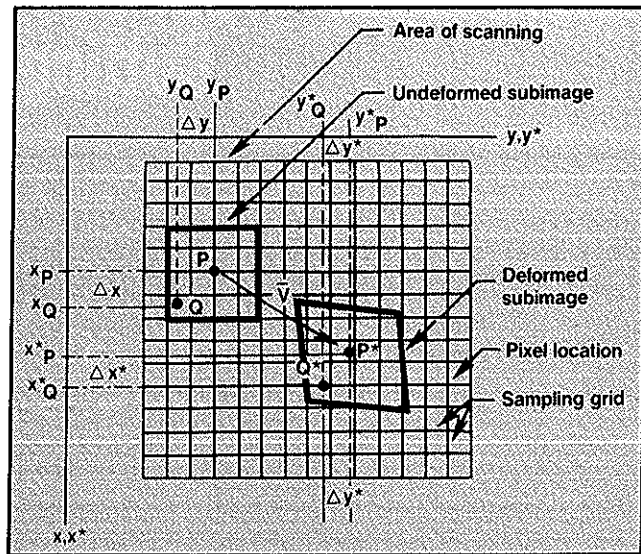
and

V = the displacement vector with com-

3. The digitized intensity values within a 10×10 subimage



4. The deformation of a subimage in a sampling grid



ponents u and v in the x and y directions, respectively

ΔV = the displacement gradient tensor

X = the location of a point in the undeformed image

X^* = the location of a point in the deformed image

dX = the differential vector with components dx and dy

dA = a differential in area

$I(X)$ = the intensity of the image at position X .

The cross-correlation defined in the equation accounts for the presence of reasonable nonuniformity in the illumination of the specimen by normalizing the intensity values.

The concept is illustrated graphically in Fig. 4. Points P and Q are located at positions $x(P), y(P)$ and $x(Q), y(Q)$, respectively, in the first image. After deformation, points P and Q are located at positions P^* and Q^* , respectively. The goal of the digital correlation method is to determine the values of V and ΔV which give the best match of all points P and Q to points P^* and Q^* within a given subset. The calculated values for V and ΔV are the estimated values of the deformation at the center of the subset.

Computer programs have been written to compute the displacement of any subset of an image, by minimizing the functional in Eq. 1. For the analysis of a paper specimen's images, all components of ΔV were set equal to zero; the strains were small and had little effect on the displacement calculations. Hence, the components of V were computed as if the subsets did not distort.

The subset size used in Eq. 1 to

compute deformation parameters is equivalent to the gauge length in the case of a strain gauge. By varying the size of the subset, the "gauge length" can be controlled to obtain the desired information. For example, if a smaller subset is used, then the local variations in deformation can be detected. On the other hand, if a larger subset size is chosen, the deformations calculated will correspond to the average or "macroscopic" response of a region of material. We refer to this capability of varying the subset size to obtain localized or macroscopic material behavior as "variable sensitivity."

The computer programs used to estimate the displacement of a subset from the discrete intensity data employ a surface fitting routine to fit a bicubic spline interpolation surface to the deformed images. By combining this surface fitting with successive averaging of twenty images to obtain an average image, we can improve the accuracy of the method by a factor of approximately 20. Currently, the errors in the method are estimated to be ± 0.05 pixels for each displacement component. Since the actual size of the region imaged onto a pixel is dependent on the image magnification factor (MF), then the actual error estimate is $\pm(0.05 \times MF)$ mm, where MF has a unit of millimeters per pixel. The MF may vary with direction because most charge-coupled device cameras have sensors that are rectangular; hence, both MF_x and MF_y are required.

Conclusions

A computer-based, automated, data

acquisition system and an image analysis method for the extraction of deformations from the images have been developed. The advantages of the method for use in the analysis of deformations in paper are that (a) it has variable sensitivity to variations in material response through changes in the subset size, (b) it is a noncontacting method for the analysis of paper deformations, (c) it is capable of determining deformations in a full-field manner, and (d) it is insensitive to typical laboratory vibrations.

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