Digital image correlation and its application in an undergraduate Civil Engineering Materials Laboratory

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Abstract

Digital image correlation (DIC) is an innovative non-contact displacement measurement technique which provides the surface deformations and strains by comparing the digital images of a specimen surface taken before and after deformation. DIC is simple to use, cost effective, and commonly used to investigate deformation of engineering materials and structures. The goal of this paper is to present (a) the theory and concepts of DIC, (b) the process of implementing DIC including specimen preparation, image acquisition, and image processing, (c) the DIC system developed at IPFW’s civil engineering materials laboratory, and (d) the demonstration of the DIC application in measuring the displacement field and strain maps during compression tests performed on clear wood specimens parallel to the grains.

Introduction

Surface displacement measurement of materials is an important part of various laboratory experiments. The DIC technique is an innovative particle tracking method by which the in plane surface deformations are measured by comparing the digital images of a specimen surface taken during the experiment. DIC is now widely accepted and commonly used as a powerful tool in experimental mechanics. The use of the two dimensional (2D) DIC, as a continuous non-contact displacement measurement technique, provides great potential for measuring displacements and strains during undergraduate laboratory experiments. The main assumption in using the DIC is that the displacements of the image should be directly proportional to the displacements of the object surface. Other optical methods including both interferometric and non-interferometric techniques can be used for surface displacement measurements. However, the DIC has several advantages including simple experimental setup and specimen preparation, ability to work in ambient light with no special illumination, and great measurement accuracy. The main limitations of the DIC method, however, is that the specimen surface has to be planar with a random pattern on the surface. In this paper, the fundamentals of DIC and its application to a common civil engineering materials experiment is presented.

Fundamentals of 2D-DIC

The implementation of the DIC method requires three consecutive steps: (a) specimen preparation and experimental setup, (b) recording images of the planar object during the experiment, and (c) processing of the images using a correlation algorithm through a computer program.
Figure 1 shows schematically the DIC measurement setup for in-plane displacement measurements. The camera needs to be mounted perpendicular to the object surface with its optical axis on the geometric center of the specimen. The specimen surface must be planar and most importantly remain in the same plane perpendicular to the camera axis during the experiment. The specimen surface must have a random pattern (texture) to provide a random gray value intensity distribution on the recorded images. The pattern can be either from the natural texture of the specimen surface or from an artificially made pattern such as a painted surface. The pattern deforms together with the specimen surface and carries the specimen’s deformation. The 2D-DIC system is only capable of measuring in-plane deformations and any out-of-plane deformations on the specimen surface are neglected. The measurement accuracy depends on the quality of the images taken during the experiment and there should be no geometric distortion on the images.

![Figure 1 - Typical DIC setup for in-plane displacement measurement](image)

After recording the digital images of the specimen surface during the experiments, DIC compares the acquired images and computes the motion of small regions of each image using a correlation algorithm\(^1,3,4\). The technique relies on a direct correspondence between the displacements in the images recorded by the camera and the deformations of the specimen surface. The image taken before deformation at the beginning of the test is called the reference image and is used as the basis for comparison with images taken during deformation or loading.

In 2D-DIC, only one charge-coupled device (CCD) camera is needed to acquire the digital images during the experiment. Depending on the shade of grey reflected from a point on the specimen surface, a cell in the array of pixels embedded in the CCD camera stores the grey-scale value light intensity of the point. An 8-bit image has \(2^8\) grey-level values ranging from zero to 255. A grey-level value of 0 denotes the black color and a grey-level value of 255 represents the white color. A calculation area or a region of interest (ROI) needs to be defined first within the image, and the ROI is then divided into smaller portions (subsets) by an evenly spaced virtual grid so that the displacement field can be calculated at the grid points\(^1\). In DIC, subsets of images are tracked between the deformed and the reference image. The reason for choosing a subset rather than a single point is that a square subset provides a unique arrangement of grey-level values that makes it identifiable compared to a single point with a single gray-level value.

To track the subset, a correlation algorithm/criterion is used\(^1\). When the correlation coefficient between the reference and the deformed subsets reaches an extremum (i.e., minimum or maximum, depending on the type of correlation criterion), optimal matching is found between
the two subsets. The coordinates of the extremum position define the new (displaced) position of the deformed subset. The difference between the new position of the deformed subset and the center of the reference subset yields the displacement. The peak position in the distribution of the correlation coefficient defines the location of the best match and the deformed subset. The same procedure is repeated for the other grid points in the ROI to obtain the full-field displacement.

Figure 2 demonstrates the process of image correlation, in which a reference subset from the reference image is compared with the deformed subset in the deformed image. The figure contains the distribution of correlation coefficients obtained from the correlation criterion used around the center point of the reference subset. The peak position of the distribution of the correlation coefficient obtained from the correlation criterion yields the new position of the deformed subset. As an illustration, the figure shows the peak position in the correlation distribution occurring at u=5 and v=10 pixels; where u and v are values of the x and y coordinates, respectively. This means that the deformed subset has been translated 5 pixels in the horizontal direction and 10 pixels in the vertical direction with respect to the reference subset.

![Image](image.png)

**Figure 2- DIC process and image correlation**

**DIC system and experimental setup**

The camera and the lens should be designed to capture the entire surface of the specimen during the experiment. Figure 3 shows a picture of the experimental setup developed in IPFW’s Civil Engineering Materials Laboratory. A 5-mega pixel Blackfly (Point Grey) CCD camera with 2448×2048 square pixels is used in combination with a Tamron lens with focal length of 16 mm with manual control of aperture, focus, and zoom. Digital images were recorded at the rate of 2 frames per seconds during the experiment. The camera remained in a fixed position with respect to the specimen throughout the experiment. Finally, the computer software Vic-2D was used to correlate the images taken during the test and provided displacement field and strain maps on the specimen surface.
Specimen preparation

Appropriate setup of the imaging system and proper specimen preparation are vital for accurate image correlation. Specimen preparation involves creating a random pattern of speckles on the specimen surface so that the speckles deform with the specimen surface representing the deformation of the specimen. Image artifacts such as dust spots on the camera sensor or lens, local reflections on the object surface and camera sensor dead pixels need to be identified and minimized prior to imaging\(^1\). In DIC, each speckle on the specimen surface should be imaged by at least 3 pixels to ensure minimal oversampling and good accuracy in the image correlation process\(^1\).

The wood specimen tested here for demonstration of the DIC technique were 38 by 38 mm in cross section and 87 mm along the grain, as shown in Figure 4a. Due to the lack of a natural texture on the specimen surface, an artificial pattern was constructed on the surface by spray-painting the specimen surface.

Considering the assigned number of pixels in the images taken by the camera (i.e., 464 pixels in the horizontal direction) and the size of the specimen (i.e., 38 mm in the horizontal direction), the speckles needed to be larger than 245 \(\mu\)m (i.e., speckle size \(> 38 \text{ mm}/(\# \text{ of speckles}=464/3)\)) to ensure that each speckle is imaged with the minimum of 3 pixels. To create a unique and random speckle pattern for the purpose of image recognition, a textured spray-paint (product of Rust-Oleum) was used to coat the surface of the wood specimen. The applied speckle size by spray painting the specimen surface was approximately 400 \(\mu\)m and provided about 5 pixels for each single speckle. Therefore, the speckle technique used here met the minimum requirement of 3 pixels per speckle. Figure 4b shows a digital image of the specimen surface with the speckle pattern.
DIC displacement measurements

DIC image correlation is performed on the digital images taken during the test. Because the image correlation is performed on digital images and the unit of measure from the computational analysis is pixel-based, a magnification factor needs to be introduced to transform the results from the digital image to the related physical dimension. The magnification factor depends on the imaging system and the field of view, and relates the physical dimension on a specimen surface to the corresponding dimension on the digital image. For example, in the experimental setup described above (see Figure 4), the 38 mm width of the specimen is imaged with 464 pixels. Therefore, the magnification factor in our imaging system will be equal to $M = 81.9 \ \mu\text{m/pixel}$ (i.e., $38 \ \text{mm} / 464 \ \text{pixels} = 81.9 \ \mu\text{m/pixel}$). It is an accepted fact that the resolution of DIC is about 0.01 pixels\textsuperscript{1}. Considering the magnification factor for this experiment, the resolution of our DIC imaging setup will be about 0.82 \ \mu\text{m}. The smaller the magnification factor, the more accurate the DIC results.

Experimental results

A Tinius Olsen Model “L” Testing machine was used to apply compression on the small, clear, test specimens of pine. The compression load was applied parallel to the grain at the rate of 25 lb/s. The axial displacement was recorded by both the testing machine load displacement transducer and the DIC method.

Figure 5 illustrates the typical displacement field obtained from compression parallel to the grain at different stages during the test. Figure 5 (a,b) show the horizontal and vertical displacement plots on the surface of the specimen at the load of 20.8 kN (50\% of the failure load) while figure 5 (c,d) show similar plots under the axial load of 41.6 kN (failure load).
Figure 5- Displacement profiles from DIC at different stages of the test

(a) Horizontal displacement profile at 50% of failure load

(b) Vertical displacement profile at 50% of failure load

(c) Horizontal displacement profile at failure load

(d) Vertical displacement profile at failure load
An examination of figures 5a and 5b indicates that the distribution of the displacement field is not as homogeneous as one might expect. This is mainly because of the end effects (i.e., friction and damage) occurring locally at the contact between the specimen and the compression platens. Figure 5a shows the horizontal displacement profile on the specimen surface, indicating lateral expansion of the specimen due to the Poisson’s effect in response to the applied axial compression. It is interesting to note that the vertical displacement profile (figure 5b) has a linear distribution along the height of the specimen for the regions which are far from the two ends of the specimen. This observation indicates that the specimen is being uniformly loaded under compression. Figure 5c and 5d show the displacement profile obtained by DIC just prior to the failure of the specimen at the applied load of 41.6 kN. The displacement profile clearly indicates the failure mode of the specimen. The locations of discontinuity in the displacement profile exactly correspond to the location of visible failure lines on the test specimen.

DIC computes strains by numerical differentiation of the measured displacement\(^1\). Figure 6 shows the distribution of major principal strain on the specimen surface acquired just prior to the failure of the specimen. An examination of the strain field reveals that the strain is not homogenous likely due to orientation of the grains along the height of the specimen. Interestingly enough, the location of the highest strain on the strain plots corresponds to the location of local failure on the specimen.

![Figure 6 - Major Principal strain contour plot for compression test specimen at a load level of 41.6 kN](image)

Figure 6- Major Principal strain contour plot for compression test specimen at a load level of 41.6 kN
Summary

This paper described the procedure underlying the DIC technique to capture strain profile and major principal strain contour of a specimen under compression loading. The DIC technique is an innovative particle tracking method which provides surface deformations by comparing digital images taken during the experiment. Implementation of DIC required three steps: (a) specimen surface preparation, (b) image acquisition, and (c) image correlation using a computer program. A compression test on clear small specimen of wood was conducted to demonstrate the application of DIC technique in Civil Engineering Materials Laboratory. Specimen preparation involved creating a random pattern of speckles on the specimen surface so that the speckles deform when the specimen is deformed. To create a unique and random speckle pattern, a textured spray-paint was used to coat the surface of the wood specimen. A camera was used to image the entire area of the specimen at a rate of 2 frames/sec. The camera remained in a fixed position perpendicular to the specimen surface throughout the experiment. Finally, a computer software was used to correlate the images taken during the test and provided displacement field and strain maps for the specimen surface. The DIC system not only enabled students to observe visually different failure modes occurring in wood specimens but also provided the opportunity to measure mechanical properties of the tested materials such as the Poisson’s ratio and modulus of elasticity. In sum, the addition of DIC system allowed for more thorough understanding of material properties in the laboratory. Students were exposed to state-of-the-art alternative techniques in measuring properties of the materials, and considering the fast growing use of DIC in industry, the gained experience in the laboratory with DIC provided students with a competitive advantage in using this advanced tool.

References


