DEVELOPMENT OF FINITE ELEMENT BASED DIGITAL IMAGE CORRELATION (DIC) TECHNIQUE FOR ANALYSIS OF DEFORMATION BEHAVIOR IN GEO-MATERIALS

Short Report for PMRF Reveiw

by

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1 Introduction

Knowledge of deformation during the loading process is a very crucial input required for designing of structures and quantitative estimation of mechanical constitutive parameters. There are many experimental measurement methods available to investigate the deformation process in laboratory conditions. Broadly these methods can be divided into two categories contact methods and non-contact methods [Sharpe, 2008]. Contact methods do not give a comprehensive understanding of the failure process as the information is collected only at specific locations, but non-contact methods give the full field of surface displacements and strains of the test sample. Getting deformation information through image analysis is one of the most active research area in non-contact measurement methods. A very recent technique in this field is Digital Image Correlation (DIC).

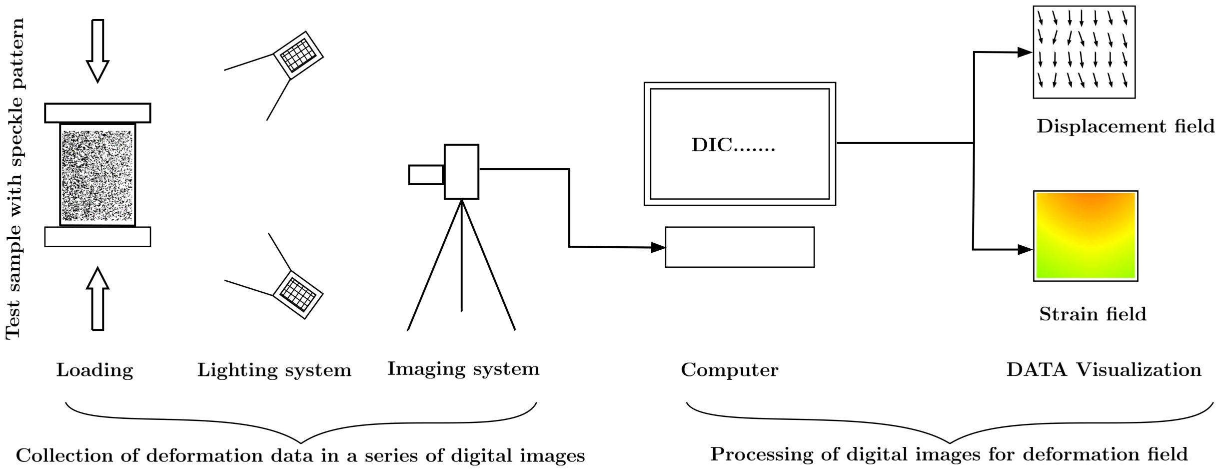


Figure 1: Digital Image Correlation Method

Digital Image Correlation (DIC) method can be divided into two parts i) collection of deformation data in a series of digital images ii) processing of series of digital images for deformation field, as shown in Fig 1. Data in the form of images are collected by the image acquisition system (consists of camera and illumination system), and then processing is done on a computer to access the deformation behavior. The test sample surface should be randomly dotted (speckle pattern) to have unique correspondence between the consecutive images to get the deformation fields that occurred on the measured surface. Artificial speckle pattern either by paper or by paint or by stamp should (one of them) be used if the natural surface of the sample is not randomly speckled. DIC is considered as the most advanced technique after strain gauge in the experimental mechanics, which allows visualization of the surface deformation (strain) field of the object [Reu, 2012].

2 Present State of Art

Peter and Ranson from the University of South Carolina introduced the initial concepts of Digital Image Correlation in the paper published in 1982. The research group from Dept. of Mechanical Engineering, University of South Carolina, under the leadership of Michael Sutton, highly contributed to developing the foundations of DIC. Other prominent research groups involved in the advancement of DIC are Laboratoire de Mecanique et Technologie, Univ. Paris-Saclay (under Francois Hild) and Institute of Solid Mechanics, Beihang University, Beijing (under Bing Pan). Most of the literature dealing with the development of DIC are from these three research groups.
The algorithms used for image matching are broadly divided into two categories local algorithms and global algorithms. Local algorithms use a subset around a point to get the displacement. Global algorithms use a mesh all over the surface to get displacement at the nodes. The local algorithms have following shortcomings: i) Inter-subset continuity is not imposed, and this

results in wrong data points [Sun et al., 2005] ii) For the quantitative estimation of mechanical constitutive parameters, the measured displacement data should be consistent with numerical simulation for reducing uncertainty propagation in the estimation chain[Besnard et al., 2006] iii) They cannot handle physical discontinuities which appear on the surface of test sample during the loading or pre-existing on the surface iv) They cannot capture highly varying displacements (heterogeneous deformation) because of limitations on the size of the subset [Pan, 2018].

3 Research Objectives

1. Development and implementation of finite element based digital image correlation algorithm for measuring displacement field and strain field of a two-dimensional deformable surface under static and dynamic loading conditions.

2. Development of finite element based digital image correlation algorithms for handling pre-existing discontinuities and fractures appear during loading.

3. Inverse algorithms to be developed for deforming constitutive parameters of rocks with the help of measured kinetic fields using DIC.

4 Relevance and Novelty

- The DIC technique generates a large amount of data. This data is used for visualization of the displacement and strain of the surface of the test object. From recent years there is an increasing interest in using this data for calculation of material properties. Inverse algorithms used for calculation of material properties are based on the finite element framework. The DIC data from local algorithms is not consistent with the finite element framework, hence increasing the uncertainty in the inverse algorithms. This research focuses on the development of a global algorithm, where the DIC data will be consistent with the finite element framework, which allows seamless integration with finite element simulations.

- The finite element based DIC algorithm gives scope to integrate principles of X-FEM, which can handle the discontinuities and fractures on the surface of the test object.

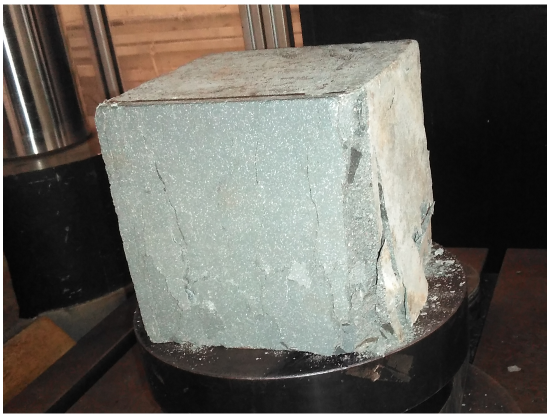
5 Experimental Details

The developed algorithm is tested with numerically simulated speckle images and real experiment images. Numerically simulated speckle images are generated by a procedure given by Pan et al. [2006]. 150 mm sized cube specimens made with cement concrete of M30 grade are used for experiments. One surface of the cube is pasted with a speckle sticker developed at Dept. of Mining Engineering, IIT Kharagpur, and patented in India by Deb and Bhattacharjee [2014]. A universal testing machine capacity of 3500 KN is used for uniaxial compressive tests with a loading rate of 0.45 mm/min. A Nikon D3400 camera is used to capture the images of the speckled surface with a frequency of 12 images/min, and Simpex setup is used for lighting, as shown in Fig. (2). The results of lab experiments are discussed in next sub-section.

(a) Camera

(b) Lighting system

(c) Image capturing



(d) Test sample

Figure 2: DIC setup developed in Rock Mechanics Lab

SPECIFICATIONS OF THE HARDWARE	
Camera	Nikon D3400 with AF-P NIKKOR 70-300mm f/4.5-5.6E ED VR Lens
Lighting system	Simpex (Light stand + Portrait light + White umbrella)
Tripod	Samsung tripod ST2000
Loading Machine	Instron UTM SATEC Series 3500 KN

Table 1: DIC setup specifications

5.1 Uni-axial Compressive Strength Tests

The stress-strain graph of a 150 mm sized cube concrete specimen is given in Fig. 3a. The close view of the ultimate failure zone is given in Fig. 3b. The image captured locations on the curve are marked with circular dots. The surface images and and axial strain visualizations of the dark colored marks are arranged in chronological order in Fig. 3c to get the perspective of strain accumulation and crack formation with the loading. The Fig. 3c depicts that FE-DIC algorithm spotted the zones of strain accumulation and crack formation well ahead of visible cracks on the surface. It can be seen that at $t = 230$ sec, FE-DIC algorithm recognize lateral strain accumulation, however no visible cracks/fractures occur on the surface of the sample. A slightly visible faint crack is developed at $t = 270$ sec and visible crack is developed at $t = 330$ sec (cracks are enclosed with in a red color closed loops in Fig. 3c).

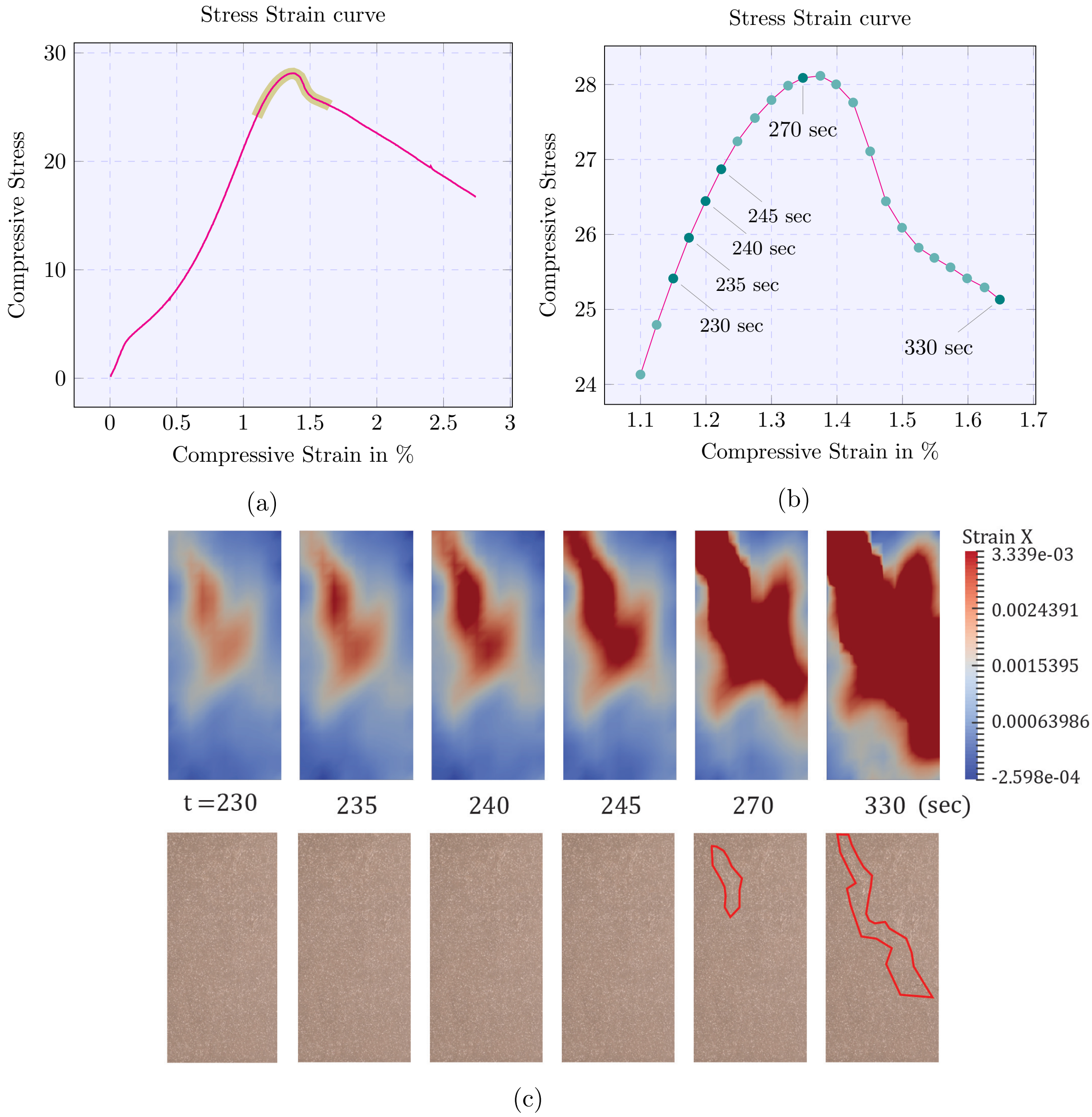
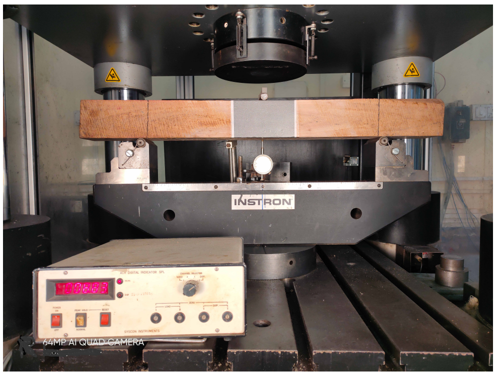


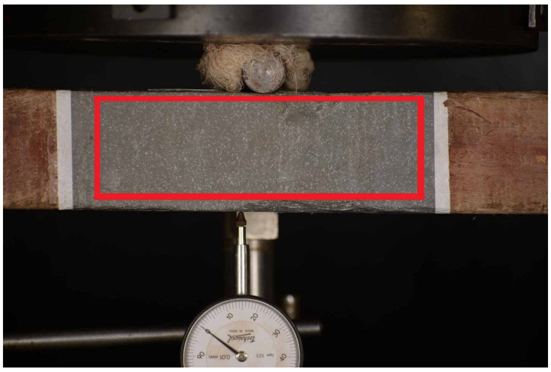
Figure 3: UCS Test

5.2 Three Point Bending Test

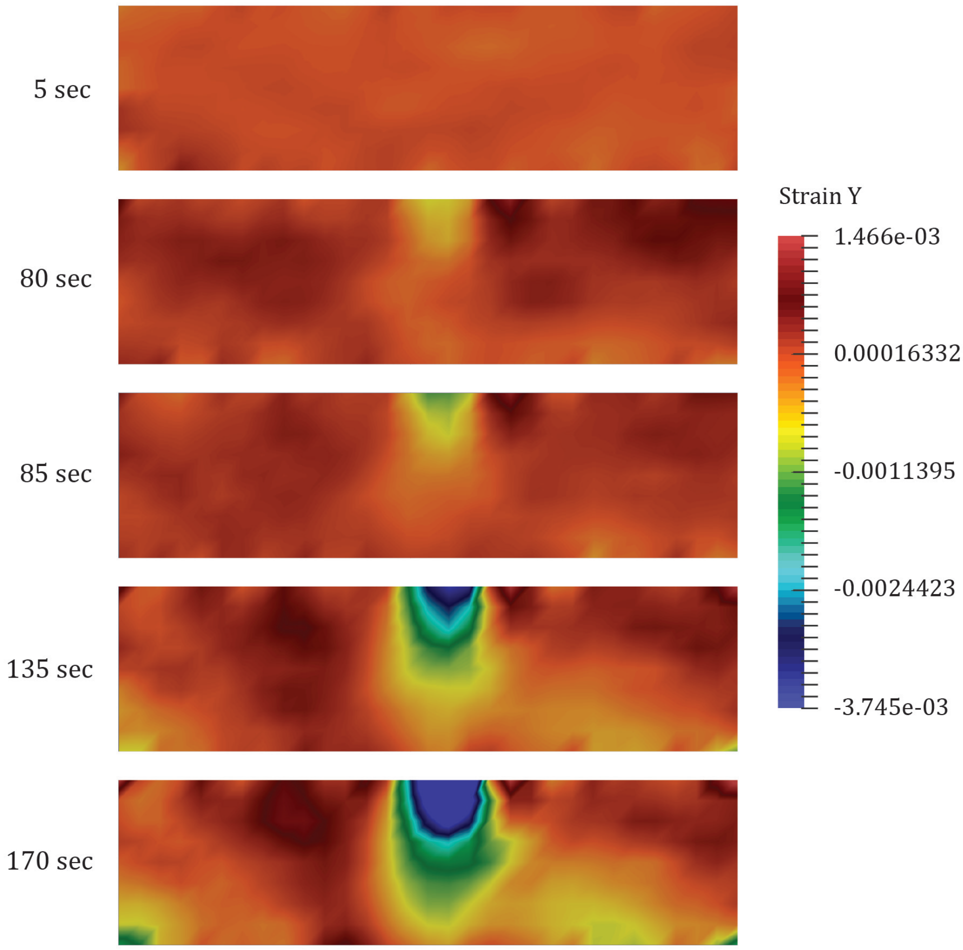
Three point bending tests were performed on a x cm long wood whose cross section dimension are breadth X Height. A loading rate of xx mm/min is used for this test. The images were captured at a frequency of 12 images/min. The setup of the experiment is shown in Fig. 4a. The close view of the speckle pattern and the area of interest (red color rectangle) are shown in Fig. 4b. The vertical strain visualization of the area of interest is given in Fig. 4c. The purpose of this test is to examine the capability of the FE-DIC algorithm to identify the zone of compression.



(a)



(b)



(c)

Figure 4: Three Point Bending Test

6 2D-DIC Challenge 2.0

The SEM (Society of Experimental Mechanics) and iDICs (International Digital Image Correlation Society) conducted 2D-DIC Challenge 2.0, to test the performance of the DIC algorithms/codes all over the world including codes from both industry and academia. The FE-DIC code (by the author) passed this challenge and the DIC Challenge board accepted to publish the results. DIC Challenge board consists of leading experts on DIC from both industry and academia.
More information about the challenge is available at `https://sem.org/dicchallenge`.

7 Research Output

Conference Papers:

1. Reddy, C. S. and Deb, D. (2019). Estimation of geo-material deformation and strain using finite element based dic and smooth particle hydrodynamics (sph). 4th Annual International DIC Society Conference (iDICs 2019), 14-17, October 2019, Portland, OR, USA.

2. Reddy, C. S., Deb, D., Maheshwari, B., Kumar, S., and Gupta, R. K. (2019) Deformation monitoring using finite element based digital image correlation (dic) method. 3rd Technical Conference on "Asset Integrity, Reliability Management, Inspection/NDT techniques," 5-6, August 2019, New Delhi, India.

3. Reddy, C. S. and Deb, D. (2019). Prediction of failure process in geo-material using finite element based digital image correlation (dic) method. Conference on Non Destructive Evaluation (NDE 2019), Indian Society for Non-Destructive Testing (ISNT), 5-7, December 2019, Bengaluru, India.

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