An Investigation of Digital Image Correlation for Earth Materials

Nutan Shukla, Manoj Kumar Mishra

Department of Mining Engineering
National Institute of Technology Rourkela, India 769015

ABSTRACT
Strain measurement is vital in material and mechanical testing. The conventional contact based approaches as strain gauges, extensometers, acoustic emission, seismic waves etc. have limitations like sensitivity to contact areas, susceptible to external noise, vulnerable to breakage, influenced by surrounding environment etc. Recently, the development of non-contact based methods has eliminated these challenges. Digital Image Correlation is an optical, non-contact based technique which is being widely used in measuring full-field displacement. The technique is based on acquisition of digital images taken before and during loading and developing a correlation between them with subpixel accuracy. In this paper, the behavior of equivalent coal specimens at varying depth from 92m to 126m have been evaluated for static loading condition using non-contact based approach i.e. Reliability-guided Digital Image Correlation technique (RG-DIC). There exists a good agreement between the contact (strain gauge) and non-contact based approaches (DIC) for static loading condition. So, Digital Image Correlation (DIC) can also be a reliable strain measuring approach for investigating earth materials.

Keywords: DIC, RG-DIC, Strain Measurement, Static Loading, Full-Field Displacement

INTRODUCTION

Strain measurement is an important tool to evaluate the behavior of any material for its both short and long term usage. Experimental strain analysis has gained popularity in manufacturing industries because of its ability to test the durability of the specimen. However, measuring the parameters outside the laboratory, in real cases, requires a tough choice among conventional methods keeping accuracy, simplicity and cost balanced. The conventional methods are mostly contact based methods that include electrical strain gauges, mechanical dial gauges, acoustic emission techniques etc. The contact based methods have issues like sensitivity to noise, damage to the recording unit, loss of contact of sensors with the surface, influence of environmental noise and temperature, measurement error etc. [1, 2]. Non-contact based methods are categorized as interferometric technique and non-interferometric technique which precede contact based methods in terms of accuracy, human error and repeatability of experiment. DIC technique is evolving to be a very effective strain measuring tool for continuous material. [3]

In this work, a non-contact based optical method Digital Image Correlation (DIC) [4-6] has been used that acquires an image of the object, stores it and performs image correlation analysis to extract full field deformation of that object. The concept involves comparing the gray intensity changes of the object surface in the acquired images with the reference image. This technique has become widely popular in measuring full field deformation in various industries viz. automobile, solar wind power, medical etc. [7-10].

Optimizing the underground coal pillars dimension is very important to maximize the extraction without compromising the safety of the system. This involve investigation into the deformation behavior of the coal pillar at varying load. So far there is limited data available on the efficiency of DIC technique on earth materials.

SAMPLE PREPARATION

Model pillars have been fabricated with sand-cement to represent coal pillars with comparable strength values. It has been done to eliminate influence of multiple weaknesses in the deformation behavior investigation. The coal specimens were extracted from a depth of 92m to 126m from an operating underground mine located between latitude 20^0 55'00'' to 21^0 00'00'' and longitude 85^0 05' 00''and 85^0 10' 00'' from MCL, Talcher, India. The uniaxial compressive strength (UCS) test was carried out and the values obtained were between 15 and 33MPa. The equivalent samples were prepared after many trial and error experiments with varying sand, cement and water ratios. The UCS values of the equivalent specimens obtained are as below.

Table 1 Uniaxial Compressive Strength of Modeled specimens

Ratio	**Compressive strength (MPa)**
1:1.5	27-31

The prepared model specimens have the UCS values that compares favorably with that of coal samples. Hence, the modeled specimens have been used in further experiments. The model specimens are made of ordinary portland cement and river sand (-0.5mm mesh). Proper care was taken to achieve uniformity of the cube. The exact amount of sand and cement as per the defined ratio were dry mixed thoroughly and a fixed amount of water (cement: water = 0.42) was mixed to achieve consistency. This mixture was poured in the mould of 10cm cube and shaked at 3000 rpm to eliminate any void spaces. The moulds were removed after 24 hours and specimens were cured at 99% humidity for effecting the chemical reactions for 7 days (Fig.1). The cube specimens were brushed to remove any loose surface particles.

Fig. 1 Prepared cube samples (at 28 days)

Fig. 2 Strain gauge installed on a specimen

The generation of speckle pattern on the surface is very important in DIC investigations. White and black spray paints were applied on the three sides of the cube to create the speckle pattern (Fig.3). Strain gauge (350.8±0.1Ω) were fixed on the other side of the cube (Fig.2). The results obtained from those are reported here.

EXPERIMENTATION

The prepared models were loaded for UCS values in a servo controlled machine (CCTM, 100T, make: HEICO, India) at a loading rate from 0.5 to1.0 MPa/sec [11]. The entire loading process till fracture was captured by three image acquisition units in three sides in addition to the data generated by the strain gauge from the other side. The entire setup was well illuminated by illuminating lights (Fig.3). The image acquisition unit has a resolution of 1920 x 1080 pixels and 3:2 aspect ratio. The reference and deformed images are given in fig.4.

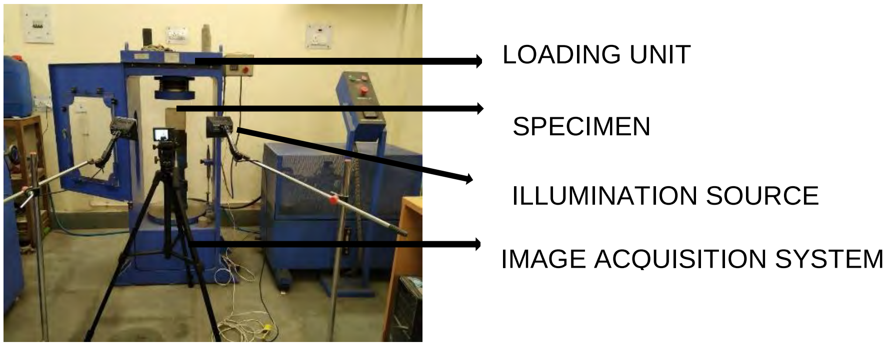

Fig. 3 Laboratory Setup

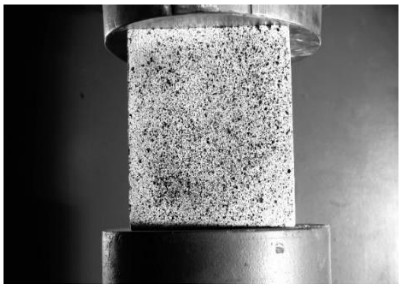

Fig. 4 (a) Reference image

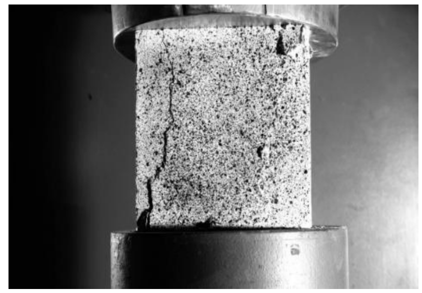

Fig. 4(b) Deformed image

The tests that produced a few irregular failure pattern were not considered. The one which exhibited both strain gauge and DIC outputs are discussed here. A total number of 16,368 frames were extracted, out of which 165 frames were taken into consideration for further analysis. An open source 2D digital image correlation MATLAB program Ncorr [12] was used for the analysis which used Reliability Guided DIC algorithm. The strain $€_{xx}$ and displacement x and y profile are given in figures 5,6. A total strain of 2.484% was observed using the Digital Image Correlation technique.

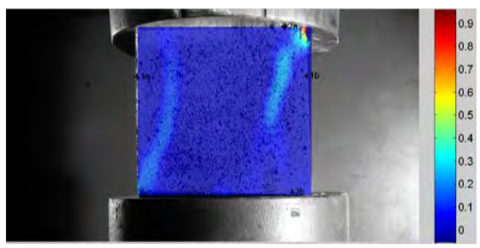

Fig. 5 Strain $€_{xx}$ profile

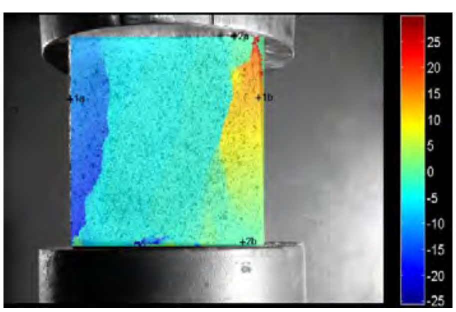

Fig. 6(a) X displacements profile

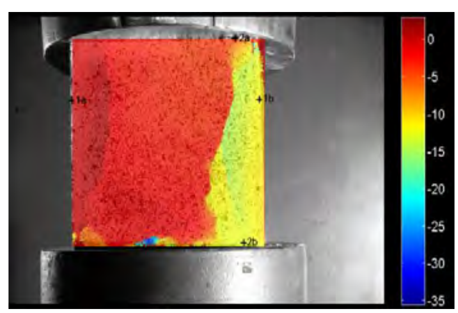

Fig. 6(b) Y displacements profile

The strain gauges readings are converted to percentage change. In the instant case, the strain gauge reading went up to 2.62%. The stress-strain behavior of the specimen obtained in contact based method and non-contact based method is shown below (Fig.7).

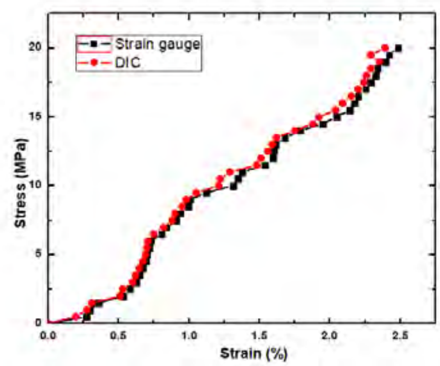

Fig. 7 Stress-Strain behavior of a sand cement specimen using DIC and strain gauges

It is observed that both DIC and strain gauge readings were very close to each other in the initial loading phase when specimen offered maximum resistance (± 4.6%). There is significant though of lesser magnitude (± 9.7%) change seen in the linear range of the loading. However, the difference is wider towards the peak loading where the specimen undergoes irreversible physical disintegration (± 21.4%). The contact based method and noncontact based method were analyzed on the equivalent specimen and the strain obtained in both the method are well matched and correlated. An average error of 12% was observed in mapping strain in both the methods.

CONCLUSION

The investigation was carried out on an equivalent material of coal, an earth material. The Reliability Guided Digital Image Correlation (RG-DIC) algorithm was used to measure the strain under loading condition. A strain of 2.484% was achieved from Digital Image Correlation technique and the same specimen was investigated using strain gauge, a contact based way of measurement. A good correlation between them has been found with a deviation of 12 % has been observed between the strain mapping methods.

REFERENCES

[1] Gale W. J., Heasley K., Iannacchione A., Swanson P., Hatherly, P., King A., Rock damage characterization from microseismic monitoring in *Proceedings of the 38th US rock mechanics symposium*, Washington, DC; 7–10July, pp. 1–313, 2001.

[2] Cai M., Kaiser P., Tasaka Y., Maejima T., Morioka H., Minami M., Generalized crack initiation and crack damage stress threshold soft brittle rock masses near underground excavations, *International Journal of Rock Mechanics and Mining Sciences*, vol. 41, no.5, pp.833–47, 2004.

[3] Yang Y., Zhang F., Hordijk D.A., Hashimoto K. & Shiotani T., A comparative study of acoustic emission tomography and digital image correlation measurement on a reinforced concrete beam, Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision, pp. 2419-2126, 2019.

[4] Bhattacharjee S., Deb D., Automatic detection and classification of damage zone(s) for incorporating in digital image correlation technique", *Optics and Lasers in Engineering*, vol. 82, pp. 14-21, 2016.

[5] Zhou P., Goodson K.E., Sub pixel displacement and deformation gradient measurement using digital image/speckle correlation, *Optical Engineering*, vol.40, no. 8, pp. 1613–20, 2001.

[6] Acciaioli A., Lionello G., Baleani M., Experimentally Achievable Accuracy Using a Digital Image Correlation Technique in measuring Small-Magnitude (<0.1%) Homogeneous Strain Fields, *Materials*, vol. 11, pp. 751, 2018.

[7] Alan B. , Nik R., Claire D., Towards a practical structural health monitoring technology for patched cracks in aircraft structure, *Composites Part A: Applied Science and Manufacturing*, vol. 40 . no. 9, pp. 1340-1352, September 2009.

[8] Reddy K.C., Subramaniam K.V.L, Experimental investigation of crack propagation and post-cracking behaviour in macrosynthetic fibre reinforced concrete, *Magazine of Concrete Research*, vol. 6, no. 9, pp.467-478, 2017.

[9] Winder R. J., Morrow P. J., McRitchie I. N., Bailie J. R., and Hart P. M., "Algorithms for digital image processing in diabetic retinopathy, *Computerized Medical Imaging and Graphics*, vol. 33, no. 8, pp. 608–622, 2009.

[10] Elmahdy A., Verleysen P., The Use of 2D and 3D High-Speed Digital Image Correlation in Full Field Strain Measurements of Composite Materials Subjected to High Strain Rates, Proceedings, vol. 2, no. 8, pp. 538, 2018.

[11] Standard method of test for elastic moduli of rock core specimens in uniaxial compressions. American Society for Testing and Materials, ASTM Designation D 3148-72.

[12] Blaber J, Adair B, and Antoniou A, Ncorr: Open-Source 2D Digital Image Correlation Matlab Software, *Experimental Mechanics*, 2015.