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Deepak, A; Jenkins, DFL

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Comparison of Digital Image Correlation (DIC) technique with Nanomaterial based Sensor for the Analysis of Strain measurements

A. Deepak[1] and D. F. L. Jenkins[2]

[1] deepakarun@saveetha.com, [2] d.f.jenkins@plymouth.ac.uk

[1] Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, India- 602105.

[2] Wolfson Nanomaterials & Devices Laboratory, School of Computing, Electronics and Mathematics, University of Plymouth, Devon, PLA 8AA, UK

Abstract:

Digital image correlation techniques can be used to visually map and measure strain in materials such as metals and metallic alloys. The strain induced in an American Society for Testing and Materials (ASTM) standard specimen can be measured using a digital image correlation technique. Image patterns indicating the localized strain variations as a function of time for constant load applied were also obtained. Results obtained using digital image correlation technique were more accurate compared to conventional strain sensors. Digital Image correlation results were also compared with nanomaterial-based strain sensor output. Localized strain induced in the material can be visualised and quantified analytically using digital image correlation.

Introduction:

Strain sensors have been extensively used in many sectors like metallurgy, chemical, automotive and nuclear industries. They are used to identify induced strain levels in engineering components and systems during service. Some of the conventional sensors in today's scenario are extensometers, strain gauges, optical fibre strain sensors and piezo-resistive sensors [1-3]. There is always a need to enhance the sensitivity, selectivity, accuracy and precision of these measurements [4]. In order to meet these expectations, new types of a strain sensor which possess all the above-mentioned superior qualities need to be developed [5].

The means of mixing graphene with a range of suitable polymers, including epoxy, polyaniline (PANI), polyurethane (PU), polyvinylidene fluoride (PVDF), Nafion, polycarbonate or PET to form graphene-based nanocomposite films is important in this research [Das and Prusty, 2013]. Graphene platelets are preferred to carbon nanotubes, carbon nanofibers for a number of reasons, and these include; high aspect ratio, high tensile strength, surface area, good thermal conductivity, good electrical conductivity, flexibility, electromagnetic interference shielding and optical transparency. Graphene based and CNT based polymer strain sensors were also developed [1-2].

Digital Image Correlation (DIC):

Digital image correlation is an optical technique for full field observation of strain induced surface deformation measurements from the macroscopic to the nanoscale. It is a proven tool for non-contact strain measurement.

DIC is able to reduce computation complexity and achieve high accuracy in strain induced deformation measurement. A single fixed camera is constrained to in-plane deformation measurement of the planar object surface in 2D. To extend this to out of plane deformation and obtain reliable measurements, some requirements on the measuring system must be met [6, 7]. If three-dimensional (3D) deformation occurs after loading, this can be circumvented using 3D DIC [8,9].

Srinivasan Nagarajan et.al;[10] explored the feasibility of DIC for analysis of Lüders deformation. Enhanced understanding of the micro mechanisms involved in Lüders deformation based on the associated macroscopic thermal and strain evolutions is provided.

Digital image correlation is also used here to examine digital image data as samples are subjected to mechanical loads. It uses mathematical correlation analysis, whereby a sequence of images are captured as a function time to examine the surface deformation of the specimen when it is subject to incremental loads. Random dot pattern is applied to its surface in order to prepare the specimen.

This technique starts with acquiring a reference image before loading and then a series of images are recorded during the deformation process. All the deformed images show a different random dot pattern relative to the initial non-deformed reference image. Differences between patterns can be calculated by correlating all the pixels of the reference image and subsequently the deformed images using computer software. Finally the strain distribution map need to be generated [11-13]. Accurate Results will depend on the digital image resolution (pixels columns × pixels rows), specimen height and specimen width, the distance between specimen and camera selection and application of appropriate speckle patterns and the focal length of the lens.

The specimen surface requires a random dot or speckle pattern [14], to enable the software to calculate the $x-y-z$ displacements with accuracy. To obtain accurate results with the digital image correlation the speckle pattern size and distribution is important. The speckle pattern requires black speckles with different shapes and sizes, according to the sample of interest. The effectiveness of the speckle pattern depends on the quantity of pixels per black speckle. A good speckle pattern must contain small black speckles (10 pixels), medium black speckles (20 pixels) and large black speckles (30 pixels). The quantity of pixels per black speckle size is approximated [15].

The specimen surface to be studied must have a random dot pattern [16], and the number of pixels / per line in an image defines the spatial resolution. A random dot pattern enables the software to identify and calculate the displacements with accuracy. Suitable patterns need to be defined in order to achieve better results using DIC. Patterns can be both naturally occurring features or can be applied.

Strain and displacement are critical parameters within engineering and construction projects. Accuracy, simplicity and cost must be considered when designing the type of sensor. Several strain gauges are required to measure strain distribution across the entire surface of the specimen. Measuring strain distribution occurring on the whole surface of the specimen by strain gauges is not practical using physical sensors, such as strain gauges. To circumvent this, digital image correlation can be used to measure displacement and deformation without any contact to the specimen, to reveal the full image of strain variation and distribution. Digital image correlation uses two or more digital images to measure strain distribution on the specimen surface from the displacement of each raster point. Raster points and sizes of the subset required for tracking these raster points are identified on the specimen surface. Intensity values of the subset including a center pixel and its neighbor pixels are compared with the intensity values of the reference image. The pixel location where the difference is minimal is identified as the new location of the current subset's Centre. The distance between new and old locations of the points are calculated as displacements. Specimen preparation and test setup, image acquisition, and measurement of displacement and deformation by utilizing image correlation methods are the steps involved in digital image correlation method [17-18].

Implementation of 2D DIC method comprises specimen and speckle pattern; recording images of the planar specimen surface before and after loading and processing the acquired images to obtain strain information and displacement using a computer program [19]. Image patterns indicating the localized strain variations as a function of time for constant load applied were obtained. Figures 1 and 2 shows the Digital Image Correlation (DIC) system, which is a full-field image analysis method, based on grey value digital images, which can determine the contour and the displacements of an object under load in three dimensions [20].

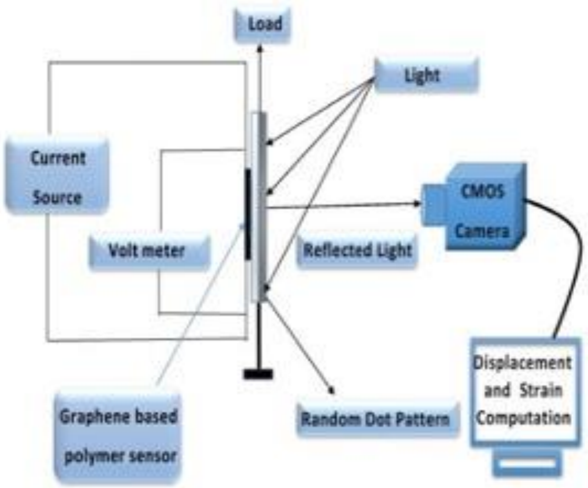

Figure 1: ASTM Specimen Subjected to UTM Load and Strain Measured using DIC Technique and nanomaterial based sensors on either side

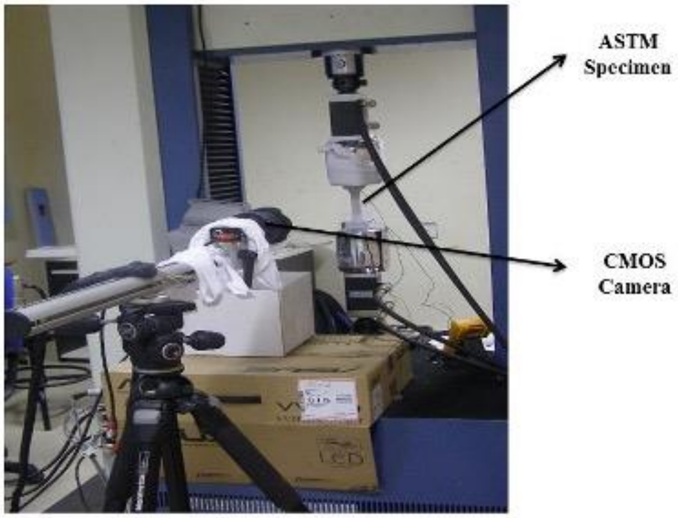

Figure 2: ASTM Specimen attached to UTM machine with DIC setup containing CMOS camera, with nanomaterial based sensor attached at the opposite side

DIC techniques is a flexible tool for deformation analysis. DIC has wide dynamic range and capability to measure large strains (>100%), but accuracy is lower for strains < 3%, where strain gauges perform better [21]. Resolution is scalable since it depends on the field of view. Stereoscopic sensor setup is used to focus each object point on a specific pixel in the image plane of the respective sensor. Calculation of position of each object point in three dimensions is carried out by knowing the imaging parameter (intrinsic parameter) for each sensor and the orientation of the sensors with respect to each other (extrinsic parameter) on the object surface. By using a stochastic intensity pattern, the positional change of each object point in the two images can be identified by applying a correlation algorithm. The subset size used here for correlation was 25 x 25 pixels.

For evaluation, structural materials like Zirconium alloy, which is used in Pressurized Heavy Water Reactors (PHWR) as a structural material, SS316LN (structural material of Proto type Fast Breeder Reactor (PFBR)), MOD T91 (steam generator material of PFBR),12Cr-Mo ferritic-martensitic steel (turbine blade material of PHWR) and carbon steel which is used in many commercial applications are used as test specimens. These materials are machined into dog bone shaped specimens according to ASTM standards and dimensions are specified according to Figure 3.

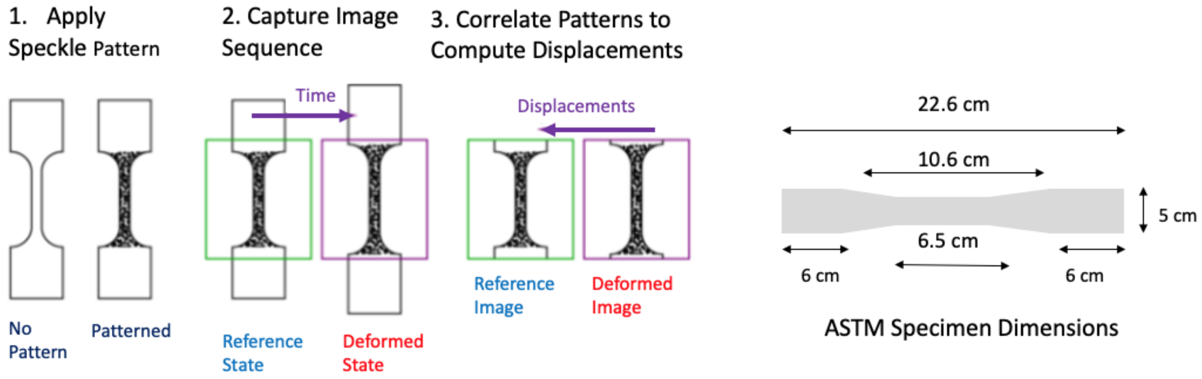

Figure 3: ASTM standard specimen with specified dimension

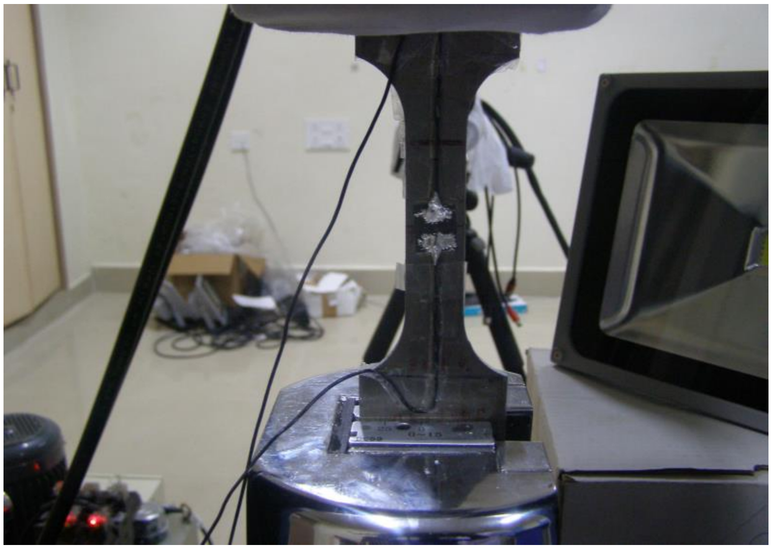

Figure 4: ASTM specimen with nano material based sensor attached at one side

Methodology:

A Universal Testing Machine is used to apply an incremental load to the ASTM specimen, to which sensor film with the measurement probes are also attached. Graphene – PVDF films (of dimensions 10 mm × 5 mm) are attached to specimens using a non-conductive adhesive. A two-point probe is attached to the film using silver epoxy as shown in Figure 4. A tensile load (4 KN to 30 KN) is applied by connecting the material to the Universal

Testing Machine, with a pulling rate of 0.2 mm/min. The ASTM material is subjected to tension whilst current is passed through the sensor film simultaneously.

For the DIC setup, a CMOS camera (MarlinF131) with a resolution of 1380 x 1035 pixels and a pixel size of 6.7 m resulted in a spatial resolution of 125 m for the focal distance used. For image correlation, the camera was focused on opposite sides of the flat surface of the tensile specimen, which was coated with a random pattern. Strain fields were obtained by using associated 2D-DIC to perform image correlation. The subset size used for correlation was 29 x 29 pixels. Uncertainty in strain measurement using this system was ±0.8 μm. Imaging of the surface started from the beginning of loading, capturing images at 5 Hz frame rates.

The correlation subset was 29 x 29 pixels in size. The strain measurement uncertainty using this method was 0.8 m.The imaging of the surface began as soon as it was loaded, with images captured at 5 Hz frame rates. Despite the fact that the camera's field of view was large enough to examine the fillet region of the specimen, the study only focuses at the strain evolutions on the neck.

Results and Discussion

Digital image correlation Images obtained were processed using 2D-DIC processing software which is shown in Figures 5 (a-d). A 100 KN displacement controlled servo hydraulic tensile testing machine was used to calibrate the sensor. Graphene based polymer films were attached on one side of a zirconium alloy tensile specimen and a constant current source of 4 mA connected to one side of the specimen.

Figure 5 shows the DIC pattern of tensile specimens undergoing stress at various time instances. Digital Image correlation patterns indicating the strain variation at different time instant during loading is shown. As the time interval increases there is a constant increase in load and correspondingly there will be an increase in strain. It is clearly visible in the digital image correlation images, with a gradual increase in strain as the applied load increases from 4 KN to 30 KN.

Initially, due to loading, the initial strain is more in the top right corner of the tensile specimen as shown in Figure 5(a) and slowly as the time prolongs the strain extends to other regions of the tensile specimen, as shown in Figure 5 (b,c,d). Red colour areas shows where the strain is maximum at that particular region and the magenta (pink) color area shows where the strain is minimum in that region. This localized strain variation is obtained using DIC technique which is one of the main advantages compared to other techniques.

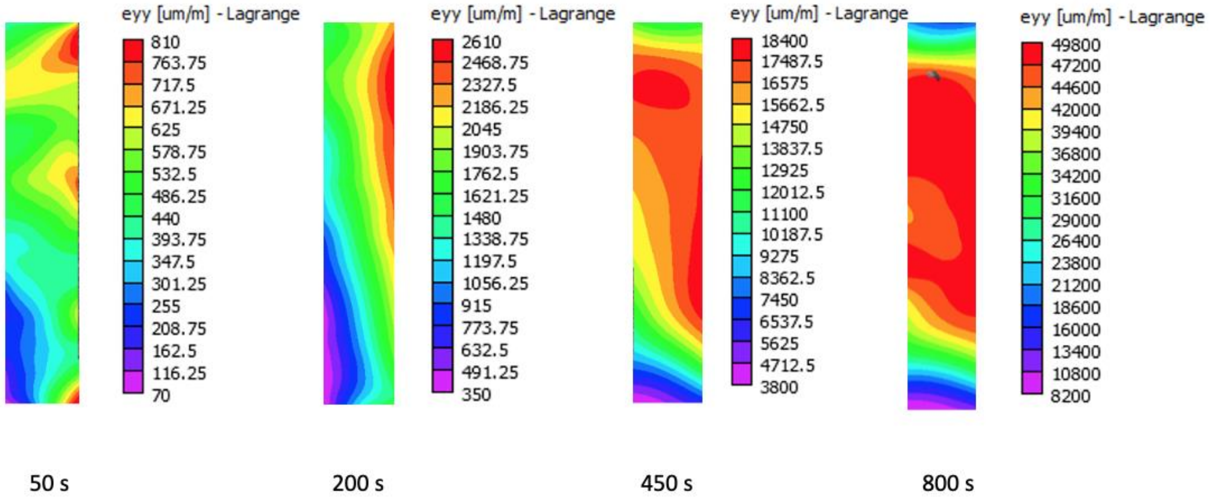

Figure 5 (a-d): DIC pattern indicating the strain variations at different time instant during loading.

Figure 6 shows the comparison graph of nano sensor output and load applied with respect to time. Figure 7 shows variation of nano sensor output with respect to load applied. As the load increases from 4KN to 30 KN the voltage drops from 21 volts to 18 volts. Figure 8 shows variation of nano sensor output with respect to time. As the load applied increases the internal resistance of graphene- PVDF film decreases and in turn the voltage of graphene –PVDF (nano material) based sensor decreases and the change in voltage can be measured for corresponding change in applied load.

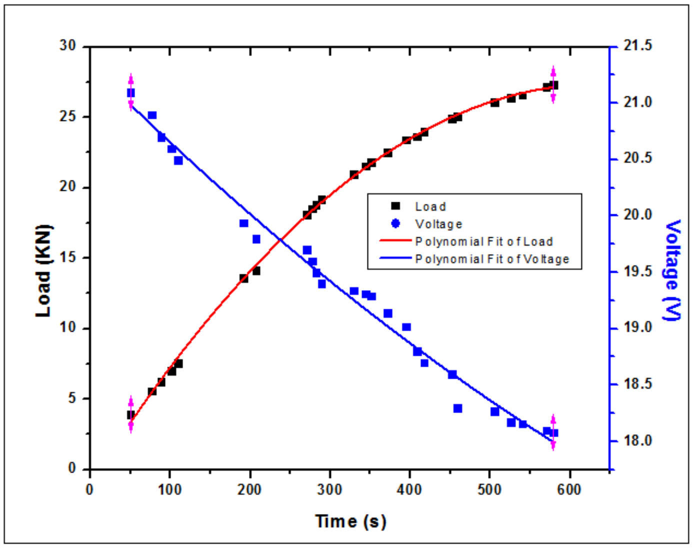

Figure 6: Comparison of nano sensor output and load applied with respect to time.

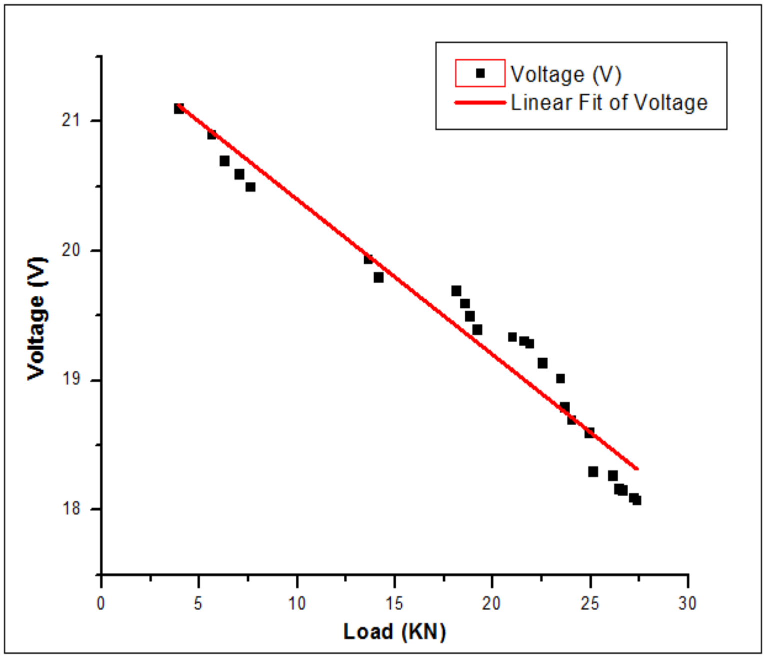

Figure 7: Variation of nano sensor output with respect to load applied. Voltage decreases as the resistance

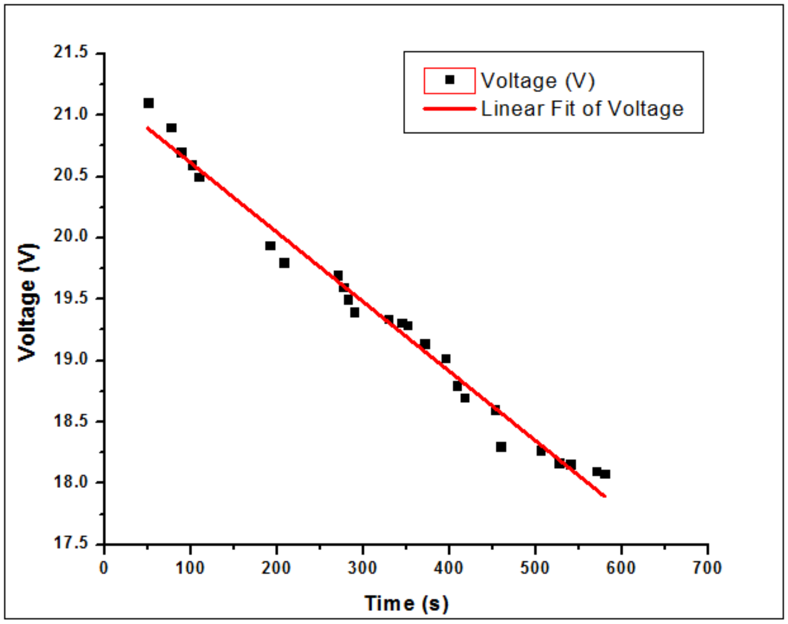

Figure 8: Variation of nano material based sensor output with respect to time

On comparing the results obtained using both DIC technique and nano sensor technique the following predictions can be obtained. Digital Image correlation is a non-contact method for full field optical imaging and interpretation of strain over a large area. It is a highly precise technique. Image pixel variation is high for small variation in strain. Disadvantage of digital Image correlation includes sample preparation, high initial cost and more processing time.

Conclusion:

Digital Image correlation techniques were used to obtain image patterns as a function load, load rate and time. Digital Image correlation can be used to indicate and measure localized strain in the material under testing. However Digital Image correlation techniques involve sample preparation and also it requires significant computation time. The initial cost is also high, and accuracy is high. Digital Image correlation can be used as an alternative technique to measure strain and identify defects in nuclear and other metallurgy industry, especially where there is requirement for non-contact visualisation of strain in complex structures. Nanostructured strain sensing is also a way to observe strain, and the sensor output here is easier to integrate within control systems, such as for active vibration control.

REFERENCES:

[1] Deepak, A., Ramya, S., Ganesan, V., and Shankar, P. (2014). Non Destructive Analysis of Carbon Nanotube Based Strain Sensor Using Raman Ananlysis and Raman Mapping. Advanced Composites Letters, 23: 27-31.

[2] Deepak, A., Ganesan, V., Karthik, V., and Shankar, P. (2014). Nanomaterial Based Non- Destructive Evaluation Sensor for Defect Detection and Strain Measurement. Journal of Nanostructured Polymers and Nanocomposites, 10: 5-12.

[3] Deepak, A., Srinivasan, N., Ganesan, V., Karthik, V., Ramya, S., and Shankar, P. (2015). Graphene based Polymer Strain Sensors for Non- Destructive Testing. Advanced Materials Research, 1101: 314-317.

[4] Deepak, A., Jahnavi, M., Durga, K. D., Ganesan, V., and Shankar, P. (2014). Movement Of Robotic Arm Using Graphene Mixed Polymer Based Nanocomposite Film. International Journal Chem Tech Research, 7: 897-902.

[5] Das, K, T., and Prusty, S. (2013). Graphene-Based Polymer Composites and Their Applications. Polymer- Plastics Technology and Engineering, 52: 319- 331.

[6] Sutton M A, McNeill S R, Helm J D and Chao Y J 2000 Advances in two-dimensional and three-dimensional computer vision Topics in Applied Physics vol 77 ed P K Rastogi (Berlin: Springer) pp 323–72

[7] Schreier H W 2003 Investigation of two and three-dimensional image correlation techniques with applications in experimental mechanics PhD Thesis University of South Carolina

[8] Luo P F et al 1993 Accurate measurement of three-dimensional displacement in deformable bodies using computer vision Exp. Mech. 33 123–32

[9] Pan B, Xie H M, Yang L H and Wang Z Y 2009 Accurate measurement of satellite antenna surface using three-dimensional digital image correlation technique Strain 45 194–200

[10] Srinivasan Nagarajan, Raghu Narayanaswamy, and Venkatraman Balasubramaniam, An Insight into Lu¨ ders Deformation Using Advanced Imaging Techniques, Journal of Materials Engineering and Performance, Volume 22(10) October 2013—3085

[11] Maschmann, M, R., Ehlert, G, J., Park, S, J., Mollenhauer, D., Maruyama, B., Hart, J, A., and Baur, J, W. (2012). Visualizing Strain Evolution and Coordinated Buckling within CNT Arrays by In Situ Digital Image Correlation. Advanced Functional Materials, 22: 4686-4695.

[12] S. Nagarajan, R. Narayanaswamy, and V. Balasubramaniam: “An Insight into Lűders Deformation Using Advanced An Insight into Lu Imaging Techniques,” *J. Mater. Eng. Perform.*, vol. 22(2013), pp. 3085–3092.

[13] Tung, S., Shih, M., and Sung, W. (2008). Development of digital image correlation method to analyse crack variations of masonry wall. Sadhana, 33: 767-779.

[14] Limess Messtechnik & Software GmbH, ìVic-2Dî, 16 Jun. 2008 .

[15] Strain Measurements with the Digital Image Correlation System Vic-2D , Rommel CintrÛn, University of Colorado, Boulder Summer 2008

[16] Tung, S., and Sui, C. (2010). Application of digital-image-correlation techniques in analysing cracked cylindrical pipes. Sadhana, 35: 557-567.

[17] Utku Albostan, Özgür Kurç, Application of 2D Digital Image Correlation: Three Point Flexure Test of Reinforced Concrete Beam, 12th International Congress in Advances in Civil Engineering, Istanbul , September 2016

[18] Romeo, E. (2013). Two-Dimensional Digital Image Correlation for Asphalt Mixture Characterization: Interest and Limitations. *Road Materials and Pavement Design*, 747-763.

[19] Hild, F. and Roux, S. [2006] Digital Image Correlation: from Displacement Measurement to Identification of Elastic Propertiesî, The Authors, Journal compilation, Blackwell Publishing Ltd, Strain 42, 69-80. Limess Messtechnik & Software GmbH, ìVic-2Dî, 16 Jun. 2008

[20] Tusini, E. [2008] ìPerformance Evaluation of Reinforced Concrete Masonry Infill Walls, Concentration on Evaluation of Masonry Infill Propertiesî, Research paper, Civil Engineering Dept., University of Colorado, Boulder, Colorado.

[21] https://www.stress.com/dic-to-measure-large-areas-of-strain-displacement].