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Non-Destructive testing using Digital Image Correlation

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***Abstract:* -- This paper presents a new optical method referred to as Digital Image Correlation (DIC). It permits full-field measurement of surface displacements. DIC works by comparing digital photographs of a component or test piece at different stages of deformation. By tracking blocks of pixels, the system can measure surface displacement and build up to full field 2D and 3D deformation vector fields and strain maps. Software techniques have been developed to obtain sub-pixel resolutions and allow efficient execution of the algorithms. Images can be obtained from a wide variety of sources including conventional charge-coupled device (CCD) image sensors or digital cameras. The DIC correlation process is not restricted to optical images and can also be applied to other datasets such as surface roughness maps and 2D surfaces of structures like tunnels. Theory of the method as well as its applications to strain measurements and nondestructive testing are presented further.**

***Index terms*: - Digital Image Correlation, DIC, full field displacement, nondestructive testing.**

I. INTRODUCTION

Strain and displacement are critical parameters within engineering and construction projects. However, measuring these parameters outside of the lab requires a difficult choice between conventional techniques, as accuracy, simplicity and cost must all be balanced. Non-destructive testing (NDT) is a technique which may prove to be ideally suited for the study of strain calculation, crack propagation and material deformation in real-world applications, as it has the potential to become a cheap, simple yet accurate solution. NDT provides a wide group of analysis techniques used in science and industry to evaluate the properties of a material, component or system without causing damage. The terms Non-destructive examination (NDE), Non-destructive inspection (NDI), and Non-destructive evaluation (NDE) are also commonly used to describe this technology. NDT seeks to employ advanced image-based, non-contacting measurement methods to measure the shape and deformation of a material undergoing thermal, mechanical or variable environmental conditions. These methods are broadly applicable in various fields such as civil engineering, mechanical engineering, material science, biomedical, manufacturing and others [1]. Recent advances in NDT have enabled the use of digital image correlation (DIC) to calculate the surface displacements of chosen targets in a series of digital images with a high degree of accuracy. Images are recorded during an experiment and are afterwards post-processed to find relevant information. DIC can be used to find the movement of chosen targets in a series of digital images relative to an initial un-deformed state. Recent advances in high resolution digital cameras and increasing computing performance have improved the accuracy and precision of the DIC techniques to the point where it can potentially be used as a tool to provide the measurements required for structural assessment.

II. DIGITAL IMAGING CORRELATION

DIC is an innovative full field non-contact optical technique for measuring strain and displacement in components over a wide range of applications. It is a versatile tool that is now being used extensively in experimental mechanics in a diverse range of applications. DIC is simple to use and cost effective compared to other techniques such as speckle interferometry, and more accurate and subjective than manual measurement methods, leading to a huge range of potential applications [2]. DIC has been extensively used for displacement and strain field estimation in various applications like material characterization, structural health monitoring, fatigue crack growth, high temperature testing etc. DIC works by comparing digital photographs of a component or test piece at different stages of deformation. By tracking blocks of pixels, the system can measure surface displacement and build up full field 2D and 3D deformation vector fields and strain maps. For DIC to work effectively, the pixel blocks need to be random and unique with a range of contrast and intensity levels. It requires no special lighting and in many cases the natural surface of the structure or component has sufficient image texture for DIC to work without the need for any special surface preparation. Images can be obtained from a wide variety of sources including conventional CCD or consumer digital cameras, high-speed video, macro scopes, and microscopes, including scanning electron and atomic force microscopes. In case of plane digital image correlation, object deformations are determined by observation with camera vertically aimed at surface which provides determining displacements in parallel plane with imagine plane. Fig.1 shows the schematic illustration of a typical experimental setup using an optical imaging device for the 2D DIC method [3].

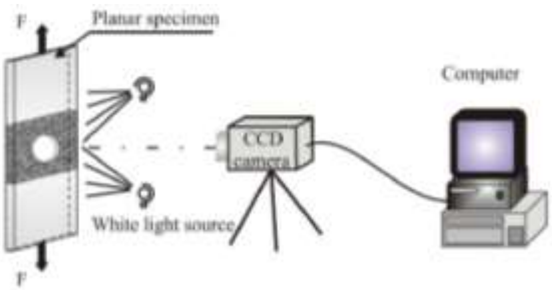

Fig. 1: Typical optical image acquisition system for the 2D DIC method [3]

The DIC correlation process is not restricted to optical images and can also be applied to other datasets such as surface roughness maps and 2D surfaces of structures like tunnels. Image matching / texture is a discipline of computer vision that is of central importance to a large number of practical applications. To name just a few, image matching is used to solve problems in industrial process control, automatic license plate recognition in parking garages, biological growth phenomena, geological mapping, stereo vision, video compression and autonomous robots for space exploration [1]. Since the applications are so varied, there are a wide variety of approaches and algorithms in use today; many specialized to a given task. The concept of image texture in digital image correlation can be defined as a pattern to characterize objects. Development of an image texture descriptor has been the focus of research over the past several years as it has been found to have a significant influence on measurement accuracy and precision. Knowing what is good or bad texture can be intuitive, but quantitatively comparing one image's texture to another is challenging. An image with bad texture can lead to poor tracking results. A typical approach to improving a target image texture is to apply an artificial pattern to the surface of the object being measured. These artificial textures, called speckle patterns, are created by spraying white and/or black paints to create randomly sized and shaped high contrast patterns. This pattern deforms together with the specimen's surface and improves the quality of correlation between images. It has been found that the displacement measurement accuracy is influenced by the size of the texture and the quality of the artificial pattern [4]. Some examples of speckle patterns are shown in Fig. 2.

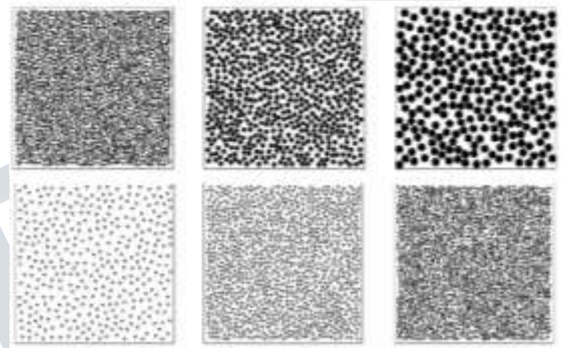

Fig. 2: Examples of typical speckle patterns [4]

One of the key features of good speckle patterns is their high information content. Since the entire surface is textured, information for pattern matching is available everywhere on the surface, and not only on a comparatively sparse grid. This permits the use of a relatively small aperture for pattern matching, commonly referred to as a subset or window as shown in Fig. 3.

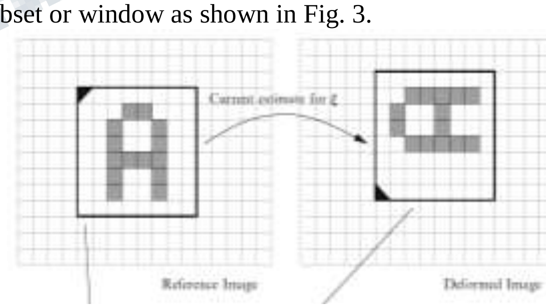

Fig. 3: Subset formation for reference and deformed image [1]

In the DIC method, digital images of a zone of interest are captured at different deformation states and post-processed by tracking a collection of smaller areas known as subsets. The ability to accurately track the subsets which after is dependent on both the sub-pixel interpolation scheme of the DIC search algorithm and the texture/uniqueness of the subset. The post-processing of the image analysis therefore allows for subsets to be placed in the reference image with a

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priori knowledge of where the cracks will form. Placing a subset on either side of the crack plane, allows for the crack width and slip movement to be calculated from the initial and final position of the subset pair. The image matching algorithms discussed so far are limited to the determination of the average in-plane displacement of a typically square or circular subset between two images. In many engineering applications, however, the measurement of complex displacement fields is of interest, and the specimen might experience elongation, compression, shear or rotation. In other words, an initially square reference subset might assume a considerably distorted shape in a later image after deformation. Consider an image that is slowly rotated around its center. As the rotation angle increases, the similarity between the original subset and the rotated subset decreases. Experimental condition of a loaded element with speckle and subset formation is as shown in Fig. 4[1].

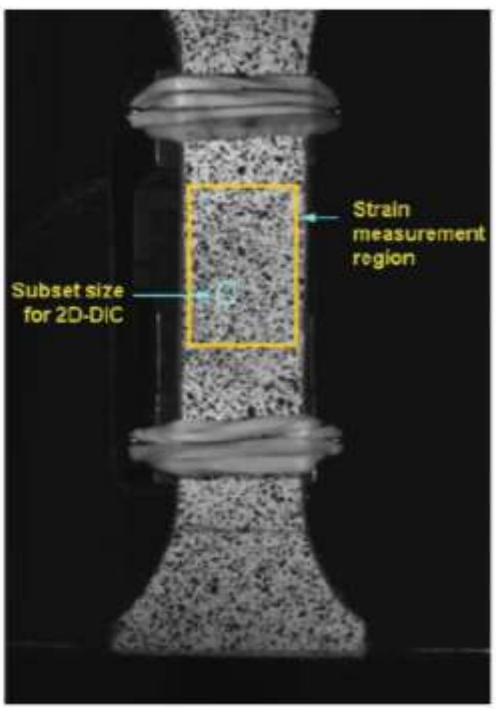

Fig. 4: Reference image for 2D-DIC measurements [1]

III. ADVANTAGES OF DIC

DIC has several advantages over conventional NDT methods and some of the other optical techniques, which are generally more expensive and more difficult to use outside the laboratory as they require precise setup and low vibrational environments, also the equipment is not always suitable for use outdoors. In contrast DIC uses conventional digital photography and in combination with civil engineering surveying techniques can be used to provide suitably accurate measurements of structures in typical outdoor environments. Any changes in the structure can easily be compared to the captured images. For large civil engineering structures, such as bridges and buildings and power generation infrastructure manual inspection techniques are often still used. This leads to inspections that can be influenced by subjectivity particularly when operatives are tired. By capturing accurately positioned and aligned images, comparisons can be made between surveys and differences readily identified, whether these are due to surface change, deformation or crack opening. The key to long term cost-effective management of these structures is to use low-cost measurement techniques that can be cheaply deployed, and are suitably accurate. By using DIC, with one image taken before cracking occurred and one taken afterwards then the full extent of crack opening can be seen. This has the benefits of identifying cracks that have opened in a non-contact, low-cost fashion. It can provide accurate crack opening measurements, even if the edges of the crack are ill defined and provide useful information on where to fit crack opening sensors.

IV. APPLICATIONS

The use of DIC provides the ability to create a two-dimensional displacement or strain field for the entire surface of the material or structure under observation throughout each stage of the test. Fig. 5 shows displacement contour for a beam under four point bending [5].

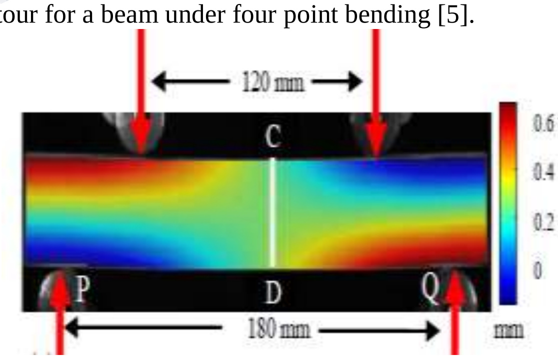

Fig. 5: Displacement contours along the length obtained for an epoxy beam under four point bending [5]

The DIC technique has been used previously in structural research as a method to examine fracture mechanics in concrete [6]. By using DIC, with one image taken before cracking occurred and one taken afterwards then the full extent of crack opening can be seen in Fig. 6 and Fig. 7.

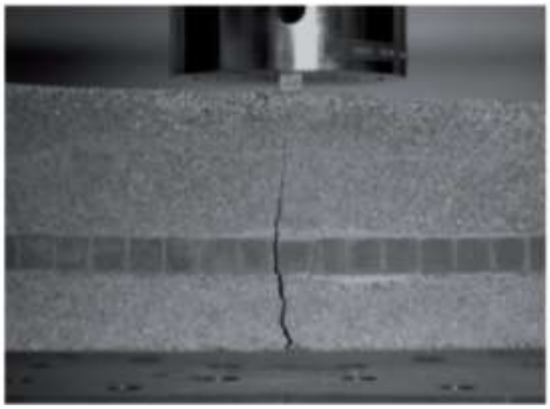

Fig. 6: Concrete showing one large crack but no other visible cracks under point loading [6]

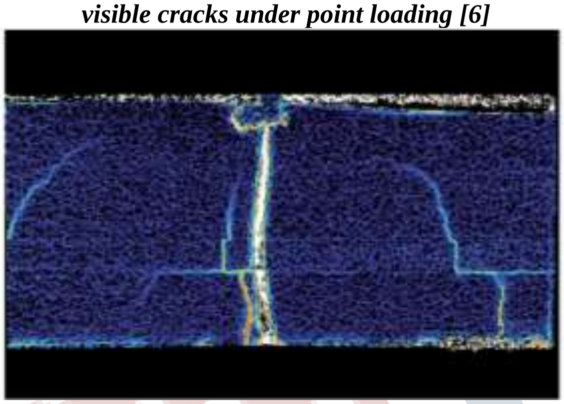

Fig. 7: Output from the DIC as a map of local deformation showing cracks not visible to the human eye [6]

An example of displacement contours extracted from DIC measurements on the surface of a tensile specimen of steel is shown in the Fig. 8 [7].

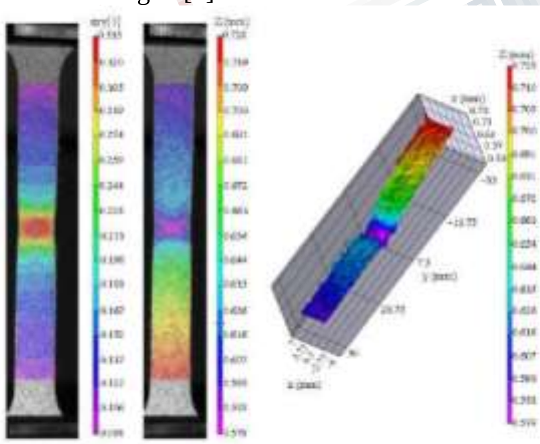

Fig. 8: Tensile specimen of steel [7]

Example of Plate with a hole indicating full field displacement of strain is shown in Fig. 9[10]

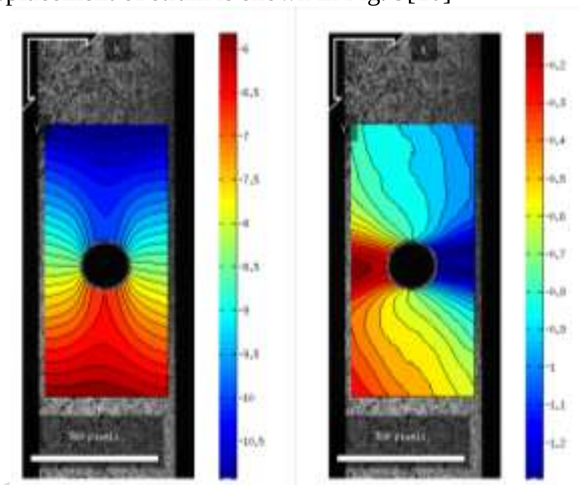

Fig. 9: Strain variation in plate with a hole [10]

DIC has also been used to find hoop and axial strain variations in FRP wrapped concrete cylinders at different locations. This method carries several important advantages for studying concrete fracture. First and most important, full-field deformations can be obtained with a high-speed computation by virtue of automated processes, which are essential in the event that a large number of specimens are to be examined. Second, because the fracture patterns of concrete are complicated, gages attached to the specimen do not give accurate readings. With a noncontact method such as computer vision, gage readings are not disturbed while failure progresses. Furthermore, because computer vision uses different sub images for each measurement, displacements can be measured on specimen pieces that are broken into multiple parts by cracks. This is a major advantage over other full-field measuring techniques such as laser interferometry methods.

V. CONCLUSION

DIC is simple to implement providing cost effective unambiguous results leading to a huge range of potential applications. It has been used to examine a diverse range of material specimens including examining the evolution and uniformity of strain in materials testing, crack tip and crack propagation studies, detecting damage development in composites, structural deflections, high temperature strain mapping and dynamic vibrational analysis. The DIC technique can be applied to monitor and understand the important aspects of structural evaluation as the movement along shear planes, specifically along shear cracks in reinforced concrete beams and in the evaluation of changes in strain due to variable geometry and loading variation in beam elements. As the development of cracks in RC is to be expected, an understanding of how cracks in RC structures impact their capacity and formation of maximum strains in specimen is of importance in the civil engineering community. Furthermore, an understanding of the strain behavior due to flexure can help engineers to determine areas of deterioration or where the flow of strains does not match traditional beam theory. The use of DIC has several advantages when applied to these applications. First of all, the technique does not require a priori knowledge of crack locations and so measurements can be tailored to the actual cracked condition of the structure. Additionally, the DIC technique can be used to provide a 2-D strain profile where traditional strain gauges are limited by both cost and data logging constraints.

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