Engineering Fracture Mechanics 77 (2010) 2063–2076

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Quantifying crack tip displacement fields with DIC

J.R. Yates, M. Zanganeh, Y.H. Tai *

Dept. of Mechanical Engineering, University of Sheffield, Mappin Street, S1 3JD, UK

ARTICLE INFO

Article history:
Received 18 December 2009
Received in revised form 12 March 2010
Accepted 16 March 2010
Available online 27 March 2010

Keywords:
Crack tip displacement fields
Digital image correlation
K
T-stress
CTOA

ABSTRACT

Crack paths under both fatigue and fracture conditions are governed by the crack tip displacement field and the material deformation characteristics, including those influenced by metallurgical anisotropy. Experimental techniques such as thermoelasticity and photoelasticity have been successfully used to characterise the elastic stress fields around cracks but they do not take into account either plasticity or anisotropy. Considerable work has been carried out to characterise crack tip stress fields from displacement measurements. The current method of choice for obtaining displacement field data is digital image correlation (DIC) which has undergone significant advances in the recent years. The ease of use and capabilities of the technique for full field displacements has led to improved methods for characterising crack tip displacement fields based on data obtained from DIC. This paper gives an overview of some of the applications of DIC for crack tip characterisation such as *K*, *T*-stress and crack tip opening angle (CTOA) measurements as well as data obtained from 3D measurements of a propagating crack.

1. Introduction

The path that a crack follows, whether it is under cyclic or monotonic loading, is strongly influenced by the elastic and plastic displacement field at the crack tip. These displacements are governed by a combination of material deformation behaviour, the mechanics of the loading and the geometry of the structure [1].

For many years, our investigations into crack paths, has been based on characterising the crack path displacement field through the elastic component. Photoelastic stress analysis, thermoelaticity, caustics, Moire interferometry and many other have been used to successfully characterise the elastic stress fields around cracks but these techniques are not able to take into consideration effects of plasticity or anisotropy [2]. This has led to considerable work on developing techniques for characterising crack tip stress fields from displacement field measurements.

The current method of choice for characterising displacement fields is digital image correlation (DIC) which is a relatively straight forward and cost effective technique. With the recent availability of high quality, high resolution digital cameras as well as the development of image correlation algorithms, it has enabled the possibility for full field elastic–plastic displacement field to be measured directly. This has opened up the opportunity of exploring the influence of plastic deformations around the crack tip on the growing crack.

In this paper, an overview of some the possible applications of DIC for crack tip characterisation will be presented. This will include *K* and *T*-stress [3,4] characterisation for fatigue cracks in double cantilever beam (DCB) specimens, crack closure effects on measured *K* using CT specimens, CTOA characterisation from displacement field data as well as 3D full field displacement data for tearing cracks in an anisotropic material.

* Corresponding author. Tel.: +44 1142227892; fax: +44 1142227890.
E-mail address: y.tai@sheffield.ac.uk (Y.H. Tai).

0013-7944/$ - see front matter
doi:10.1016/j.engfracmech.2010.03.025

2. Basic principles of digital image correlation

A digital image is essentially a two-dimensional array of intensity values which can be discretized into small subsets. Image correlation works by matching small square subsets of an undeformed image to locations in the image of the surface after deformation as illustrated in Fig. 1 by means of a series of mathematical mapping and cross correlation functions. For this technique to work well a grey scale random pattern is needed on the surface of the specimen. To recognize this pattern mathematically, the intensity of each pixel in the reference and deformed images can be traced and the displacement vector can be determined. However, it would be extremely difficult to distinguish every single pixel on the image and therefore at least 3×3 pixels are needed for one recognizable feature. The ideal subset size should contain at least three clear features but it is often a compromise between resolution and accuracy. As a general rule, larger subset sizes will increase the accuracy whereas a smaller subset will increase the resolution but realistically the size of a subset is determined by the quality of the image and speckle pattern.

A variety of methods can be used to produce a random pattern on the surface. Sometimes the natural pattern of the material is enough to produce a suitable pattern. Glass or emery paper can be used to scratch the surface of the specimen to generate a random pattern [5]. More conventionally, the random pattern is produced by spray painting the surface or using dry toner with an adhesive medium. These techniques normally suffice for macro digital image correlation applications but for micro scale applications more care is needed when producing the random pattern due to the speckle size and often requires the use of an airbrush or lithography. Fig. 2 illustrates the typical set-up of a 2D DIC. A 3D system will have two cameras at different angles to obtain a 3D perspective of the specimen surface.

2.1. Displacement mapping

Assume that a point P in the reference image with an x- and y-coordinate system is mapped into point P^* in deformed image with an x^* and y^* coordinate system (Fig. 3). The mapping can be performed as,

$$\begin{aligned} x^* &= x + u(x,y) \\ y^* &= y + v(x,y) \end{aligned} \tag{1}$$

To find the displacement fields, the vertical, v, and horizontal, u, displacements can be approximated using the Taylor series around a point $P(x_0, y_0)$ as,

$$\begin{aligned} x^* &= x_0 + u_0 + \frac{\partial u}{\partial x}\Delta x + \frac{\partial u}{\partial y}\Delta y + \frac{1}{2}\frac{\partial^2 u}{\partial x^2}\Delta x^2 + \frac{1}{2}\frac{\partial^2 u}{\partial y^2}\Delta y^2 + \frac{\partial^2 u}{\partial x \partial y}\Delta x \Delta y \\ y^* &= y_0 + v_0 + \frac{\partial v}{\partial x}\Delta x + \frac{\partial v}{\partial y}\Delta y + \frac{1}{2}\frac{\partial^2 v}{\partial x^2}\Delta x^2 + \frac{1}{2}\frac{\partial^2 v}{\partial y^2}\Delta y^2 + \frac{\partial^2 v}{\partial x \partial y}\Delta x \Delta y \end{aligned} \tag{2}$$

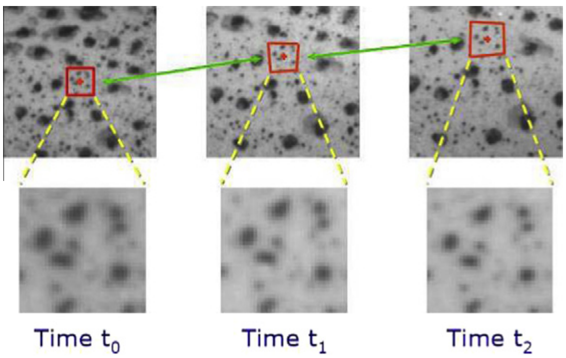

Fig. 1. Illustration of subset matching and deformation tracking used for DIC (*Image courtesy of Limess GmbH*).

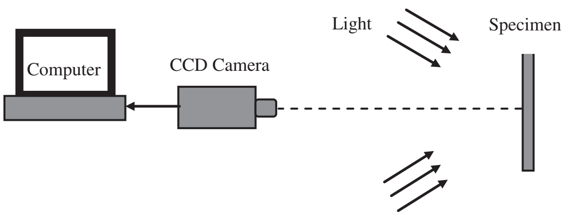

Fig. 2. Schematic diagram of typical 2D DIC equipment.