Optics and Lasers in Engineering 96 (2017) 94–106

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

An autonomous surface discontinuity detection and quantification method by digital image correlation and phase congruency

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ARTICLE INFO

Keywords:
Digital image correlation
Fracture mechanics
Crack
Phase congruency
Segmentation

ABSTRACT

Digital image correlation has been routinely used to measure full-field displacements in many areas of solid mechanics, including fracture mechanics. Accurate segmentation of the crack path is needed to study its interaction with the microstructure and stress fields, and studies of crack behaviour, such as the effect of closure or residual stress in fatigue, require data on its opening displacement. Such information can be obtained from any digital image correlation analysis of cracked components, but it collection by manual methods is quite onerous, particularly for massive amounts of data. We introduce the novel application of Phase Congruency to detect and quantify cracks and their opening. Unlike other crack detection techniques, Phase Congruency does not rely on adjustable threshold values that require user interaction, and so allows large datasets to be treated autonomously. The accuracy of the Phase Congruency based algorithm in detecting cracks is evaluated and compared with conventional methods such as Heaviside function fitting. As Phase Congruency is a displacement-based method, it does not suffer from the noise intensification to which gradient-based methods (e.g. strain thresholding) are susceptible. Its application is demonstrated to experimental data for cracks in quasi-brittle (Granitic rock) and ductile (Aluminium alloy) materials.

1. Introduction

Observing the interaction of cracks with the encompassing microstructure of engineering materials is a critical process in structural integrity. Quantitative image-based techniques, such as Digital Image Correlation (DIC), have gained in popularity due to the advances made in the recent years with cheaper CCDs (Charged Coupled Device) and computational power. However, with the advancement of data acquisition, users are faced with the burdensome task of rigorous analysis of large volumes of data, which require user judgement and intervention. The ability to detect and quantify features such as cracks and their associated parameters, such as dimension, from many images is becoming a critical task.

Most approaches to identify cracks in digital images use edge detection methods such as global and local grey-scale intensity thresholding. These require human interaction to be optimal [1,2]. For instance, Ikhlas et al. [3] presented a study of different edge detection techniques including wavelet transform and Fast Fourier Transform (FFT) to identify cracks in bridges, concluding that wavelet transform is more reliable than other methods. However, the method is based on a chosen threshold value, which is a parameter crucial to its performance. Tomoyuki et al. [4] proposed a fast crack detection method, applied to concrete surfaces, that was based on percolation-based image processing; their quantitative analysis showed this to be computationally more efficient that the wavelet approach but at the cost of precision. Additionally, these methods assume that the crack is sufficiently open enough to be detectable in the image. This inherently limits these methods' accuracy to a pixel at best. However, there are image analysis techniques that have sub-pixel accuracy. They track the surface displacement of the features near the discontinuity and therefore can detect cracks that are not otherwise visible in the raw image [5]. For example, Avril et al. [6] introduced a method of detecting surface discontinuities and calculation of the crack width with sub-pixel precision, using a grid that is periodically spaced on the surface of the cracked body and with the aid of Windowed discrete Fourier transform to calculate the phase shift between the cracked faces.

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http://dx.doi.org/10.1016/j.optlaseng.2017.04.010
Received 21 February 2017; Received in revised form 10 April 2017; Accepted 20 April 2017
0143-8166/

DIC is now the most widely used optical based method in fracture mechanics. Introduced in the 1980s by Peters and Ranson [7–9], DIC is a full field non-contact displacement measurement method that is relatively easy to set-up and provides high resolution and high spatial resolution. The fundamental principle of DIC is to compare grey-scale images of an object surface captured before and after deformation; these are referred to as the reference and deformed image, respectively. Conventionally, the reference image is divided into interrogating windows or subsets that are matched (or tracked) in the deformed image, using a shape function, to obtain the displacement of each interrogation window. Higher order shape functions can be used to obtain improved displacement approximations but usually first or second order provides sufficient accuracy [10]. Different matching procedures can be used to search and evaluate the similarity of the grey-scale pattern [11]. This study used the iterative least square method (ILS) method, proposed by Pan et al. [12] and incorporated in LaVision Davis Strain Master Code [13].

Parameters that are descriptive of the crack fields that control fracture, such as the stress intensity factor [14] and strain energy release rate [15,16] can be extracted from DIC analyses that provide the full field displacements or strains. Two families of methods tend to be used. Firstly, the linear elastic stress intensity factor may be obtained by fitting a theoretical displacement field to the DIC measured field [14,15,17,18]; maximising the correlation between the two fields finds the optimal stress intensity factor that describes the measurement. This forces experimental data to fit a theoretical model and neglects possible incompatibilities. Critically, this family of methods are quite sensitive to accurate identification of the crack tip location [19], which can be computationally difficult or conceptually impossible, in the case of diffusive damage zones, to find [20].

An alternative method is to calculate energy release rate via a contour integral method, such as the *J*-integral [21], to obtain the difference between the work of traction exerted on a finite volume of material and the elastic strain energy in that volume in the presence of a crack. The rate of this difference with respect to an infinitesimal increase in the crack length is the strain energy release rate associated with a crack. This strain energy release rate can be related to an equivalent stress intensity factor [22]. Becker et al. [16] introduced a method to calculate *J*-integral as an area integral using digital image correlation displacement field measurements and the finite element method. A critical point in this [16] and similar techniques [18,23,24], is that although there is less sensitivity to the crack tip position, the crack geometry needs to be identified correctly as the contour integral should be carried out on a path that starts and ends on traction free surfaces, i.e. the crack face.

The displacement discontinuity across the faces of the crack, known as the crack opening displacement (COD), has also been used for both elastic and elastic-plastic materials as a crack quantifying parameter [25–27], as it has a direct relationship with the stress intensity factor or *J*-integral. It is applied in engineering standards less frequently (e.g. see BS7910) as direct measurements can be difficult to obtain reliably [28]. It can, however, be quantified by digital image correlation [29–35] of surface observations. For instance, Mekky et al. [36] have presented a methodology to calculate COD profile along the crack by a least-square method to evaluate the opening displacement by fitting the displacements from opposite sides of the crack. Wells et al. [37] fitted a Heaviside function to the discontinuity across the crack faces to located the boundaries of the crack faces. However, most methods in the literature simply requires the user to manually select virtual displacement gauges across the crack faces [38–40], the halfway points between them was used to define the crack path [23,33,41,42].

In a typical experimental study to quantify cracks and their interaction with the microstructure, hundreds of images may be recorded of a growing crack in a complex microstructure; the task of manual segmentation of the crack [43] can be a major obstacle. In this paper, we present a novel algorithmic method of obtaining the crack path and its opening displacement profile autonomously and reliably. We evaluate the theoretical accuracy of the algorithm and compare it

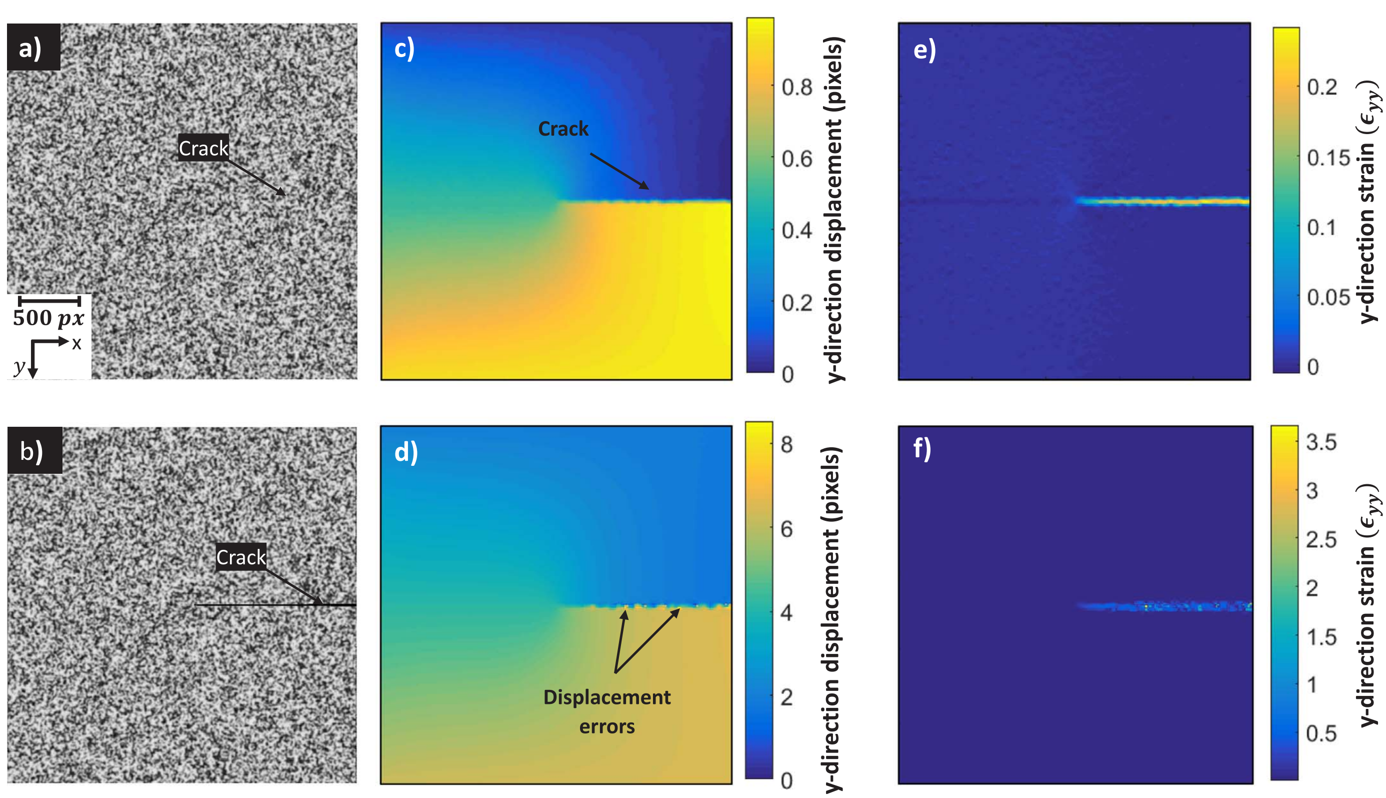

Fig. 1. (a) a 2024 × 2048 pixel synthetic image containing a crack with mouth opening displacement of 1 pixel; (b) An image similar to (a) with crack mouth opening displacement of 5 pixels; (c) Opening (i.e., Y-direction) displacement of associated with image (a) (d) Opening (i.e., Y-direction) displacement associated with image (b) (e) Opening strain of (c) (f) Opening strain of (d).