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Analysis of standard fracture toughness test based on digital image correlation data

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This paper deals with an experimental methodology based on the 2D Digital Image Correlation method for precise full-field in-plane stress-strain analysis of a region containing a crack. The presented methodology is employed as a supporting and comparative method for the standard J-integral testing defined by the ASTM. The methodology utilizing the DIC-based displacements for a subsequent evaluation of strain, stress and final extraction of the J-integral from its definition. This J-integral is compared with the value obtained by the ASTM standard and with the value obtained by the DIC-based CTOD measurement. Several techniques improving the conventional DIC and data post-processing are proposed to achieve reliable full-field strain/stress results. A direct comparison between the experimental and FEM full-field results is carried out.

1. Introduction

Stress-strain analysis of materials and structures subjected to various loadings is an essential task in experimental solid mechanics. Various well-known image-based, non-contact and full-field methods like Photoelasticity [10], Moiré [18] and Speckle interferometry [29] have been developed and applied for this purpose in addition to the widely-used strain gauge technique, in which strains are measured locally. Among others, 2D Digital Image Correlation (DIC) [17] has become very popular nowadays in the experimental solid mechanics community for its accessibility and easy-to-use implementation. An important discipline in which DIC-based full-field measurements find usage is experimental fracture mechanics (FM) [24,31]. The main benefit of full-field measurements in the region surrounding a crack is the possibility to extract fracture parameters such as the stress intensity factor or the J-integral.

Among the first works, Chiang and Asundi [5] attempted to evaluate the stress intensity factor (SIF) from the displacement field measured by the speckle method. Huntley and Field [11] employed laser speckle photography for full-field measurement, and then optimized numerical results on the basis thereof evaluated the SIF and J integral. The direct extraction of the J-integral and J-R curve from strain/stress analysis obtained by MI was carried out by Dadkhah [6] and Kang [12]. One of the first works utilizing DIC for the extraction of fracture characteristics is by McNeil [15] and Han [8]. Noteworthy works from recent times are by Abanto-Bueno and Lambros [1] and Réthoré [20], in which they deal with the determination of SIF. Becker [4] attempted to measure the J integral using DIC, utilizing the equivalent expression of the J-integral as an area integral. Most of the works mentioned, which have tried to extract the fracture parameters from measured fields, have faced the problem of the insufficient accuracy of DIC results. For that reason, the proposed techniques often combine experimental

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Nomenclature

ASTM	American Society for Testing and Materials
CT	compact tension specimen
DIC	digital image correlation
FM	fracture mechanics
FEM	finite element method
ITP	incremental theory of plasticity
NCC	normalized cross-correlation
SSD	sum-squared difference
SSY	small scale yielding
a	crack length
Apl	plastic area under load-displacement curve
b	remaining ligament
B	specimen thickness
CTOD (δ)	crack tip opening displacement
De	elastic stiffness matrix
Dep	elastic-plastic stiffness matrix
E	modulus of elasticity
I	image
J, *JC*	J-integral, critical J-integral
KI	stress intensity factor for mode I
m	plastic constraint factor
P	load, remote force
p	affine transformation coefficients
n	normal vector to Γ
r	correlation coefficient
t	traction vector
T	image template
u	displacement vector (field) 2
U	right stretch tensor
w	strain energy density
W	specimen width
W	affine transformation
Γ	path around crack tip
ε	strain tensor (field)
ε *H*	Hencky finite strain tensor (field)
η*pl*	geometric factor
v	Poisson's ratio
σ *ts*	tensile strength
σ *y*	yield stress
σ	stress tensor (field)

results with numerical simulations based on FEM, trying to optimize the simulations so that the results match the measured fields. Subsequently, on the basis of the best fit, the parameter is extracted from the numerical solution. The low degree of accuracy of DIC can arise from multiple factors: the low resolution of image data, poor quality of the "speckled" pattern, errors caused by out-of-plane motion, or insufficient smoothing procedures. All these factors can be significantly improved with the use of suitable techniques and corrections, improving DIC accuracy so that there will be no need for FEM. Here is a list of difficulties that one is encountered when attempting to measure displacements and to evaluate strain and stress fields in the region surrounding a crack:

- Selection of an appropriate surface coating to create speckled pattern with sufficient speckle size and density at a relatively high optical magnification. The pattern has to enable measurement of a wide range of strain (from elastic to plastic deformation). Moreover, due to large strains, such coat has to ensure good adhesion.
- The presence of high displacement/strain gradients in the vicinity of the crack. The set of points in which the displacements are measured using DIC should reflect this feature.
- In DIC, the reliability of the evaluated strains depends strongly on smoothing of the measured displacements which are inevitably noisy (locally non-monotonic). The presence of a crack or a notch causes a discontinuity within the displacement field, making smoothing difficult in such a region. The problem of discontinuity has been solved in [19] introducing the X-DIC method for example.