Quantitative measurement of the J-integral of loaded cracks using 2D and 3D Digital Image Correlation

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Abstract. Full field mapping of displacements between successive images by digital image correlation is a powerful and well-established technique, used in fields as diverse as geo-tectonics, engineering mechanics and materials science. Analysis of cracks is challenging due to the discontinuities in the displacement field and the consequent influences of this on the image correlation techniques.

A novel method based on the conjoint use of full field displacements measured by image correlation and finite element simulations has been developed to extract the crack strain energy release rate, described by the J-integral. The method is shown to be robust to image noise and provides accurate and precise results when applied to elastic and elastic-plastic materials, using synthetic datasets obtained by image deformation. Mixed mode loading is also examined. The application of the method to three-dimensional experimental datasets is shown in the quantitative analysis of a propagating fatigue crack in a ductile cast iron, observed by computed synchrotron X-ray tomography.

Introduction

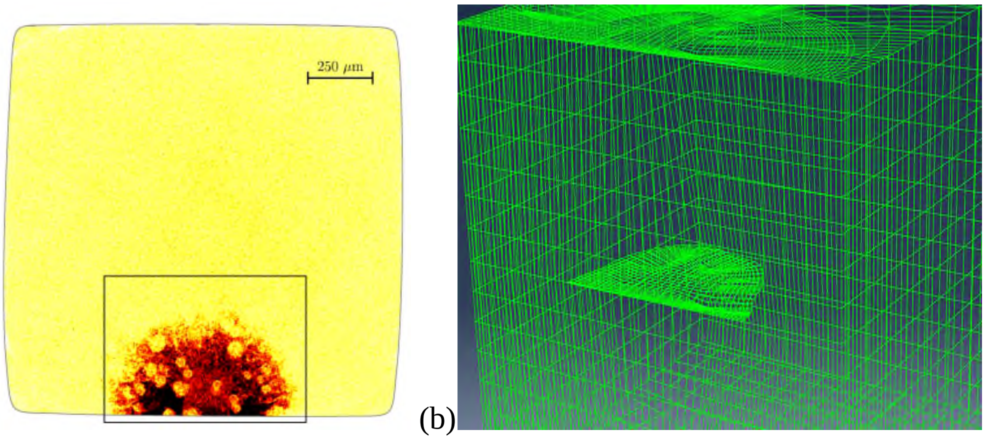
Precise determination of crack parameters in fracture experiments is not straightforward: the crack shape can be complex and the loading state cannot be perfectly controlled experimentally. A compound approach using finite element modelling and image/volume correlation is proposed to tackle this problem.

Method Overview

The method is presented here for a 3D dataset but it is also applicable for 2-dimensional datasets. Extensive benchmarking has been done via the use of synthetic datasets - created with the image deformation tool ODIN [1], which describe cracks of known stress intensity factor values. The sensitivity to correlation subset size, image masking and image noise has been investigated.

The typical input consists of the results from a digital volume correlation analysis of a sequence of X-ray tomographs; typically a pair of images of a crack in the unloaded and loaded states. The first step is to define the crack path; this can be done by segmenting a strain map derived from the displacement field. The field is calculated with a small subset size image correlation analysis, which provides a good spatial resolution at the expense of some precision in the displacement measurements. The correlation coefficients map could also be used for this purpose (Fig. 1a).

A finite element model is then created; it follows the sample geometry and contains the crack surface that was defined at the previous step. The remeshing approach implemented does not use any enrichment of the elements and takes care of correct definition of nodal planes, which includes the crack path normal vectors that are required for the J-integral calculation (Fig. 1b).



(a) (b)

Figure 1. (a)Projection of the correlation residuals [2] (b)Definition of a complex 3D crack geometry for J-integral calculation

The boundary conditions applied to the model are also defined by the volume correlation results; precision can be increased through using data from a large subset size correlation analysis. All nodes in the region remote from the crack, where the correlation results are trustworthy are constrained by these boundary conditions. Those nodes that lie in the region near to the crack borders are left free to deform, according to the defined material properties; the digital correlation result quality is generally poor in this region due to the effect of the crack discontinuity and also the high strain gradients. The finite element calculation determines the displacements of the “free nodes” from the surrounding boundary conditions. The J-integral is then computed by the finite element software (here Abaqus was used) via the surface integral method, which makes use of the FE-calculated strain field in the vicinity of the crack. This approach is quite versatile and computationally efficient, which is of particular interest in the case of 3D datasets. It also allows analysis of datasets where other methods, such as displacement field fitting, would suffer of dataset noise.

Results

Results presented here are from a fatigue crack growth experiment that was conducted at the European Synchrotron Radiation Facility (ESRF, beamline ID19) on a nodular graphite cast iron. The volume correlation data are computed from tomographs obtained in the same cycle, within which the material’s response can be treated as linear elastic. The J-integral is calculated using the surface integral method, as described above, and obtained as a function of the position around the crack front; the normalised stress intensity factor obtained from the J-integral at the maximum crack depth is 50% of that where the crack path intercepts the surface, which is consistent with the expected behaviour of a semi-elliptical crack [3].

Conclusion

The presented method allows accurate determination of the energy release rate of a three-dimensional crack, even when the crack geometry and the material loading are complex.

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