A Novel Photomechanical Approach for Measuring Dynamic Fracture Toughness

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Abstract. The accurate modelling of dynamic failure of engineering structures requires thorough understanding of dynamic fracture processes. With the advent of new ultra-high speed imaging technology it is possible to make full-field measurements at frame rates up to 5MHz and capture fracture processes in real-time. The purpose of this work is to develop new approaches for measuring dynamic fracture toughness that take advantage of ultra-high speed full-field measurement techniques. The concept for a new dynamic fracture test based on a direct energy balance is presented, along with validation using explicit dynamics simulations. Future development of the technique will involve the use of image deformation simulations and experimental validation.

Introduction

The efficient design of impact resistant structures requires accurate models of material fracture processes under dynamic loading. For example: the design of ballistic armour or the design of composite panels to resist hail strikes. There has been significant work undertaken to measure dynamic fracture properties using a variety of experimental and numerical modelling techniques [1]. More recently, dynamic fracture toughness has been determined utilising full-field displacement measurements taken using digital image correlation [2–4]. This methodology utilises the quasi-static solution for the displacement field around the crack tip given by a series expansion with a square root singularity. However, for the case of dynamic crack propagation stress wave interactions lead to a complex and rapidly oscillating stress state at the crack tip which is not fully captured by the analytical displacement field solution. Therefore, as current fracture models utilise quasi-static solutions to determine the dynamic fracture toughness they do not fully account for inertial effects in the material during crack propagation.

The aim of this work is to develop a new dynamic fracture test that alleviates some of the drawbacks of current methods. The proposed method utilises ultra-high speed full-field measurements to perform a direct energy balance on a fracture specimen and calculate the energy consumed during crack growth. In order to develop this new methodology the following objectives are proposed: 1) numerical validation using finite element simulations; 2) image deformation simulations to account for measurement errors coming from camera noise spatial resolution and temporal resolution; and 3) experimental validation of the test concept using a model brittle material acrylic (PMMA). In this paper the formulation of the test concept is presented along with numerical validation. Future work will include implementation of image deformation simulations and experimental validation.

Formulation of the Test Concept

The proposed test concept is based on an energy balance applied to a dynamically impacted sample (shown schematically in Fig. 1). For the case of an un-cracked sample that does not fracture the energy balance takes the form:

$$E_I = E_K + E_S \tag{1}$$

where E_I is the work done by the impact force on the sample, E_K is the kinetic energy of the sample and E_S is the strain energy in the sample. When the energy balance is applied to a cracked specimen an additional term is introduced to account for the energy consumed by fracture processes 'E_F'. For this case the energy balance can be written as:

$$E_F = E_I - E_K - E_S \tag{2}$$

If full field displacement data is available with sufficient temporal and spatial resolution then impact energy E_I, kinetic E_K and E_S can be calculated. The impact energy can be calculated by using the average acceleration over the field of view to reconstruct the impact force; the kinetic energy is obtained from the velocity field; and the strain energy can be obtained from the strain field by assuming a suitable material model to reconstruct the stress field. The fracture energy is then the energy remaining after subtracting the kinetic and strain energy from the impact energy.

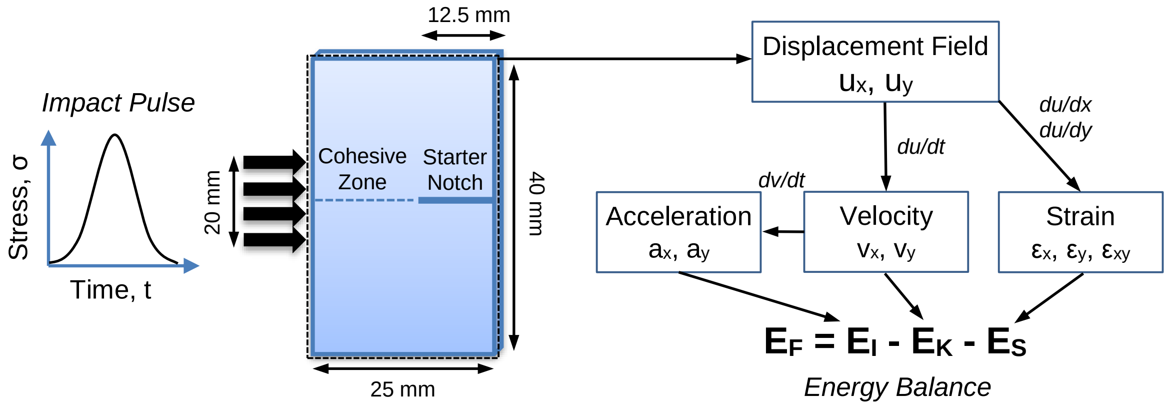

Figure 1: Schematic of proposed fracture test configuration

Numerical Validation

The fracture specimen configuration shown in Fig. 1 was modelled in Abaqus explicit (v 6.14). The bulk of the model was meshed using three dimensional 8-node reduced integration elements (C3D8R). The mesh size, time step and damping were selected to minimise the error on the energy balance for an un-cracked specimen. The mesh size was set to 0.25x0.25x1.00mm, the simulation time step was fixed at 100ps and beta damping was set to 10ns. The material chosen for the simulation was PMMA with nominal material properties of ρ = 1300kg/m^3, E = 3.2GPa, ν = 0.42. The input loading was modelled as a half sine pulse with a peak amplitude of 75 MPa. The loading pulse was applied over half of the specimen height to simulate a one point bend test. Cohesive surface elements were used to model the crack path with a bi-linear traction separation law. The cohesive law was specified using the input maximum surface traction T_{max} = 25MPa and the critical strain energy release rate G_c = 5000 J/m^2.

In order to assess the error in the energy balance taken from the finite element model the cohesive zone parameters were set to effectively infinite values (i.e. no crack growth occurred). For this case the energy balance is given by Eq. 1; that is, the impact energy equal to the sum of the kinetic and strain energy. Note that due to the use of numerical damping in the explicit dynamics simulations an additional term is added to the energy balance to account for energy consumed by damping 'E_D'. The results for the case of 'no crack growth' are given in Fig. 2a. The maximum error in the energy balance for this case is 2.4% of the maximum impact energy. Fig. 2b shows the energy balance for the case when the cohesive zone model is active and crack growth occurs. For the crack growth case the total fracture energy is given as 9.1% of the total impact energy.

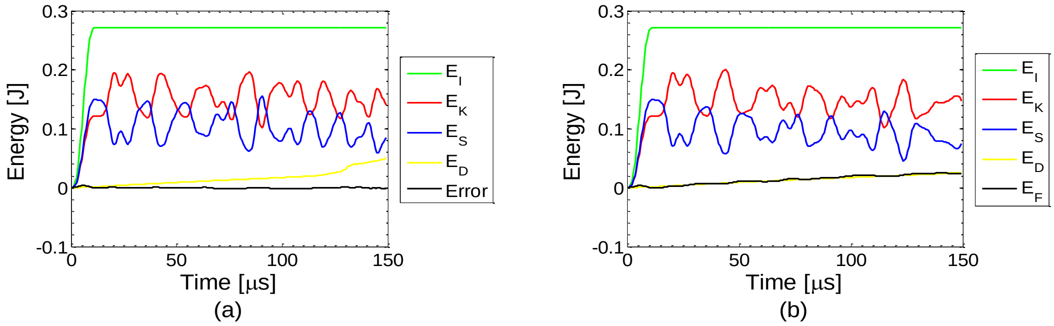

Figure 2: (a) Energy balance for the 'no crack growth case'. (b) Energy for balance for the cohesive model.

Summary

Current dynamic fracture models do not fully account for transient inertial effects. Therefore, this work presents a new methodology for determining the dynamic fracture toughness of a material using full-field measurements. The concept of this new test method is to apply full-field measurement techniques to calculate a dynamic energy balance during a fracture test. The new test concept has been validated using explicit dynamics simulations. Continuing work is underway to perform image deformation simulations and preliminary experiments.

References

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