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Influence of elastic wave on crack nucleation – Experimental and computational investigation of brittle fracture

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ABSTRACT

Understanding the phenomenon of fracture is very important for many industrial applications. Numerical tools are needed to describe the crack pattern and the energies evolution in any specimen. Then, for example, the acoustic properties of any structure can be used for nondestructive testing. The aim of this article is to demonstrate the capabilities of the phase-field model for these processes. It can be used not only to study the wave propagation in materials consisting of several different materials or phases in composite pieces, but also to study the crack nucleation and propagation in homogeneous or composite materials. Numerical analysis of brittle fracture using the phase-field model is elaborated in this paper. We focus on the behavior of the linearly elastic bodies submitted under quasi static and dynamic loading. The influence of considering the kinetic energy on the dynamic phase-field pattern and on energies evolution is detailed. In fact, using the finite element method with Newmark scheme, we show the influence of the transverse wave and the celerity C_T on energies evolution. Also, some numerical computations in quasi static fracture using phase-field model and staggered scheme will be elaborated. A qualitative agreement with experiments is shown. A comparison between quasi static and dynamic crack propagation is made.

1. Introduction

Prediction of the fracture mechanics problem, especially in ductile and brittle materials is very important for many engineering applications. Numerical methods are needed to predict the crack pattern in material with complex geometry. Research is concerned with dynamic fracture mechanics for technical materials and structures due to fast loading. In fact, the study of structure problems has been usually made in the quasi static case which means that kinetic energy was neglected. However, it was found that this simplification hypothesis is not valid in many cases such as in the field of material fracture [1,2]. Therefore, recent researches focus on the dynamic study and interest in the dynamic behavior of the different materials and analysis of the fracture problem. In fact, Laleg-name and Sandig [3] analyzed the crack propagation in a bounded linear elastic body under the influence of incident waves. They discussed the influence of plane elastic waves to crack propagation. Also, tests are performed by Masmoudi et al. [4] on composites while constantly monitored by acoustic emission technique. They study the influence of incorporation of piezoelectric sensor on the fracture load and the mechanical properties of material. The propagation of shear transverse waves in a dispersive composite was studied by Fedotovskii [5].

One of these approaches, the so-called phase field method, represents cracks by means of an additional continuous field variable. The phase-field model is numerically very robust and able to describe many mechanics phenomena and can be applied to various processes involving wave's propagation and fracture problems. The general idea of the numerical model is not to track the location of interfaces or defects explicitly, but instead to introduce a damage variable α called phase-field. In the case of a brittle material, the value $\alpha = 1$ is assigned to the damaged zone and $\alpha = 0$ to the safe one.

Today, the main goal of brittle fracture research works is to extend the quasi static formulation of brittle fracture to a dynamic one by including the kinetic energy terms. Since an inertial term is included we have to add the kinetic energy as a part of the total energy in comparison with the quasi static case. The developments related to the theory of brittle fracture are mainly based on the ideas of Griffith [6]. Recently, the fracture mechanics has been revisited by a number of important accomplishments incorporating the Griffith viewpoint.

Inspired from image segmentation problems, a phase field model was detailed by Bourdin et al. [7] aiming to model brittle

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Nomenclature

$E(\varepsilon(u),\alpha)$	regularized total energy	β	parameters of the Newmark method
α	damage scalar (phase-field)	μ	shear modulus
ε	strain tensor	λ	Lamé coefficient
ν	Poisson's ratio	M	mass matrix
η	regularized numerical parameter	K	stiffness matrix
G	energy release rate	V	applied velocity
G_c	toughness	F	external load
E_{elast}	elastic energy	U	displacement vector
E_{surf}	surface energy	$\dot{U}$	velocity vector
E_{kine}	kinetic energy	$\ddot{U}$	acceleration vector
E_{tot}	total energy	C_T	wave speed scalar
$x(x_1; x_2)$	spatial coordinate	$\delta(t)$	time-dependant boundary condition
κ_η	positive infinitesimal parameter	ρ	mass density
γ	parameter of the Newmark method	E	Young's modulus

fracture. The main idea consists in introducing a new variable α, which controls the damage of the structure. A numerical method to solve the problem based on staggered algorithm is detailed in [8]. Otherwise, Ambati et al. [9] present an overview of the existing quasi static and dynamic phase-field fracture formulations from the physics and the mechanics communities. Significant contributions to the phase-field model were made by Miehe et al. [10]. A staggered scheme was employed in which a local energy history field is introduced as a state variable to ensure irreversible crack growth. The ability of the phase-field model to simulate crack propagation and sophisticated fracture pattern in the quasi static and also in the dynamic regime has been examined in several simulations [11,12]. The robustness of the staggered algorithmic implementation was proved [9,12,13].

Dynamic phase-field model which is able to model the complex crack patterns is outlined in this paper. This model is based on the regularization of crack discontinuities. For that, the main computational results in quasi static fracture are presented and validated with experiment results. After that, we focus on the dynamic crack propagation problem, in which analysis of the transverse wave propagation in brittle material is shown.

The current paper is organized as follows: First, in Section 2 we introduce a phase-field model which can be used to study the fracture processes in brittle material. The accuracy of this method is proved in Section 3 by tensile test on quenched non-alloy steel with a rapid cooling. In Section 4, the propagation of transverse wave phenomena in brittle material is elaborated. The influence of the celerity and the existence of hole in material are determined. Here, the dynamic phase-field is not relevant and only the elastic properties are investigated. Finally, the phase-field dynamics is discussed in Section 5. Numerical computational tests were done in order to study the influence of the kinetic energy on displacement and phase-field. Experimental tensile test were conducted. A good agreement, in term of crack pattern, will be shown between computational results and experimental ones obtained by a high speed hydraulic actuator.

2. Phase-field model of brittle fracture

2.1. Diffusive representation of crack

The sharp crack topology may be described by a field variable $\alpha(x)$, characterizing for $\alpha = 0$ the unbroken state and for $\alpha = 1$ the fully broken state of the material. We denote the variable $\alpha(x)$ as the crack phase-field. The phase-field approach is related to the continuum theory of damage. The scalar damage field α describes in a homogenized macroscopic sense the development of micro cracks. Fig. 1 represents a body with approximation of internal discontinuities by phase-field α. It smears out the crack over the axial domain of a piece, representing a regularized or diffusive crack topology.

The one-dimensional description of a diffusive crack topology can be extended to multi-dimensional solids as shown in Fig. 2. The regularized crack surface $\Gamma(\alpha)$ is a functional of the crack phase-field α. The body might also contain cracks $\Gamma(\alpha)$, i.e. internal discontinuities with respect to the macroscopic fields. The regularization is governed by the length scale parameter η and gives for $\eta \to 0$ the sharp crack topology.

In order to approximate these jumps in a regularized way, an additional continuous field is introduced. The purpose of this order parameter, phase-field or crack field is to distinguish between undamaged and broken material. At a crack surface the

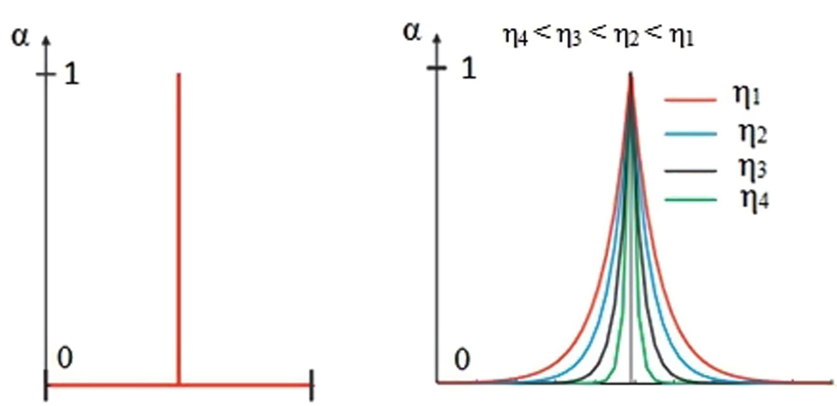

Fig. 1. Regularized representation of a crack: (left) sharp crack model; (right) regularized representation through phase field.

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