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A computational study of the dynamic propagation of two offset cracks using the phase field method

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ABSTRACT

The study of the propagation of multiple cracks is essential to modeling and predicting structural integrity. The interaction between two cracks depends on a number of factors such as the domain geometry, the relative crack sizes and the separation between the two crack tips. In this paper, we study the interaction between two dynamically propagating cracks. We use the phase field method to track the crack paths, since this method can handle complex crack behavior such as crack branching, without any ad hoc criteria for crack evolution. The results from our dynamic simulations indicate that, unlike crack interaction under quasi-static or fatigue loading, the presence of another crack does not accelerate crack propagation when dynamic loads are applied. However, some similarities in the crack topologies are observed for both quasi-static and dynamic loading.

1. Introduction

1.1. Motivation

Fracture is a primary cause of catastrophic failure in structures. Since analytical solutions for crack propagation do not exist except for a few special cases, accurate numerical modeling of fracture is essential. Broadly speaking, numerical modeling of fracture can be done using three classes of methods: 1. Discrete modeling (cohesive zone modeling, extended finite element methods, element deletion methods), 2. Continuum damage description, and 3. Phase field methods.

Cohesive zone modeling either requires prior knowledge of the crack path (see, [6,5,3]) or it requires insertion of cohesive zone in between all element edges as done in Xu and Needleman [45], which increases the computational cost. Also, since the crack can propagate only along finite element boundaries, different shapes of triangular elements might lead to different crack paths for the same boundary conditions, as seen in Xu and Needleman [45]. The extended finite element method (XFEM) method requires that the current and predicted paths be checked at every step (see [35]). Also since discontinuities are injected on the basis of a failure criterion, the use of level sets tends to favor propagation of a single crack, limiting its use for cases involving crack branching [39]. The element deletion method does not predict any crack branching in simulations carried out by Song et al. [39]. In continuum damage models, a change of the character of the governing partial differential equations occurs locally, beyond a certain level of accumulated damage or plastic strains [11]. Thus, many existing methods are ill-suited to modeling the dynamic behavior of cracks.

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1.2. Phase field models

Phase field models can capture complex crack behavior without any ad hoc criteria for crack evolution [9] and are thus effective in capturing interactions among dynamically propagating cracks. In these approaches, the fracture surface is approximated by a phase field [10]. A continuous scalar-valued phase field c is introduced in the domain to indicate whether the material is in the fractured phase ($c = 0$) or the unfractured phase ($c = 1$). The phase field is allowed to take on intermediate values ($0 < c < 1$) signifying a smearing of the crack over a small region characterized by a length scale parameter l_0. The phase field determines the stiffness of the material; it reduces the strength of the material in areas where $c < 1$. An equation for the evolution of this phase field is derived using the Euler-Lagrange equations for an approximation of the Lagrangian for the fracture problem. This depends on the history of the strain energy of the domain. This couples the momentum and the phase field evolution equations, and the equilibrium state at any given time is determined by solving this coupled system of equations.

We now review the evolution of various phase field models briefly. Aranson et al. [2] put forward a phase field model in which the displacement field obeys the elasto-dynamic equations together with a damping term. They introduced an order parameter ρ which is used to describe the damage evolution. In this model, the elasticity modulus is assumed to be proportional to order parameter such that $E = E_0\rho$. Karma et al. [26] (KKL model) use a scalar order parameter ϕ that describes the state of the material in Lagrangian material coordinates; $\phi = 0$ for broken state and $\phi = 1$ for unbroken state. The evolution of the crack is derived variationally from a free energy functional. However, the crack motion is a reversible process in this model. Henry [21] use a model in which crack growth is irreversible. The same model is applied to nonlinear elastic materials in Kuhn and Müller [27]. In Hakim and Karma [19] and Hakim and Karma [20], the KKL phase field model from Karma et al. [26] is used to derive the principle of local symmetry and it provides generalized conditions for crack path prediction. Wang et al. [42], Jin et al. [23], Wang et al. [41] use this method to model the interaction between dislocations with free surfaces, voids and cracks. With the research in the past decade, phase field methods have been used to successfully model cracks at low speeds [40]. These models can describe quantitatively, crack kinking and oscillatory instabilities with biaxial loading and with thermal fracture.

The phase field method overcomes numerous complexities of discrete fracture models. It does not require numerical tracking of discontinuities or re-meshing of the domain as the crack propagates. This allows for efficient modeling of branching and merging of cracks, which in turn allows us to study the interaction between multiple cracks as demonstrated in this work. This approach can also efficiently model fracture in three-dimensional problems [10,43] and can represent complex fracture surfaces simply through the phase field variable.

The phase field approach suffers from some drawbacks. Firstly, the parameter l_0 is both a material parameter that determines the critical stress for crack nucleation, as well as a numerical parameter that determines the degree of approximation of the crack. Consequently, the crack path can change significantly with the value of l_0 (see [1]). If l_0 is considered to be a numerical parameter, then a smaller value leads to a more accurate solution. However, a small value of l_0 also requires a finer discretization of the domain, which in turn increases the computational cost. Another computational consideration in using the phase field method is the cost of solving for an additional field quantity, namely the phase field itself. What is also not clear is how the parameter l_0 can be determined for a given material from experimental data and what types of experiments are needed for this purpose.

The method used in this paper is based on the work by Bourdin et al. [12], who implement the variational formulation for quasistatic crack growth proposed by Francfort and Marigo [16]. The method uses a two-field functional, the first field being displacements and the second being a scalar phase field. Bourdin et al. [13] modify this formulation for modeling dynamic crack propagation. The work of Miehe et al. [34] proposes a thermodynamically consistent phase field formulation, in which energy-release-driven fracture occurs only in tension. Further modifications include the introduction of a local history field that drives the evolution of the crack path, making the formulation more robust; see Miehe et al. [31]. Borden [9] extends the phase field formulation to ductile fracture and also derives a higher-order phase field approximation for improved accuracy. Notable recent extensions and improvements of the phase field method include modeling fracture in rubbery polymers [33], thermo-elastic-plastic solids [30] at large strains, crack evolution in piezoelectric ceramics [44], and pressurized fractures [43].

1.3. Crack interaction

The presence of multiple cracks is significant because of the potential for interaction among the cracks. This can have catastrophic consequences like in the case of Aloha Airlines Flight 243, which experienced an explosive decompression following a structural failure of the fuselage in 1998. The National Transportation Safety Board (NTSB) reported the cause of the damage to be failure of a fuselage lap joint from multi-site cracking of the skin adjacent to rivet holes along the lap joint [7].

In general, the interaction between two cracks depends on the domain geometry, the relative crack lengths and the separation between the two crack tips. Kamaya and Totsuka [25] show the variation in crack interaction as the distance between the two crack tips varies. Their experiments and subsequent simulations show that in most cases, approaching cracks tend to accelerate due to the interaction except in the presence of a relatively large crack, in which case crack growth might be arrested due to the stress shielding effect. The propagation of the larger crack leads to a reduction in stiffness and a release of residual stresses, due to which the stress intensity at the crack-tip of the smaller crack decreases, see Hutchinson [22]).