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A dynamic multiscale phase-field method for cracks

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ABSTRACT

The displacement discontinuity at a crack poses severe challenges to numerical solutions. Dynamic crack growth simulations using the standard continuum framework require careful treatment of appropriate jump and boundary conditions at the crack faces as well as crack kinetics to ensure unique solutions. This is difficult to implement and computationally expensive particularly when there can be multiple interacting cracks. An alternative approach that has been developed is to use phase-field methods. These introduce a phase parameter that tracks the cracked and uncracked regions of the body. A spatial regularization ensures that the phase field does not have singularities. This is coupled to standard momentum balance with the elastic stiffness going to zero in the cracked region. The evolution of the crack is then governed by the interplay between momentum balance and the evolution of the phase field. An important shortcoming of these existing phase-field methods is that the phase field evolution is typically a simple gradient flow. Therefore, the kinetics of the crack motion is restricted to fairly simple possibilities, and the dynamics of fracture is based only on the interaction with momentum balance. We present a phase-field formulation for dynamic fracture with the key feature that complex crack kinetics can be readily prescribed. We use a geometric interpretation of the gradient of the phase parameter field as a linear density (density per unit length) of crack faces. For any curve in 3D space, we write a balance for these crack faces by accounting for appropriate flux and source terms. This balance in addition introduces a crack velocity field – distinct from the material velocity – that can be constitutively prescribed as a function of crack driving force, temperature, and any other relevant fields. The net result of our approach is an evolution equation for the crack faces for which complex kinetics (e.g., stick-slip) can be easily prescribed, yet the field remains nonsingular and amenable to simple numerical methods. The balance law additionally contains a source term that enables a straightforward and transparent prescription of crack nucleation. We show that this model can simulate cracks faster than shear wave speeds by using anisotropic kinetics. We analyze energy flow around the crack tip to understand crack branching and reasons for crack speeds being limited by elastic wave speeds.