Engineering Fracture Mechanics 172 (2017) 39–60

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

The Thick Level-Set model for dynamic fragmentation

Andrew J. Stershic [a], John E. Dolbow [a,*], Nicolas Moës [b]

[a] Department of Civil and Environmental Engineering, Duke University, Durham, NC 27708, USA
[b] Institut de Recherche en Génie Civil et Mécanique, UMR-CNRS 6183, École Centrale de Nantes, Nantes, France

ARTICLE INFO

Article history:
Received 21 July 2016
Received in revised form 9 December 2016
Accepted 14 December 2016
Available online 4 January 2017

Keywords:
Thick Level-Set
Fragmentation
Gradient damage

ABSTRACT

The Thick Level-Set (TLS) model is implemented to simulate brittle media undergoing dynamic fragmentation. This non-local model is discretized by the finite element method with damage represented as a continuous field over the domain. A level-set function defines the extent and severity of damage, and a length scale is introduced to limit the damage gradient. Numerical studies of one-dimensional problems demonstrate that the proposed method reproduces the rate-dependent energy dissipation and fragment length observations from analytical, numerical, and experimental approaches. Additional studies emphasize the importance of appropriate bulk constitutive models and sufficient spatial resolution of the length scale.

1. Introduction

In this work, we build upon the previous implementations of the Thick Level-Set model (TLS) [31,4,32,35] to apply it to dynamic brittle fragmentation. In doing so, this work represents the first application of a gradient-limited damage model to this class of problems. Whereas previous realizations of the TLS have focused on simulating domains with a small number of cracks, this local/non-local TLS approach models cases in which the stress distributions and material properties are sufficiently uniform that highly-interacting cracks develop innumerably in the domain. Therefore, we have introduced a level-set update and reinitialization technique that tracks the growth of each crack individually. Lastly, we employ a specific softening/post-yield function in the constitutive model that matches the quasistatic crack opening behavior of a cohesive traction-separation law [39]. This choice is influential in achieving the expected scaling of fragment size and energy dissipation with strain rate.

A conventional concept for characterizing fracture is the cohesive zone model (CZM), which represents the opening of cracks by a traction-separation law [38]. In a finite element model, this can be implemented by the cohesive element approach (CEA) in which zero-thickness cohesive elements are placed between physical elements in the domain anywhere a crack is allowed to propagate: either along a prescribed crack path or throughout the domain [48,8]. Once the traction across the cohesive element exceeds a failure criterion, it begins to open, representing the formation of a crack. The cohesive traction that resists opening is given by the traction-separation law. Once the critical opening has been reached, the cohesive element offers no resistance, representing the discontinuity of fields across a crack. The length scale incorporated by the critical opening accounts for the size effect of fracture [2] and provides for a finite amount of energy dissipation.

The cohesive element approach has been used extensively to simulate fragmentation. Camacho and Ortiz [8] employed the CEA to study the spall of a slender plate under uniaxial impact. Miller et al. [28] simulated dynamic fragmentation of a

---

[*] Corresponding author.
E-mail addresses: andrew.stershic@duke.edu (A.J. Stershic), jdolbow@duke.edu (J.E. Dolbow), nicolas.moes@ec-nantes.fr (N. Moës).

http://dx.doi.org/10.1016/j.engfracmech.2016.12.012

one-dimensional bar under uniform tension with the CEA in order to evaluate the accuracy of predictions based on analytical energy-balance considerations. That study confirmed that there are two competing effects that characterize fragmentation: the rate at which the system is loaded, and the finite speed at which stress release waves can propagate from existing cracks [28]. Zhou and Molinari and colleagues have used CEA simulations of a brittle expanding ring in order to create an empirical fragment size prediction [52], to describe the shape of the fragment size distribution [50], and to study the convergence of the dissipated energy using deterministic and stochastic simulations [33].

While the cohesive approach has been used to successfully represent crack initiation, extension, branching, and coalescence in a variety of problems, it suffers from mesh sensitivity because the crack path is limited to element boundaries. This may result in a lack of spatial convergence between an ideal crack path and its discrete representation, increasing the energy required to open the crack and limiting the model's accuracy [37,40]. Consequently, the crack path may be influenced by the existence of energetically-favorable extension directions [40].

In an effort to alleviate the mesh dependency, the cohesive approach is often coupled with the eXtended Finite Element Method (XFEM). In the XFEM, cracks are represented by enriching nodes on either side with a Heaviside jump function, introducing a discontinuity in the displacement field [30,11]. Cracks are allowed to exist and grow throughout the domain, independent of the mesh, with the crack propagation and direction determined by extension algorithms. Cohesive crack growth is modeled by placing cohesive zones across the crack surface as it opens [29]. While this approach does allow for crack geometries to be represented independently from the mesh, the geometric representation of the crack surface can be cumbersome, especially when dealing with crack branching and coalescence in three-dimensional problems [43].

An alternative to modeling the crack discretely is to model it in the continuum by using a damage model. The TLS model is a relatively new non-local damage model that uses a length scale parameter to limit the damage gradient and a level-set field as an indicator of damage [31]. Since the model is based upon a continuum damage representation, it is able to capture crack branching and coalescence in a straightforward manner, even in three dimensions. The extent of damage or damage front is characterized by the zero level-set of the damage indicator field. By defining this level-set field as a signed distance function in non-local damage zones (small neighborhoods around cracks), crack boundaries are defined independently of the finite-element mesh as a level-set of the indicator field and require no post-processing [31]. Further, the update of damage fields in the TLS is performed independently in each damage zone, removing the necessity for a global solve of the damage indicator field [31]. TLS implementations can include XFEM enrichment across fully-damaged zones to introduce a sharp discontinuity at narrow crack surfaces [4].

Our specific contribution to the TLS approach to fracture modeling is the individual consideration of highly interactive cracks in the level-set reinitialization. Previous TLS implementations project the level-set field as a signed distance function from its iso-zero, effectively merging the representation of cracks that grow adjacent to one another. In contrast, we reinitialize by projecting the level-set field from all local minima, an approach that preserves the individual damage zones that represent cracks regardless of their proximity, until the damage gradient forces their coalescence. Another contribution is the time-independent softening constitutive model which allows for an exact level-set update in the explicit approach, whereas in a previous dynamic implementation, a delay-damage evolution model had been employed for the update [35]. We find that our specific choice of post-yield function achieves the expected fragmentation results while other constitutive models may not.

Another modern approach for diffusive crack modeling is the phase-field model for fracture. This model consists of a continuum phase field that represents damage in the domain [13]. This technique has been applied to dynamic fracture problems, reproducing the expected behavior observed in physical experiments [6,21]. With phase-field modeling, cracks are represented in a diffuse manner and displacement discontinuities are not explicitly modeled [31]. Because damage is expressed as a scalar field, damaged areas (corresponding to cracks) can grow, branch, and coalesce in multi-dimensional problems without the implementation of front-tracking or extension algorithms [13]. While the relation of the damage field to an indicator field is conceptually similar to the TLS approach, the mechanism for damage evolution differs significantly. The TLS approach updates damage in the neighborhood around a crack by limiting a weighted energy-release average; in contrast, the phase-field model introduces a fracture energy functional and evolves damage to minimize the energy potential in a coupled manner [6]. Shortcomings of the phase field model include that the discrete location of the crack (i.e. displacement discontinuity) is not explicitly resolved and that a global solve of the phase field on the entire domain is required, adding computational expense [31]. The TLS approach provides an alternative modeling technique that addresses these drawbacks.

This paper is organized as follows: Section 2 describes the initial-boundary value problem of interest and the TLS approach. The numerical discretization and all implementation details are then given in Section 3. The TLS model is applied to the one-dimensional fragmentation problem and compared to CEA predictions in Section 4. A discussion of the results and the particular choices of constitutive model and length-scale is given in Section 5. The final section provides a brief summary and conclusions.

2. Thick Level-Set model

The following is a description of our implementation of the TLS to study dynamic brittle fragmentation in one dimension.