

# Crack propagation in dynamics by embedded strong discontinuity approach: Enhanced solid versus discrete lattice model

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## Abstract

In this work we propose and compare the two models for crack propagation in dynamics. Both models are based on embedded strong discontinuities for localized cohesive type crack description and both provide the advantage to not to require tracking algorithms. The first one is based on discrete lattice approach, where the domain is discretized with Voronoi cells held together prior to crack occurrence by cohesive links represented in terms of Timoshenko beams. The second one is based on constant strain triangular solid element. In both models, propagation of cracks activates enhancements in the displacement field leading to embedded strong discontinuities. The latter remain localized inside the element, regulated by the localized traction separation behavior defined through exponential softening law. Thus, the both models provide the result that remain mesh-independent, with fracture energy as the model parameter. We show that implementation in dynamics framework can be obtained by adding inertial effects without modifying the existing quasi-statics models. In order to provide reliable results, classical implicit Newmark algorithm can be used for time integration. The two presented models are subjected to dynamic crack propagation benchmarks, where detailed analysis on strain, kinetic, plastic free and dissipated energy during simulation is verified by comparison to the amount of total work which is introduced into the system. The main strength of the proposed approach is that cracks initiation, propagation, their coalescence, merging and branching are automatically obtained without any tracking algorithms. In addition, since the discontinuities remain localized inside elements, accurate results can be obtained even with coarser grids, leading to efficient methodology capable of capturing complex crack patterns in dynamics.

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## 1. Introduction

The description of dynamic crack propagation remains a challenging task due to the presence of complex phenomena pertinent to cracks initiation, propagation and growth, branching, multiple cracks interaction, their coalescence and merging. These phenomena are also under the strong influence of the size of the fracture process zone (FPZ), i.e. the zone around the crack where nonlinear and dissipative mechanisms occur. Numerical methods are often the only way to find the solution for such problem, with the main challenge to make it reliable. Since the standard finite element procedure shows strong dependence on mesh when simulating cracks [1], many enhanced and extended finite element methods based on inserting discontinuity lines and enriching the displacement fields, have been developed. Depending on the type of material and the size of the FPZ, one can choose the enrichments for the method either based on the theory of linear elastic fracture mechanics (LEFM) or cohesive zone formulation. LEFM can be used in the case when FPZ around the crack (and the crack tip) is small compared to the size of the crack or specimen, and when the bulk is isotropic and linear elastic. For instance, extended finite element method (X-FEM) with crack tip asymptotic fields and discontinuous enrichment for displacement jump across the crack line can be found in [2–4]. On the other hand, when LEFM is not applicable and when FPZ influences the behavior of the material, cohesive type formulation of fracture can be used. Cohesive approach is described as a gradual separation of crack surfaces across the crack tip or cohesive zone which is resisted by cohesive tractions when material elements are pulled away. Namely, once the critical value of traction is reached, softening in material is triggered with decreasing traction and increasing crack opening. This represents the constitutive model for crack opening and input for our simulations. Enhanced methods which allow for arbitrary cohesive crack growth are cohesive X-FEM [5–7] and embedded strong discontinuity finite element method (ED-FEM) [8–10]. They can both deal with cracks in a mesh independent way due to their enrichments. Tracking algorithms, which can be quite computationally costly, are often used with these methods, especially to solve the complex crack phenomena in dynamics, such as branching. Recently, phase field models [11,12] have been used to successfully represent complex brittle crack behavior in dynamics, by smearing and smoothing the boundary of the crack over a small region. They can be used to avoid tracking algorithms, but apparently very fine meshes usually with adaptive refinement are needed to resolve steep displacement fields.

In this work we propose the two models for dynamic crack growth based on localized cohesive crack representation, which will also surpass the need for crack tracking algorithms, and that moreover can be equally used for fine and coarse mesh. Both models are based on embedded strong discontinuity approach (ED-FEM), which is a discrete crack description where displacement fields are enhanced with additional kinematics to provide displacement jumps [8]. The main difference with respect to X-FEM (see [13]), where discontinuity is considered globally through additional nodal unknowns, is that additional degrees of freedom and corresponding enrichment functions related to crack opening are kept at the element level. One can solve the corresponding equations locally, which allows for the straightforward implementation within standard computer code architecture. Any ED-FEM formulation provides localized interpretation of cracks leading to mesh-independent post-peak softening response, which is defined through cohesive traction separation law. Mesh independency is considered here in the context of fracture energy, which we use here as the input parameter for our cohesive softening behavior. Namely, it has been observed that softening curve depends on the size of the FPZ and dissipative mechanisms in the zone. The main benefit of present formulation is that it acts as a natural localization limiter for the FPZ and one does not need to implement the characteristic length parameter to stabilize its size and correspondingly the post-peak softening behavior [1,14].

The first model that we propose herein relies on discrete lattice element approach with embedded strong discontinuities for quasi-static crack propagation described in [14]. In the present work we extend such quasi-static formulation into dynamic framework. The second model is based on enhanced triangular constant strain element where strain localization band collapses into a surface leading to embedded strong discontinuity, or jump in displacement field. The latter approach is described in [15] for quasi static case with further development to show how to extend it to dynamic framework in [16], and its resulting benefits for quasi-static test with slow loading rate in reducing the total number of iterations. Here we seek to extend these two models and to provide their validation on well known dynamic benchmarks. The difference in the two models is that post-peak softening behavior related to discontinuity is governed by plasticity framework in discrete lattice model, while damage framework is chosen in enhanced triangular model. This is applicable in quasi brittle or plastic materials with pronounced FPZ where diffuse micro-cracks or plastic dissipation around the crack and crack tip influence the failure mechanisms. Although these two models are different and are initially developed for different purposes (the presented discrete lattice model is developed for failure in heterogeneous quasi brittle materials such as rocks and concrete, while enhanced solid triangular element is

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