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Elastic damage to crack transition in a coupled non-local implicit discontinuous Galerkin/extrinsic cohesive law framework

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Highlights

- A continuum damage to crack transition framework is presented.
- The continuum damage model is written in the non-local implicit form.
- The fracture model uses the discontinuous Galerkin/extrinsic cohesive zone combination.
- The fracture energy is obtained from the remaining damage energy to be dissipated.
- The framework is currently limited to elastic damage.

Abstract

One current challenge related to computational fracture mechanics is the modeling of ductile fracture and in particular the damage to crack transition. On the one hand, continuum damage models, especially in their non-local formulation which avoids the loss of solution uniqueness, can capture the material degradation process up to the localization of the damage, but are unable to represent a discontinuity in the structure. On the other hand cohesive zone methods can represent the process zone at the crack tip governing the crack propagation, but cannot account for the diffuse material damaging process.

In this paper we propose to combine, in a small deformations setting, a non-local elastic damage model with a cohesive zone model. This combination is formulated within a discontinuous Galerkin finite element discretization. Indeed this DG weak formulation can easily be developed in a non-local implicit form and naturally embeds interface elements that can be used to integrate the traction separation law of the cohesive zone model. The method remains thus consistent and computationally efficient as compared to other cohesive element approaches.

The effects of the damage to crack transition and of the mesh discretization are respectively studied on the compact tension specimen and on the double-notched specimen, demonstrating the efficiency and accuracy of the method.

Keywords: Continuous damage mechanics; Fracture; Cohesive zone method; Damage to crack transition; Discontinuous Galerkin method

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1. Introduction

Two approach families dedicated to failure analyses of ductile materials are traditionally used: the continuous and discontinuous approaches. Continuous approaches, as the continuous damage mechanics (CDM) [1–3, e.g.], describe the material degradation process through the evolution of internal variables. An important issue of CDM approaches in their local form is that strain-softening leads to an ill-posed problem, and consequently the numerical results suffer from pathological localization and strong mesh-dependency. This ill-posedness can be avoided by applying some regularization techniques, as a non-local model [4–8, e.g.] or a gradient enhanced model [9]. On the contrary, discontinuous approaches, which are typically used in fracture mechanics, model the crack in a discrete way. In the uncracked parts of the body, the mechanical properties of the material are assumed intact, i.e. the degradation and softening of the material are not considered, while this degradation is modeled through the crack propagation. The progressive degradation process occurring in the process zone at a crack tip can be modeled by the cohesive zone model (CZM) [10,11] through the shape of the cohesive law, also called traction separation law (TSL), which describes the irreversible evolution of the traction exerted between the crack lips in terms of the crack opening.

Both continuous and discontinuous models can be considered in the finite element (FE) framework. On the one hand, with continuous approaches, a classical FE discretization (possibly formulated in a non-local way) can be directly used. On the other hand, when dealing with discontinuous approaches as the CZM, the FE discretization requires to be modified to account for a description of the crack. The three most popular methods to represent a crack are (i) the extended finite element method (xFEM) [12,13], (ii) the embedded localization method (EFEM) [14], and (iii) the use of interface elements. For the two first approaches, the crack can be represented in an arbitrary existing FE mesh through global or local enrichment and they can also integrate a CZM [15]. For the third approach, the crack propagates at the boundary of adjacent FEs and is modeled by the insertion of interface or cohesive elements [16]. When an assumed criterion is reached, the cohesive elements allow shifting from a continuous form into a discontinuous one to integrate the TSL. The TSL can be intrinsic in which case the cohesive elements are inserted since the very beginning of the simulation. The TSL should thus represent the pre-cracked stage under the form of a penalty response [17,18], which makes the method not consistent and suffering from a mesh dependency [19]. This has motivated the use of extrinsic cohesive laws (ECL) which represent the fracturing response only, and for which cohesive elements are inserted at the fracture onset [20,21]. Nevertheless the computational efficiency of the extrinsic approach is still challenging for 3D parallel applications as it requires mesh topology modifications on the fly. An energetically rigorous and computationally efficient way to introduce a CZM is to combine the extrinsic cohesive law with a discontinuous Galerkin (DG) approach [22–27]. With this hybrid DG/ECL method, interface elements are inserted between bulk elements at the beginning of the simulation, but the consistency and continuity during the pre-fracture stage are ensured by having recourse to the DG interface terms, contrarily to a classical intrinsic CZM.

When considered separately, continuous and discontinuous approaches are unable to model with high accuracy the fracture process of ductile materials. This process within a material often begins with a global interaction of all the pre-existing microscopic defects followed by their growth in strain concentration areas, until the coalescence of some defects creates a macroscopic crack. On the one hand, this cannot be modeled by the sole recourse to a discontinuous approach such as the CZM since the degradation process cannot be modeled with the same accuracy as with a CDM. On the other hand, a CDM can capture the damage diffusion stage, the damage evolution in a process zone, and finally the localization of the damage. However, without introducing a crack, large element distortions arise as a result of the stress-carrying capacity loss of the constitutive material response. These large element distortions not only disagree with the physical reality but also hurt the numerical convergence of the simulations. Moreover, because of the non-local or gradient enhanced formulation, the excessive strain on the fictitious crack surface leads to an unrealistic extension of the damage field. These problems motivated the introduction of a crack when using a non-local CDM, either by remeshing techniques when the damage is close to one [28,29], or by having recourse to an xFEM scheme [30–32], but with a loss of energy. The remeshing technique or a method implying a loss of energy can remain accurate when the crack introduction physically occurs for damage values close to one, but this is not necessarily the case for ductile materials for which the failure was observed experimentally for lower values of the damage. Finally the crack could also be introduced in a local CDM using an EFEM upon loss of ellipticity [33] or using the thick level set approach [34] in which case the damage becomes non-local in the sense of being averaged over a certain thickness in the wake of the front.