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Two field multibody method for periodic homogenization in fracture mechanics of nonlinear heterogeneous materials

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Abstract

This paper presents a new computational approach dedicated to the fracture of nonlinear heterogeneous materials. This approach extends the standard periodic homogenization problem to a two field cohesive-volumetric finite element scheme. This two field finite element formulation is written as a generalization Non-Smooth Contact Dynamics framework involving Frictional Cohesive Zone Models. The associated numerical platform allows to simulate, at finite strain, the fracture of nonlinear composites from crack initiation to post-fracture behavior. The ability of this computational approach is illustrated by the fracture of the hydrided Zircaloy under transient loading.

Keywords: Periodic homogenization; Frictional cohesive zone model; Dynamic fracture; Zircaloy-4

1. Introduction

The dynamic fracture of heterogeneous materials (composites, Functionally Graded Materials, porous materials) is a challenging problem in many engineering fields [1]. Due to the presence of heterogeneities, the pertinent scale to analyse the ultimate overall properties of such materials, as the effective dynamic fracture toughness, is the microscopic scale. At this scale, various mechanisms of nonlinear damage have to be invoked: void growth and coalescence, crack initiation and branching, mixed mode crack growth at the interface between the different phases, post-fracture frictional contact on the crack lips. A convenient numerical modeling of the dynamic fracture of the heterogeneous materials has thus to be able to deal with nonlinear and non-smooth volumetric and surface behaviors at the microscale.

In the frame of the French ''Institut de Radioprotection et de Sûreté Nucléaire'' (IRSN) research program on nuclear fuel safety under accident conditions, a new computational micromechanical approach has been developed to analyse the effects of the microstructure heterogeneity on the overall material behavior. The

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micromechanical approach rests on an extension of the standard periodic homogenization based both on the concept of Frictional Cohesive Zone Model (FCZM) and on a multibody method in the context of the Non-Smooth Contact Dynamics (NSCD) [2,3].

The FCZMs allow the simulation of crack initiation, crack propagation and post-fracture non-smooth behavior on the crack lips such as frictional contact [4,5]. These models consist in a softening traction–separation relation on the crack lips within a multibody framework: each mesh is considered as an independent body connected to another by nonlinear and non-smooth relations [6,7]. Since velocity can become discontinuous during dynamic fracture [8], the NSCD approach [9,10] is used to treat the post-fracture frictional contact without any regularization nor penalization.

The effective properties related to fracture mechanics are obtained by periodic numerical homogenization. The standard periodic problem [11,12] is extended to the multibody approach. The Finite Element formulation becomes a two field Finite Element formulation, including a periodic displacement field and an average deformation gradient field. The NSCD framework is thus extended to these fields introducing a new discrete mapping.

The associated numerical platform is composed of three libraries with Object-Oriented Programming: a Fortran90 library dedicated to surface behaviors related to FCZM in the NSCD approach (LMGC90 [13]), a C++ library dedicated to periodic Finite Element modeling (PELICANS [14]) and a C++ library dedicated to bulk constitutive models (MatLib [15]). This software allows simulating the fracture of the heterogeneous materials at finite strain.

This paper focusses on the ability of the proposed two field multibody method dealing with the overall fracture properties of heterogeneous materials. The questions related to the cohesive-volumetric finite element scheme – in particular, to the difficulties often reported in the literature (mesh sensitivity, crack path, dependence of the crack speed to the loading rate, etc.) – are out of the scope of the present paper and are addressed in a forthcoming paper. However, some hints are given on the relative independence of the overall fracture properties. The ability of the software and of the proposed strategy is illustrated by the fracture of a heterogeneous material, the hydrided Zircaloy-4, under transient loading. The effective properties are determined on random periodic representative volume element.

2. Fracture modeling

2.1. Multibody approach

The dynamic fracture of heterogeneous materials is studied through a micromechanical modeling based on a multibody concept and FCZM. Each element of a Finite Element mesh is considered as an independent body connected to each other with mixed interface relationship (see Fig. 1). The overall progressive damageable behavior is thus obtained by coupling (see Fig. 2):

- The *volumetric* behavior inside the meshes, describing the behavior without any damage.
- The FCZM *surface* properties between the meshes, taking damage processes into account.

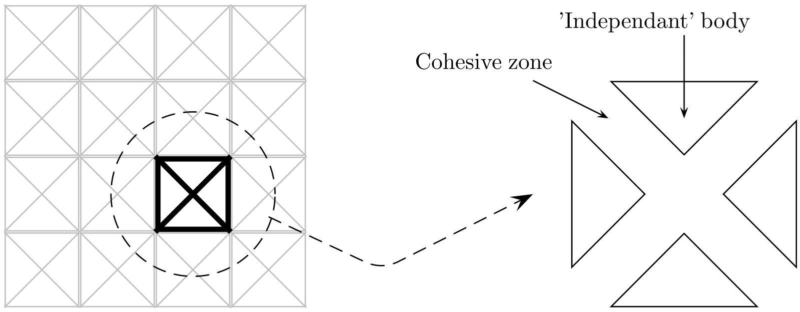

Fig. 1. Multibody strategy: each finite element is a body.