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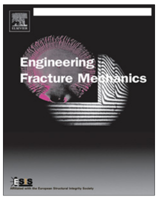

Phase field modeling of hydraulic fracturing with interfacial damage in highly heterogeneous fluid-saturated porous media

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ABSTRACT

In this work, we propose an extension of the phase field model for the modeling of hydraulic fracturing or cracking in heterogeneous saturated porous media. The involved extensions comprise: (a) taking into account interfacial damage between the inclusions and the matrix; (b) modeling fluid flow within both matrix cracks and interfacial cracks; (c) the possibility to handle geometries of the heterogeneous media in the form of regular grids of voxels e.g. as obtained from experimental imaging techniques. The developed numerical framework is based on the phase field method with a regularized description of both bulk and interface discontinuities, extended to a fully coupled hydro-mechanical framework. Both 2D and 3D examples are presented for hydro-mechanical microcracking initiation and propagation in voxel-based models of complex heterogeneous media with interfacial damage between the inclusions and the matrix.

1. Introduction

The computational modeling of fracturing in fluid-saturated porous media is of essential importance for numerous practical applications in geotechnical, environmental, petroleum engineering and biomechanics. Typical applications include the caprock integrity during the geological gas storage [47], nuclear waste disposal and hydraulic fracturing for oil and gas extraction. The computational modeling of hydraulic fracturing has attracted a special research attention due to the growing interest of the petroleum industry (see e.g. [3]). To optimize the hydraulic fracturing processing so as to maximize the extraction while preventing potential environmental contamination, developing an efficient and robust numerical methods for the modeling of the hydraulic fracturing processing is of primary importance.

Attempts to provide analytical solutions for the hydraulic fracturing problem can be found e.g. in [24,48,16,14,25]. The earliest work on numerical modeling of hydraulic fracturing can be traced back to Boone and Ingraffea [6], who combined the finite element method and the finite difference method to solve the poroelasticity problem, where the fracture was modeled by a cohesive zone on an assumed crack path. Since then, several methods have been developed to simulate the hydraulic fracturing or crack propagation in fluid-saturated porous media such as the cohesive zone model, adaptive meshing strategies [45,46], approaches based on lattice, particle models, or discrete elements [12,51,19,52,20,43], extended finite element method (XFEM) for geometrically linear setting [13,44,37,36,21], or XFEM for nonlinear setting at finite strains [23].

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An alternative simulation approach to fracture, namely the phase field method proposed by Francfort and Marigo [15], Bourdin et al. [8], Hakim and Karma [22], Miehe et al. [32,28], Borden et al. [7] (only to name a few) has shown promising computational advantages in handling very complex crack topologies and has been recently adapted in a multi-physics framework (see e.g. [31,27,29,54,9]). In this context, the sharp crack discontinuities are regularized by a diffuse phase field approximation within a continuum formulation, making it very flexible to handle crack nucleation, multiple crack fronts, cracks merging and branching in both 2D and 3D without ad hoc numerical treatment (see e.g., Nguyen et al. [41,40,39]). The phase field approach to fracture is consistent with brittle fracture through variational methods based on energy minimization as shown in [15]. This technique has been applied for the first time by Chukwudozie et al. [11] to hydraulic fracturing with the assumption of linear elastic and impermeable matrix. Phase field hydraulic fracturing of fluid-saturated porous media has been recently developed by Wheeler et al. [53] and Mikelić et al. [33,34] within the Biot's geometrically linear framework at small strains. More recently, Miehe et al. [30,29] have introduced a full variational framework for phase field fracture within a geometrically nonlinear framework of poroelasticity at finite strains [5].

The above mentioned contributions dedicated to phase field modeling of hydraulic fracturing all assume a homogeneous porous medium that can be macroscopically represented using Biot's theory. However, several potential applications of fracture due to pressurized water imply heterogeneous media. In [35,26], the effects of heterogeneities in phase field hydraulic fracture models were taken into account by local variations of mechanical properties. The most obvious application of fluid driven fracture in the presence of *aggregate-type* inclusions concerns the petroleum engineering and the unconventional oil and gas production in shale formations by hydraulic fracturing. The microstructure of oil and gas shales generally consists of a clayey matrix and inclusions of various minerals, including quartz and calcite. Another potential application concerns the safety analysis of nuclear waste disposal in claystones (similar microstructure as shales). The temperature increase resulting from the storage of high activity nuclear waste leads to a thermal pressurization of the pore fluid in the low permeability claystone, mainly due to the discrepancy between the thermal expansion coefficients of the pore fluid and the one of the porous matrix [17]. In fact the thermal expansion of water is almost one order of magnitude higher than the one of most solids. A temperature increase in a low permeability fluid saturated porous material results in a short term pore pressure increase, which can potentially yield to initiation and propagation of cracks in the claystone host rock, which similar to the shales, is composed of a clayey matrix and different mineral inclusions [4]. A similar phenomenon of thermal pressurization of the pore fluid can occur in cement based materials and concrete structures, as for example in nuclear waste disposal projects when the waste is covered by cement based materials or in the concrete structure of nuclear reactors. The cement paste has a particularly high thermal pressurization coefficient [18] and a quite low permeability. Therefore, a temperature increase results in a pore pressure increase and can potentially lead to generation and propagation of cracks. One may also think of similar thermal pressurization phenomenon in concrete subjected to fire.

In this work, we propose an extension of the phase field model for the modeling hydraulic fracturing or cracking in heterogeneous saturated porous media. The involved extensions comprise: (a) taking into account interfacial damage between the inclusions and the matrix; (b) modeling fluid flow within both matrix cracks and interfacial cracks; (c) the possibility to handle geometries of the heterogeneous media in the form of regular grids of voxels e.g. as obtained from experimental imaging techniques. The developed numerical framework employs the phase field method with a regularized description of both bulk and interface cracks, extended to a fully coupled hydro-mechanical framework. More specifically, the generalized Biot's linear theory has been adopted to model the deformable porous media combined with phase field fracture modeling and interfacial damage. The discontinuous crack topology is regularized by a continuous phase field and its evolution is driven by a threshold-based criterion in terms of the effective stress related to the solid skeleton of a fluid-saturated porous medium. The jumps at the interfaces between the porous matrix and the inclusions are also described by a regularized approximation. Displacement jumps result in additional anisotropic permeability for the assumed of Poiseuille-type fluid flow within the fracture. Note that in our framework the fluid can pass within the matrix cracks as well as within interface cracks.

The paper is organized as follows. In Section 2, we introduce diffuse approximations for cracks and interface using the phase field method. In Section 3, the phase field modeling of hydraulic fracturing with interfacial damage in heterogeneous media within the Biot's macroscopic continuum framework is presented. Section 4 provides the space-time discretization strategy and the staggered solution scheme for the updates of the crack phase field and the coupled displacement-pressure problems. Finally, we validate in Section 5 the proposed method by benchmark tests and practical examples involving interfacial cracking in pixel/voxel-based models of heterogeneous media.

2. Diffuse approximation of discontinuous fields

Let $\Omega \in \mathbb{R}^D$ be an open domain $D = 2, 3$ describing a heterogeneous medium composed of a homogeneous porous matrix embedding elastic inclusions. The external boundary of Ω is denoted by $\partial\Omega \in \mathbb{R}^{D-1}$. The internal interfaces between the porous medium and the inclusions are collectively denoted by Γ^I. Cracks which may propagate in the porous medium and pass through the interfaces as depicted in Fig. 1 are collectively denoted by Γ. In this work, we adopt the framework proposed in [38,1,32] for a regularized representation of discontinuities extended to interfaces as in [42]. In this regularized framework, the cracks are approximately represented by a scalar phase field $d(\mathbf{x}, t)$ and the interfaces by a fixed scalar function $\beta(\mathbf{x})$.