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Thermodynamic framework for non-local transport-damage modeling of fluid driven fracture in porous media

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A B S T R A C T

We present a novel non-local damage transport model for hydraulic fracture in porous media. The new model is sought to provide an enhanced description for the long-range damage and transport interactions in the fracture process zone. The non-local model is derived from thermodynamic principles, where a new thermodynamic potential expression for non-local transport is introduced. The thermodynamically consistent model is reduced to a gradient non-local permeability relationship that simultaneously provides a non-local transport description and regularized damage growth via a permeability-stress relationship. The analogy of the proposed model to Darcy-Brinkman fluid flow is demonstrated and discussed. A monolithic 3-field $(u - P - \tilde{\kappa})$ mixed finite element framework is then used to discretize and solve the nonlinear coupled physics poromechanics problem. The hydraulic fracture continuum models previously presented in the literature rely on using different fluid flow laws inside and outside the fracture zone, which introduces a discontinuity in the continuum model. Our model prescribes Darcy type fluid flow all over the domain with a non-linear permeability constitutive law that allows for elevated fluid velocity in the crack zone, which preserves the continuity of all quantities within the domain. The numerical examples confirm the capability of the proposed model in capturing the essential features of hydraulic fracture simulation. The significance of the non-local transport modeling is demonstrated through modeling hydraulic fracturing in materials with pre-existing high permeability zones. The incorporation of non-local transport effects in hydraulic fracture modeling is proved to uncover possible flow paths through pre-existing high permeability zones. The proposed model can act as a platform for quantifying the fluid leak-off from hydraulic fracture and can be further used to analyze the hydraulic fracture interaction with neighboring geological material.

1. Introduction

1.1. Hydraulic fracture modeling

In the last few decades, fluid driven fracture in porous media has become a prominent research topic due to its wide range of applications, such as: geomechanics,[1,2] glaciology[3] and biomechanics.[4,5] In standard linear poroelasticity,[6] the bulk stiffness, permeability and other physical properties of the solid-fluid mixture are assumed to be constant. While this assumption may be valid in limited cases where the mechanical deformation and fluid flow processes do not lead to changes in the properties of the mixture,[7] it is not the case when fracture processes play a role. For example, in cases of extreme loading, such as hydraulic fracture, a more general framework needs to be developed to capture the changes in the characteristics of the solid deformation and fluid flow in porous media due to fracture. A successful and more general model of poroelastic media should be capable of modeling, at least, the following key physical processes. **First, variation of the porous solid material properties:** under larger stresses/strains, the mechanical behaviour of solid grains becomes non-linear and may experience softening and/or irreversible deformation. **Second, variation of the fluid flow properties due to damage of the porous solid:** degradation of the solid material properties may lead to geometric changes in the mixture i.e. a space that was filled by the intact solid becomes available for fluid flow; thus leading to increase in permeability. In the cases of hydraulically driven cracks, the permeability increase becomes extremely important as it provides the mechanism by which fluid displaces solid material in the mixture. **Third, the effect of solid degradation on the solid-fluid interaction mechanisms:** the changes in solid stiffness affect the solid compressibility, which in turn affects the solid-fluid interaction described by Biot's coefficient and modulus.

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The above-mentioned meso-scale processes (occurring at grain-scale) affect the macroscopic response of the porous media. The mechanical failure of solid grains and consequently fluid infiltration in the fracture process zone at the meso-scale leads to the formation of macroscopic hydraulically driven fracture. The introduction of a non-local length scale to the macro-scale model has been proposed in damage mechanics[8] and transport in porous media[9] to account for the long-range meso-scale processes occurring in the fracture process zone.

1.2. Literature review

Different approaches were presented in the literature to model hydraulic fracture of porous media. Current continuum based finite/boundary element models may be classified into discrete-crack methods and continuum damage based methods.

Discrete-crack methods are mainly based on Linear Elastic Fracture Mechanics (LEFM)[10,11] or cohesive zone methods[12,13] which extend LEFM to include traction-separation laws at the crack surfaces. These approaches were enhanced using Generalized/Extended Finite Elements (G/XFEM) to model more complicated crack paths in 2d and 3d.[2,14,15,12] These fracture mechanics approaches typically neglect the meso-scale crack formation processes around the macroscopic crack and ignore the effect of crack propagation on the solid-fluid interaction mechanisms in the crack vicinity. Cohesive zone models generalize LEFM based methods by introducing damage-like effects at the crack tip but fail to account for gradual failure in other regions of the domain.[16,17] In addition, another drawback of discrete crack modeling methods is the difficulty of tracking complicated crack topology e.g. curved cracks, crack coalescence, branching and crossing and 3D crack surfaces.[14,15]

Continuum modeling approaches for hydraulic fracture may be classified as damage mechanics based methods or variants such as phase-field methods. Local damage formulations assume that distributed microcracks and voids at the meso-scale can be captured at the macro-scale by an internal damage variable which degrades the material's stiffness at a specific material point.[8,18–20] Considering discretized numerical solutions, local damage models exhibit loss of ellipticity of the governing equations leading to lack of uniqueness of the solution and the numerical solution suffers from mesh dependence.[21] Different solution techniques were proposed to overcome the problems introduced by local damage, including: integral[21,18] and gradient-type[22–25] non-local damage models. A fracture mechanics based damage model was first introduced for modeling hydraulic fracture in.[26] A constitutive ductile damage model for hydraulic fracture in shale was proposed in.[27] Continuum damage modeling of hydraulic fracture was proposed by the authors to model water driven crevasse propagation in glaciers[3] and high pressure water driven failure of rocks.[28] The phase-field method,[29,30] which is a variant of non local continuum damage, was also used to model hydraulic fracture.[31–34]

Thorough analysis of hydraulic fracture interaction with surrounding geological media show that modeling the flow in the region surrounding the fracture is essential to the correct prediction of the propagation rate and direction of hydraulic fracture.[35,36] Previously proposed approaches encounter a challenge when modeling the fluid flow inside the fluid-driven crack. Fracture mechanics models assume the domain to be elastic or poroelastic, and use the fluid filled macroscopic crack to model hydraulic fracture. A Poiseuille's flow, which is an approximation of Navier-Stokes for laminar flow between two close plates, is typically assumed inside the crack, while Darcy flow is employed away from the crack. Similarly, current continuum models[31–34] also assume Poiseuille's flow or Stokes flow model inside the crack zone and therefore need to estimate fracture-width like quantities from their continuum models. In both cases, an artificial discontinuity is introduced due to the use of different flow laws in the same model, this discontinuity hinders convergence of non-linear solvers and leads to spurious pressure oscillations at the crack tip.[34] In addition, the estimation of the fracture width leads to several problems e.g. non-physical estimated quantities and discontinuity in fluid flow description due to the use of Poiseuille's flow inside the crack and Darcy's law in the intact domain. An alternative was presented in[28] which uses Darcy's law with variable isotropic permeability to describe fluid flow in the intact porous media and fracture zone. Hence, one flow model is used everywhere in the domain and the estimate of a fracture-width quantity is unnecessary. However, while the strain dependent permeability used in[28] was able to capture the higher fluid flow velocities inside the fracture zone, the fluid pressure did not localize in the crack zone in this approach.

Since the early works on poroelasticity by Terzaghi[37] and Biot,[6] Darcy's law has always been the most widely used transport law to describe the fluid flow within the porous media. Darcy's law is believed to be an efficient simplification of Navier-Stokes equations that is valid for laminar flow cases and low Reynolds number,[38,39] which is characteristic of many geomechanics applications. More recently, the idea of “non-local transport” started to get more recognition. In transport laws e.g. Fick's law and Darcy's law, the flux is a function of local flow properties (pressure gradient and conductivity or permeability); however, experimental and theoretical analyses prove that flow is affected by the medium properties within a neighboring length scale.[40,41] Different non-local transport formulations have been proposed in the fluid mechanics literature.[9,42–44] However, these models are formulated from a fluid mechanics point of view and employing them in solid mechanics applications e.g. fracture mechanics is not straightforward.[40]

1.3. Proposed model

In this paper, we introduce a novel derivation of a non-local damage-transport model starting from thermodynamic principles with application to hydraulic fracture problems. The proposed model presents several novel contributions: (a) a thermodynamically consistent framework for non-local damage and transport in porous media, (b) a fully continuum framework for modeling hydraulic fracture, where the same constitutive solid deformation and fluid flow laws are adopted over the entire domain, (c) introduction of stress-dependent anisotropic permeability for pressure localization, and (d) finite element implementation accounting for nonlocal permeability with application to hydraulic fracture problems.

The model proposed in this manuscript overcomes several drawbacks of the approaches currently present in the literature. First, the introduction of the non-local damage and transport allows the analysis to account for long-range interactions with surrounding geological media. The numerical results show that this feature of the model can be used as a basis for the quantification of fluid leak-off and interaction with pre-existing fractures. Second, the adoption of non-linear permeability based version of Darcy's law in this model leads to a unified continuum model that is compatible in the entire domain, hence, avoiding crack tip discontinuities encountered in previous models. Third, the regularized permeability formulation alleviates mesh sensitivity issues and leads to reliable numerical results.

The manuscript is organized as follows: first, in Section 2, the governing balance laws are derived from a general thermodynamic framework which leads to the nonlocal damage-transport governing PDEs. Under certain assumptions, detailed in Section 3, the derivation of the non-local model reduces to a non-local gradient permeability model similar to that introduced in[28] that was motivated from volumetric averaging homogenization. The reduced model is derived assuming the following: 1) non-local transport arises from non-local permeability only, and 2) damage and permeability have the same length scale and are driven by the evolution of the same equivalent stress measure. Later in Section 4, the constitutive relationships defining damage and anisotropic permeability in terms of equivalent Hayhurst stress[45] are introduced. The FEM discretization and solution algorithm are briefly described in Section 5. Numerical examples in