International Journal of Plasticity 59 (2014) 199–212

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

A continuum damage failure model for hydraulic fracturing of porous rocks

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ARTICLE INFO

Article history:
Received 10 December 2013
Received in final revised form 31 January 2014
Available online 21 March 2014

Keywords:
Poroelasticity
Rock Mechanics
Hydraulic fracturing
Rock continuum damage mechanics

ABSTRACT

A continuum damage mechanics (CDM) based constitutive model has been developed to describe elastic, plastic and damage behavior of porous rocks. The pressure sensitive inelastic deformation of porous rocks together with their damage mechanisms are studied for drained and undrained conditions. Fracture mechanics of microcrack and micro-void nucleation and their coalescence are incorporated into the formulation of the CDM models to accurately capture different failure modes of rocks. A fracture mechanics based failure criterion is also incorporated to accurately capture the post fracture crack advances in the case of progressive failures. The performance of the developed elastoplastic and CDM models are compared with the available experimental data and then the models are introduced into a commercial software package through user-defined subroutines. The hydraulic fractures growth in a reservoir rock is then investigated; in which the effect of injection pressure is studied and the simulations are compared with the available solutions in the literature. The developed CDM model outperforms the traditional fracture mechanics approaches by removing stress singularities at the fracture tips and simulation of progressive fractures without any essential need for remeshing. This model would provide a robust tool for modeling hydraulic fracture growth using conventional elements of FEA with a computational cost less than similar computational techniques like cohesive element methods.

1. Introduction

Damage process through micro-cracking and -voiding is identified as one of the main reasons for nonlinear deformation and failure of brittle granular materials like rocks, concrete, and ceramics (Bažant and Planas, 1998; Voyiadjis et al., 2005). Two major consequences of formation of micro-cracks are material *softening* (additional compliance) and induced *anisotropy* due to the directional nature of the damage process. Extensive laboratory and theoretical studies have been conducted in the last half of the century to understand and predict this type of failure in different materials. These approaches range from methods explicitly considering the micro-cracks as single inclusion and non-interacting inclusions (Mura, 1987; Nemat-Nasser and Hori, 1993), to multiple interacting (Moschovidis and Mura, 1975), to homogenization (Doghri et al., 2010), and micromechanical techniques which consider the self-consistency (Budiansky and O'Connell, 1976; Needleman, 1987; Shojaei and Li, 2013; Bedayat and Dahi, 2014), or complimentary strain energy method (Sayers and Kachanov, 1991).

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http://dx.doi.org/10.1016/j.ijplas.2014.03.003

In the case of porous rocks, damage-related irreversible deformation may develop due to residual opening of micro-flaws after unloading, which may affect the hydraulic conductivity of the rock. Applying the above-mentioned methods for drained deformation of porous materials should be straightforward; however, there are many examples of failure of geomaterials in conditions different from drained conditions, where coupling between mechanical deformation and fluid pressure changes should be included. The true physics of this coupling is established in the theory of poroelasticity and poroplasticity (Biot, 1956a,b; Rice and Cleary, 1976). To describe the behavior of anisotropic porous material, (Thompson and Willis, 1991) have extended the Biot's theory to include the anisotropic material and hydraulic properties. This model was later adapted into a poroelastic damage, or more precisely a continuum damage mechanics (CDM) model, by Shao (1998). The main advantage of CDM based porous models is their capability to capture crack initiation, propagation, interaction and possible branching in an integrated framework, which allows material properties evolution during failure.

The mechanical behavior of the earth's shallow crust is complicated with elastic and plastic deformations which are coupled with pore fluid diffusion of infiltrated ground water and hydrocarbons. The porous rocks in this condition are saturated with liquid, i.e. undrained condition. Furthermore, the rock elements are under a compressive stress field from overlaying rocks. Failure and deformation mechanisms of rocks in the drained and undrained conditions have been under intensive research. For example, an asymptotic solution for crack growth in elastic–plastic undrained rock has been developed by Radi et al. (2002). Shao and coworkers have studied the elastoplastic deformation of rocks (Shao and Henry, 1991) and their damage mechanisms (Shao, 1998; Shen et al., 2013). Viscoplastic creep of rocks around a lined tunnel has been investigated by Cristescu (1988) and Krajcinovic and Mastilovic (1999) have developed statistical models of brittle deformation in rocks.

Non-local forms of damage mechanics have been developed to remove the mesh dependency in FEA problems, associated with the damage softening (Marotti de Sciarra, 2012; Voyiadjis and Faghihi, 2012; Voyiadjis and Mozaffari, 2013). The mesh deletion may result in strain-softening behavior, leading to strain localization, which is called *ill-posed* constitutive relations (de Borst and Sluys, 1991; Sluys and de Borst, 1994; Shojaei et al., 2012). This latter phenomenon results in a strong mesh dependency of the FEA in which the dissipated energies decrease upon the mesh refinement steps. This issue is usually alleviated by introducing a characteristic length into the CDM formulation. In FEA packages this characteristic length can be correlated to the element size, and the energy dissipated during the damage process is specified per unit area, not per unit volume (ABAQUS, 2011). Then the damage dissipated energy is treated as an additional material parameter and it is used to compute the displacement at which full material damage occurs. This formulation ensures that the correct amount of energy is dissipated and greatly alleviates the mesh dependency. Consequently the softening response of the constitutive law is expressed based on a stress–displacement relation, in which the displacement is computed from the energy descriptions, e.g. plastic and damage dissipation energies, instead of the *ill posed* constitutive relations.

Also CDM models for ductile material have been studied extensively in the literature, where various damage mechanisms depending on stress intensity, stress triaxiality and dynamic energy density are incorporated to study dynamic fracture, wear and cyclic loading problems (Malcher et al., 2012; Beheshti and Khonsari, 2011; Kruch and Chaboche, 2011; Aghdam et al., 2012; Brünig et al., 2013; Shojaei et al., 2013). Progressive failure analysis of polymeric matrix composites within CDM framework has also been a hot topic in recent years (Xu and Li, 2010; Li and Xu, 2011; Voyiadjis et al., 2011; Li and Shojaei, 2012; Naderi et al., 2012; Voyiadjis et al., 2012a,b,c; Hansen et al., 2013; Shojaei et al., 2012; Shojaei and Li, 2013; Kahirdeh and Khonsari, in press). Failure of granular material based on a Discrete Element Method has been investigated by Nicot et al. (2012), and stress and velocity profiles in well-developed dense granular flows has been studied by Kamrin (2010). In the case of Rock Mechanics Khan and co-workers have developed constitutive models to capture elasto-plastic behavior of Berea sandstone under a large range of confining pressure (Khan et al., 1991, 1992). A model for meso-scale plastic deformation of clayey rocks has also been developed by Shen et al. (2012).

This work aims to provide a computationally efficient approach to simulate complex pressure sensitive elastoplastic deformation of porous rocks coupled together with their mechanical and hydraulic driven damages. Due to the inherent microstructural anisotropy of the porous rocks, an anisotropic CDM framework is developed to take into account the interaction between mean stress and shear stresses in the dynamic fracture of rocks. It is shown that this developed theory performs quite well in capturing experimental data. To show implementation of this method, we considered a hydraulic fracturing problem as an example. Hydraulic fracturing is extensively utilized to enhance oil and gas productions in low permeability formations. A primary difficulty in hydraulic fracturing problems comes from the coupling of the fluid flow inside the fracture and the rock deformations, which provide crack openings. Unfortunately, analytical solutions are limited to simple geometries and limiting assumptions such as homogenous or isotropic medium. In the general case, solutions for fluid-driven fractures are tremendously difficult to construct even for simple geometries (Adachi et al., 2007). This difficulty is due to moving boundary conditions, non-linearity of the governing equation for fluid flow in fractures, high gradient of displacement near the fracture tips, and non-locality of the solution. Non-linearity comes from the fact that fracture permeability is a cubic function of the fracture width. Non-locality means that the fracture opening at one point is a function of fluid pressure at another point along the fracture. To address the above-mentioned challenges, several numerical methods using the finite element analysis (Dahi Taleghani and Olson, 2011; Sarris and Papanastasiou, 2012) and the boundary element methods (Cleary et al., 1983; Olson and Dahi Taleghani, 2009) have been proposed in the literature to model the hydraulic fracturing propagation. Methods like cohesive interface models have recently used in the literature to model failure propagation in the porous materials like hydraulic fracturing in rocks (Sarris and Papanastasiou, 2012), however, cohesive models only consider the solid part of the stress. In other words, the cohesive element technique is based on effective stress calculations for failure initiation and propagation. Therefore these models fail to predict changes in rock poroelastic properties like Biot coefficient