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A micromechanical analysis of the fracture properties of saturated porous media

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ABSTRACT

A two-dimensional single edge crack problem is employed to investigate the fracture behavior of saturated poroelastic media. The media are mimicked by a micromechanical model consisting of elastic matrix and square arrays of voids with prescribed uniform pore pressure. Finite element method is used to simulate the fracture responses of the model subject to remote stress and pore pressure loading. The stress extrapolation method is extended for the porous media to calculate the nominal stress intensity factor (SIF) from the crack tip stress field. By adopting the tensile strength criterion and assuming either brittle or ductile failure of the constituent solid skeleton of the porous media, lower and upper bounds of the fracture toughness are obtained. Theoretical expressions for the stress intensity factor and the toughness are derived, agreeing well with numerical results. The effects of the arrangement of pores and the non-uniform pore pressure on the cracking of porous media are discussed and are found to only have moderate effects on the obtained results.

1. Introduction

Porous media, such as wood, bone, sedimentary rock, and hydrogel, are widely available in nature and modern industry. Their microstructures usually contain both a solid skeleton and a moving pore fluid (either gas or liquid). A strong coupling may exist between the fluid flow and the elastic deformation of the solid skeleton (Biot, 1941; Rice and Cleary, 1976; Detournay and Cheng, 1993; Coussy, 2011). Under external loadings, the fracture of porous media is typically multiphysics coupled (Rice and Simons, 1976; Rudnicki, 2001; Exadaktylos, 2012). Furthermore, the microstructures, such as pores and micro cracks, have been found to have great effects on the mechanical behavior of porous media, especially the fracture behavior (Shafiro and Kachanov, 1997; Cramer and Sevostianov, 2009; Ponson, 2009; Nara et al., 2011, 2014; Ryvkin and Aboudi, 2011; Tokiwa et al., 2013; Tsusaka and Tokiwa, 2013; Zybell et al., 2014). A mutual understanding of the fracture behavior of porous media is of fundamental importance in fulfilling their applications and has received an increasing interest in recent years (Kovalyshen, 2010).

A number of theories have been developed for the elastic and non-elastic deformation of porous media (e.g., Biot, 1941; Rajagopal, 1995; Carmeliet et al., 2013). Among them, the theory of poroelasticity developed by Biot (1941) is well recognized in studying the elastic deformation of porous media. In its classical form, the theory is based on the principle of effective stress and the Darcy's law. The interaction between the pore fluid and solid skeleton is described through the pore pressure. Based on Biot's theory, Rice and Cleary (1976) reformulated the linear constitutive equations by using the more familiar constants (e.g. Poisson's ratio and Bulk modulus). Solutions of several typical poroelasticity problems were also obtained.

With the development of the poroelasticity, numerous studies indicate that the linear quasi-static poroelastic model be useful in a great variety of fields, such as materials engineering, geomechanics and biomechanics (Detournay and Cheng, 1993; Wang, 2000; Hong et al., 2008; Vermorel and Pijaudier-Cabot, 2014). For these fields, fracture problems are common and important, such as hydraulic fracture, bone fracture etc. Accordingly, initiation and extension of cracks in porous media is an area of both practical and theoretical interest (Kovalyshen, 2010; Barani and Khoei, 2014). For porous media, not only the external loadings but also the fluid pressure within pores promotes initial propagation of cracks. The flow of the pore fluid will be affected by the deformation of the solid skeleton. Meanwhile, the material properties of the solid can be changed with the diffusion of the fluid into the solid skeleton (Nara et al., 2012; Duda and Renner, 2013).

Based on the poroelasticity established by Biot (1941), Rice and his coworkers (Rice and Cleary, 1976; Rice and Simons, 1976)

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investigated the fracture behavior of a quasi-static semi-infinite shear crack in saturated porous media. Various boundary conditions of the pore pressure on the crack faces were considered and analytical solutions were obtained. Atkinson and Craster (1991) and Craster and Atkinson (1992) employed the integral transformation method to investigate the Mode I and II cracks embedded in poroelastic media. The crack tip pore pressure and stress fields were analytically obtained for both permeable and impermeable crack face boundary conditions. The effects of boundary conditions upon the stress intensity factor (SIF) and energy release rate were also quantified. Radi et al. (2002) considered the steady state crack growth in elastic–plastic porous media. In addition, studies of the thermally activated fracture in porous media were reported by Guarino and Ciliberto (2011).

As a typical example of poroelastic fracture, the problem of a stationary hydraulic fracture in a poroelastic medium is important in the unconventional oil and gas industry (Kovalyshen, 2010; Shojaei et al., 2014). A self-similar analytical plane strain solution for a hydraulic fracture propagating in a poroelastic media was obtained by Lenoach (1995). Adachi and Detournay (2008) presented an analysis of a hydraulic fracture embedded in permeable rock and obtained a multi-scale asymptotic solution of the crack-tip fields. A review of contributions in this area can be found in Huang et al. (2012).

The fracture behavior of porous media are complicated. In general, theoretical solutions are only available for limited boundary value problems. Consequently, numerical simulation methods, such as the finite element method (FEM) was employed to deal with more general poroelastic problems (Lewis and Schrefler, 1998; Ferronato et al., 2010). FEM has been successfully applied in the solution of problems in poroelasticity, especially in poroelastic fracture analysis (Adachi et al., 2007; Selvadurai and Mahyari, 1998; Shao et al., 2014). Selvadurai and Mahyari (1998) studied the plane strain steady crack extension in poroelastic media, in which the Galerkin technique was used and the SIF and the pore pressure fields ahead of crack front were successfully predicted. Recently, Shao et al. (2014) proposed an advanced numerical model to investigate the influence of heat transfer and fluid flow on crack propagation in multi-layered porous materials, with the extended Finite Element Method (XFEM).

In addition to theoretical and numerical studies, a number of experimental studies were conducted to improve our understanding on the fracture properties of porous media. For instance, Nara and his co-workers (2011, 2012, 2013, and 2014) reported experimental investigations on the influence of environmental factors (e.g., relative humidity, temperature, and electrolyte concentration) on the fracture behavior of rock, showing that crack growth in rock is greatly affected by the environmental factors. In addition, Huang et al. (2014) presented an experimental study for crack propagation in claystones to provide useful information for numerical simulation.

In the aforementioned studies, porous media are mostly treated as continuous media, with the influences of the microstructure ignored. In fact, the microstructure around the crack tip may have significant effects on the fracture properties (Shafiro and Kachanov, 1997; Cramer and Sevostianov, 2009; Ryvkin and Aboudi, 2011; Zybell et al., 2014). For example, Bazant (1984) discovered that the crack tip of concrete and rock was blunted by the existing of micro cracks (or pores). Similar effects were found in ductile metal because of the plastic zone. Smith (2005) showed that the role of pore located in the crack tip couldn't be ignored, regardless of how small it was. It's the so-called keyhole problem. Further study indicated that, when the pores exist at the crack tip, there exists competition between at least two mechanisms of a nominal toughness enhancement due to the crack blunting by the presence of pores and the weakening effect caused by the increasing volume fraction of pores (Leguillon and Piat, 2008). Although most of the aforementioned studies are on traditional continuous solids, their conclusions are believed to have implications on porous media. In saturated porous media, the microstructures, especially those located at the crack tip, can affect the fracture toughness and crack propagation of the porous media significantly. Therefore, it is desirable to quantify the fracture behavior of porous media, such as the influence of the microstructure and the coupling of fluid and solid on the fracture characteristics.

In this paper, a two dimensional micromechanical model is presented, which is capable of describing the influence of the microstructure of the solid skeleton, and the coupling of the fluid flow and the deformation of the solid skeleton. In this model, the interaction between fluid and solid is described by the pore pressure p, and the influence of the diffusion of fluid into solid skeleton is ignored. Based on the theory of linear fracture mechanics, theoretical expressions of the fracture parameters (e.g., SIF and fracture toughness) of porous media are obtained. In addition, the parameters are calculated numerically using FEM. The accuracy of the assumptions adopted in this model is discussed by varying the arrangement of the pores and the distribution of pore pressure. Finally, a few conclusions are drawn.

2. Micromechanical model

To investigate the fracture characteristics of saturated porous media, a two dimensional plane strain edge crack problem is considered, as shown in Fig. 1, where the porous medium is mimicked by periodically distributed pores embedded in an elastically brittle solid. A rectangular coordinate system oxy centered at the crack tip is defined and the geometrical parameters are also shown in Fig. 1, with a being the crack length, w and b being the specimen width and height, respectively, d being the pore diameter, and l being the lattice constant. Accordingly, the porosity is given by

$$\varphi = \pi d^2 / 4l^2 \tag{1}$$

It is noted that the pores in most porous media may have varying shapes and sizes and can be randomly distributed, giving rise to macroscopically isotropic behavior. For simplicity, the following assumptions are adopted in the model:

(i) The pores are circular and of the same size and are arranged in square arrays.
(ii) The saturated fluid in all pores is modeled by a prescribed constant pressure p. The effect of deformation upon p is neglected.
(iii) The crack is straight and passes through the centers of pores.

In addition to the square arrays of pores in Assumption (i), the effects of a different distribution of triangular arrays of pores upon the fracture behavior will be discussed later. Moreover, the pore pressure p in a porous medium is generally coupled with deformation. Assumption (ii) implies that only unidirectional coupling is considered here (i.e., p affects deformation, but not vice versa). As to Assumption (iii), it can be justified as follows. Note that the cross section between two pore centers is weakest. It can therefore be expected that crack advances along the weakest section. In addition to a remote uniaxial uniform loading σ_∞, the crack faces are also subject to pressure p.

3. Theoretical analysis

3.1. Stress intensity factor

According to linear elastic fracture mechanics (LEFM), the SIF in mode I of a homogenous elastic counterpart of Fig. 1 is given by