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Technical note

Behavior of propagating fracture at bedding interface in layered rocks

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ABSTRACT

The behavior of fracture penetration/abutment at interfaces in layered rock sequences is investigated numerically. Three types of fracture intersection with interface can be captured for a propagating fracture from the softer layer to a fracture-bound block in the stiffer layer: interface debonding/termination, interface debonding/penetration and penetration. The results indicate that there is a critical interface strength which controls the fracture patterns. If the interface strength is lower than the critical value, the propagating fracture would terminate at the interface and interface debonding then occurs as the tensile load further increases. If the interface strength is close to the critical value, a combining mode of interface debonding and fracture penetration can be observed. If the interface strength is sufficiently higher than the critical value, the propagating fracture directly penetrates the interface without any debonding along the interface. The evolutions of tensile stress and shear stress along the interface indicate that debonding along the interface can greatly reduce the load transferred from the softer layer and thus preclude the fracture penetration. A parametric study, including the tensile strength, layer thickness and fracture spacing is also discussed in detail.

1. Introduction

Open-mode fractures or joints are extremely common in the layered rocks (Zhang, 1995; Okko et al., 2003; Zhang and Jeffrey, 2006; Zhang et al., 2007; Ferrill et al., 2007, 2011, 2012; Li et al., 2012; Rustichelli et al., 2012; Steelman et al., 2015). These fracture networks are helpful to predict fluid flow paths in rocks and have become an important issue for geologists (Sturzenegger et al., 2007; Geshi, 2008). Many field observations and laboratory tests have demonstrated that branched and non-planar fracture growth is fairly extensive. The bedding interface in layered rocks can affect the fracture path because of changes in rock properties and in situ stress associated with layers. Therefore, bedding planes have been considered as a main factor contributing to the branching of the fractures (Warpinski and Teufel, 1987; Pollard and Aydin, 1988; Geshi et al., 2012).

In general, there are different types of interaction between a fracture and a bedding interface within layered sedimentary rocks. For a perfectly bonded interface or a strong one between layers, the fracture can penetrate the bedding interface directly without any deflection (Cook and Erdogan, 1972; Helgeson and Aydin, 1991; Gudmundsson and Brenner, 2001; Gudmundsson, 2011). Many studies have paid attention to fracture termination in strata consisting of brittle and ductile rocks (Helgeson and Aydin, 1991; Gross and Engelder, 1995; Ji and Saruwatari, 1998). For this case, a fracture can initiate in the stiffer layers and terminate at the contact with more ductile layers. Helgeson and Aydin (1991) indicated that the difference in stiffness and yield strength between layers determined the fracture path. Baer (1991) considered that the fracture termination resulted from interface slip along the interface and termination occurs only in case of extremely low normal stress or friction. Narr and Suppe (1991) observed that the fracture eventually terminated at the bedding interface and doubly or singly deflects into the layer parallel direction. Moreover, if the stresses along the interface are sufficiently high, a new fracture will initiate along the interface, which can lead to a step-over fracture. Helgeson and Aydin (1991) investigated the step-over fracture at layer interfaces in the field. They suggested that the distance between the propagating fracture and the position of greatest maximum tension along the interface determined the development of step-over fracture or penetration fracture.

Although most previous investigations have focused on fracture behavior within strata, those analytical models considered so far tend to oversimplify the rock as an elasticity medium (Baer, 1991; Helgeson and Aydin, 1991; Narr and Suppe, 1991). Fracture/interface interaction with frictional sliding, was theoretically investigated by Keer and Chen (1981) and Lam and Cleary (1984). However, the opening along the interface is not considered in these studies. Although both slip and opening at weak bedding contacts are considered by Fischer et al. (1995), Cooke and Underwood (2001), and Gudmundsson and Brenner (2001), the rock layers are also considered as elasticity medium. Few of the existing models can capture the ongoing process of the fracture/interface interaction, as well as the evolution of interfacial stress. In addition, most of existing models for fracture/interface interaction are assumed to be driven by the tensile stress from far field.

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However, once one fracture cut through the stiffer layer, far field stress can only be transmitted by the adjacent layer (Bai et al., 2000). And thus, fracture/interface interactions driven by stress from the softer layer are the most common cases.

In this paper, a numerical model is therefore developed to investigate the fracture/interface interaction (termination at, propagation through, and deflection) driven by stress from the softer layer.

2. Numerical model

2.1. Plastic-damage model for rock

The fracture evolution of a single fracture can be modeled using theoretical fracture mechanics; however, the growth for multiple fractures would be very difficult. Continuum damage mechanics was suggested as a method to describe the failure behavior of materials in response to irreversible deformation, and has become a popular method (Lyakhovsky et al., 1997; Ben-Zion and Lyakhovsky, 2002; Shcherbakov and Turcotte, 2003; Nanjo et al., 2005). In this study, also, a plastic damage model is used to model the progressive failure in the rock material with strain softening. The Drucker–Prager yield criterion is adopted, which is described as:

$$\alpha I + \sqrt{J_2} = k \tag{1}$$

where $I = \sigma_1 + \sigma_2 + \sigma_3, J_2 = [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]/6, \alpha = \frac{\sin\varphi}{\sqrt{3(3+\sin^2\varphi)}}, k = \frac{\sqrt{3}c\cos\varphi}{\sqrt{3+\sin^2\varphi}}$, c and φ are the cohesion and angle of internal friction.

The evolution of the yield surface is controlled by the hardening variables, ε_c^{pl} (effective plastic strain for compression) and ε_t^{pl} (effective plastic strain for tension). In terms of effective stresses, the yield function takes the form

$$F\left(\sigma^{ef}, \varepsilon^{pl}\right) = \frac{1}{1-\zeta}\left(q - 3p\zeta + \beta\left(\varepsilon^{pl}\right)\left\langle\sigma_{\max}^{ef}\right\rangle\right) - \frac{1}{1-\zeta}\gamma\left\langle\sigma_{\max}^{ef}\right\rangle - \sigma_c^{ef}\left(\varepsilon_c^{pl}\right) \le 0 \tag{2}$$

with

$$\zeta = \frac{(\sigma_{b0}/\sigma_{c0} - 1)}{2(\sigma_{b0}/\sigma_{c0} - 1)}, \ (0 \le \zeta \le 0.5) \tag{3}$$

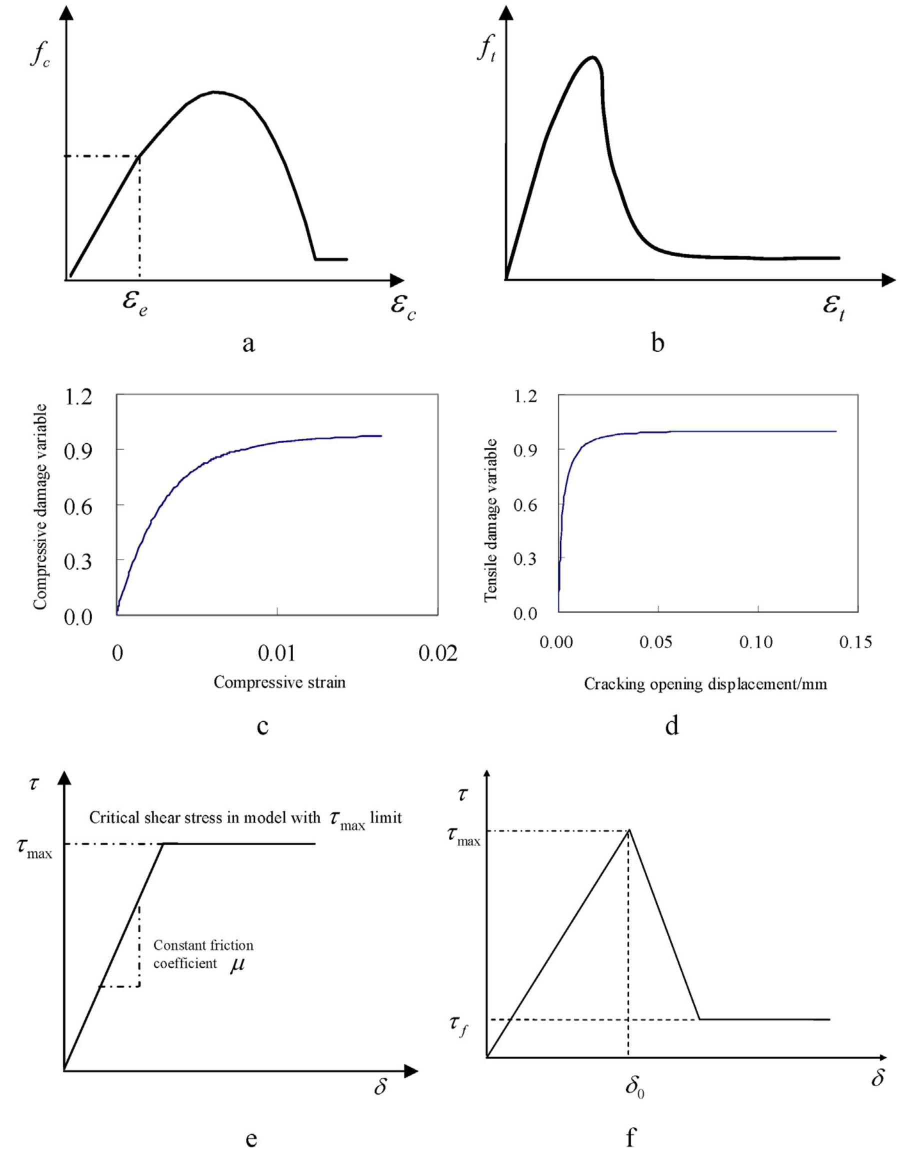

Fig. 1. Material models: a, rock in compression; b, rock in tension; c, damage variable in compression; d, damage variable in tensile; e, Column model; d, CZM model; f_c and ε_c are compressive stress and strain for rock under compressive; f_t and ε_t are tensile stress and strain for rock under tensile condition.