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Fracturing of viscoelastic geomaterials and application to sedimentary layered rocks

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ABSTRACT

We study analytically the behavior of a viscoelastic brittle solid loaded in tension, in which fractures may grow or not depending on the amount of dissipation allowed by the viscous behavior. We highlight a threshold in extension rate, below which the solid will not be fractured. Applied to sedimentary rocks, this model shows how viscous effects can prevent fracture growth in geological formations.
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1. Introduction

Sedimentary rocks form layers that are naturally fractured (Mandl, 2005; Gross and Eyal, 2007; Hanks et al., 1997; Pollard and Segall, 1987; Scholz, 2002) (Fig. 1) due to tectonic or gravity forces. For example, extensional fractures can be found in sedimentary basins in various tectonic environments, such as folds (Wennberg et al., 2006) or in area where *en-echelon* fractures develop in response to a propagating crack (Pollard et al., 1982). This fracturing process has important impact for the drainage of water or hydrocarbon fluids in geological reservoirs (Mandl, 2005; Olson et al., 2009) and controls potential leakage across cap rock layers. These fractures may be healed or sealed by the deposition of hydrothermal minerals (Mandl, 2005; Gratier et al., 2003; Smith and Evans, 1984; Holland and Urai, 2010) depending on the geological history. In clayey rocks, it is also observed that the fracture density is generally lower than in carbonates or sandstones (Mandl, 2005; Nelson, 2001; Wennberg et al., 2006). From a mechanical point of view, the study of rock fracturing is usually tackled by considering elastic behavior and some insight has been gained in geological interpretation by applying the elastic theory to the modeling of quasi-statically loaded joints, veins or dikes (Pollard and Segall, 1987). However, geological loadings can be long lasting processes, during which geomaterials may present a time-dependent mechanical behavior such that part of the elastic energy provided by the loading to the geomaterial will be dissipated. For rocks with high viscosity coefficient, such as carbonates or sandstones, located in the first kilometers of the Earth's crust, joint networks are widespread because viscous dissipation cannot account for the increase of tectonic forces. There, fracturing occurs easily. For rocks with lower viscosity coefficient (and therefore higher viscous strains), such as clayey rocks, viscous dissipation may prevent fracture growth. This is because, on one hand, it is more difficult to develop tension stress and, on the other hand, even if a tension stress occurs, fracturing is inhibited by viscous effects if the imposed extensional rate is too small.

In the present study, we develop an analysis of fracturing for viscoelastic geomaterials and apply it to layered sedimentary rocks. The paper is very much focused on crack propagation induced by a mechanical loading. No coupling between sealing or healing processes with fracture propagation is considered; it is assumed that these processes occur later to the fracture growth. We investigate how viscous dissipation may inhibit fracture propagation. Instead of adopting the linear elastic fracture mechanics point of view, we consider, following NGuyen et al. (2010), the propagation of a single family of fractures, characterized by the same radius and crack aspect ratio into a viscoelastic medium, and adopt a damage point of view to describe their propagation (Kachanov, 1986; Allix and Hild, 2002; Dormieux et al., 2006). Our approach also refers to recent studies of damage rheological models that have been applied to describe how fracturing may process in geomaterials and rocks

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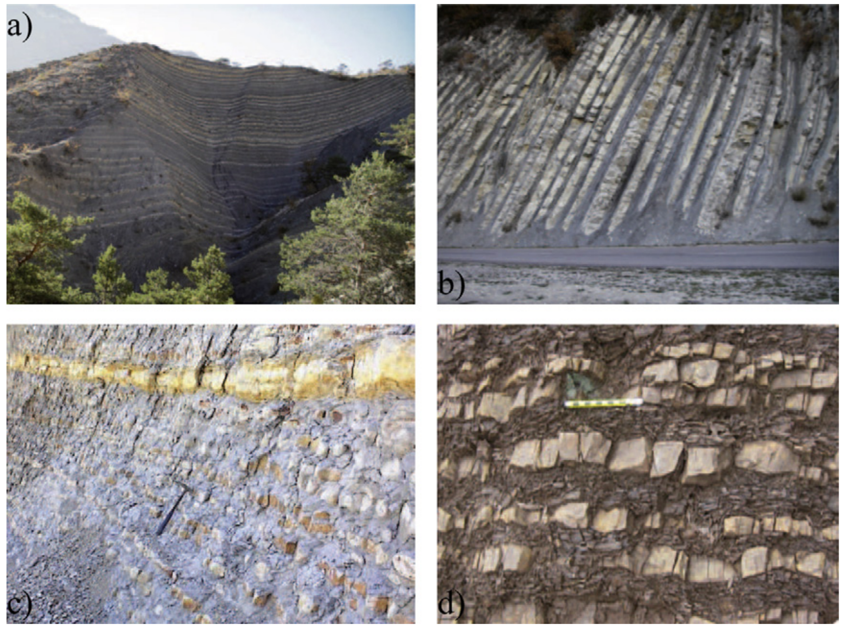

Fig. 1. Examples of sedimentary geological formations where stiff rock layers (carbonate, silts) are alternating with softer sediments (clays, marls). (a and b) Marl-limestone sedimentary strata of mid-Jurassic age in the Digne area (France). (c) Calcareous marl alternations of Cenomanian age in the Agadir region (Morocco). A hammer is shown for scale. (d) Chert sequences (alternations of silt and clay layers) of Jurassic age in the Marine Headlands formation, San Francisco basin. A pencil gives the scale.

(Lyakhovsky et al., 2011). However, we do not use a phenomenological viscous damage behavior law, but deduce this behavior law from a homogenization approach applied to viscous geomaterial.

In Section 2, we first analyze the propagation of a single fracture, and then consider the case of an infinite solid containing many fractures. Then, by a homogenization approach, we characterize the competition between viscous dissipation and elastic strain due to external loading during fracture propagation. In Section 3, this model is then applied to the case of geological sedimentary rocks by considering the development of joints and fractures in sedimentary layers (Fig. 1). Our main conclusion aims at quantifying how the interplay between external loading rate and dissipation into the rock controls fracturing.

2. Fracturing in a viscoelastic medium

2.1. Propagation of a single fracture

Classical linear elastic fracture mechanics (LEFM) aims at describing the propagation of a single plane fracture into an elastic medium (Leblond, 2003). A given fracture dissipates energy when it propagates. Let us consider a fracture of length l embedded into an elastic medium. The fracture propagates if the driving force of propagation $\mathcal{F}$ related to loading increase reaches a threshold G_f, called critical energy. The propagation criterion reads:

$$\begin{aligned} &\mathcal{F} - G_f \leq 0; \quad \dot{l} \geq 0; \qquad (\mathcal{F} - G_f)\dot{l} = 0 \\ &\text{and} \\ &\dot{l} > 0 \quad \Rightarrow \dot{\mathcal{D}} = G_f \dot{l} > 0 \end{aligned} \tag{1}$$

where $\dot{\mathcal{D}}$ denotes the dissipation associated with fracture propagation. In the elastic case, $\mathcal{F}$ is evaluated from the potential energy w, which is stored in the considered mechanical structure. For simplicity, let us assume that the loading is characterized by a prescribed kinematical loading parameter $\mathbf{E}$. In this case, the potential energy is equal to the elastic energy and the driving force of the propagation is the rate of energy release given by:

$$\mathcal{F}(l, \mathbf{E}) = -\frac{\partial w}{\partial l}_{|\mathbf{E}}(l, \mathbf{E}) \tag{2}$$

In a viscoelastic medium, the dissipation is not only due to fracture propagation, but also due to viscous effects. Denoting the viscous strain field $\{\boldsymbol{\varepsilon}^v(\boldsymbol{x}, t)\}$ in the considered structure (NGuyen et al., 2010; NGuyen, 2010), the dissipation takes the form:

$$\dot{\mathcal{D}} = -\frac{\partial w}{\partial l}_{|\mathbf{E},\{\boldsymbol{\varepsilon}^v\}}(l, \mathbf{E}, \{\boldsymbol{\varepsilon}^v\})\dot{l} - \frac{\partial w}{\partial \{\boldsymbol{\varepsilon}^v\}}_{|\mathbf{E},l}(l, \mathbf{E}, \{\boldsymbol{\varepsilon}^v\})\{\dot{\boldsymbol{\varepsilon}}^v\} \tag{3}$$

The second term in (3) represents the viscous dissipation. The driving force of propagation has to be evaluated for a fictitious fracture length increment for the current values of $\mathbf{E}$ and of the viscous strain field $\{\boldsymbol{\varepsilon}^v\}$:

$$\mathcal{F}(l, \mathbf{E}, \{\boldsymbol{\varepsilon}^v\}) = -\frac{\partial w}{\partial l}_{|\mathbf{E},\{\boldsymbol{\varepsilon}^v\}}(l, \mathbf{E}, \{\boldsymbol{\varepsilon}^v\}) \tag{4}$$

The propagation criterion can then be written on $\mathcal{F}$ (NGuyen et al., 2010):

$$\mathcal{F} < G_f \quad \Rightarrow \dot{l} = 0; \qquad \mathcal{F} = G_f \quad \Rightarrow \dot{l} > 0 \tag{5}$$

2.2. Propagation of damage in an elastic layer with parallel fractures

Instead of considering a single fracture, we consider now a set of parallel circular fractures with same radius l, crack aspect ratio and normal direction e_1 embedded into a homogeneous elastic matrix. The fracture density is denoted by N. The structure under consideration is a representative elementary volume (*r.e.v.*) of the fractured medium and the loading parameter is the macroscopic strain tensor. This description assumes that, initially, a few cracks of small size (i.e. flaws) are present in the solid and that they could grow. We do not go into the description of nucleation of fractures (see for example Leguillon, 2002).

To begin with, the homogenized behavior of this medium can be determined by Eshelby-based homogenization schemes

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