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A numerical study of fracture spacing and through-going fracture formation in layered rocks

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ABSTRACT

Naturally fractured reservoirs are an important source of hydrocarbons. Computational models capable of generating fracture geometries according to geomechanical principles offer a means to create a numerical representation of a more realistic rock mass structure. In this work, the combined finite-discrete element method is applied to investigate fracture patterns in layered rocks. First, a three-layer model undergoing layer normal compression is simulated with the aim of examining the controls on fracture spacing in layered rocks. Second, a seven-layer model with low competence contrast is modelled under direct tension parallel to the layering and bending conditions with the focus on investigating through-going fracture formation across layer interfaces. The numerical results give an insight into the understanding of various mechanisms that contribute to fracture pattern development in layered rocks.

1. Introduction

Naturally fractured reservoirs around the world are an important source of hydrocarbons. The difficulty in characterising such reservoirs is mainly attributed to the lack of sufficient sub-surface data to create realistic fracture network models (Nelson, 2001). The first fracture network models simulated by Priest and Hudson (1976) provided a basis for the development of Discrete Fracture Networks (DFNs), which are now widely used to estimate permeability in reservoir engineering (e.g. Min et al., 2004). Although DFNs have brought many benefits to reservoir engineers, they lack certain mechanically realistic fracture relations, such as cross-cutting, branching, and truncation; these relations, however, have a significant impact on the bulk flow and geomechanical properties of a reservoir. Understanding mechanisms and processes of fracture pattern formation can help to predict fracture characteristics in different stress regimes. One study area of great importance is the research of fracture development in relation to layered rocks to understand the role of fractures in vertical fluid migration across and within sedimentary rock layers (Bai et al., 2000b; Becker and Gross, 1996; Doolin and Mauldon, 2001; Helgeson and Aydin, 1991).

A considerable amount of literature exists on the geological setting and stress regimes in sedimentary rock that generate brittle and ductile structures as a consequence. A good discussion of the mechanical principles and concepts used to analyse geological structures including those mentioned below can be found in the book by Price and Cosgrove (1990). Sedimentary sequences in reservoir basins at different stages in their geological evolution to the present day may have been exposed to phases of deformation involving both layer extension and layer compression. Research on layered rock (Wu and Pollard, 1995) concluded that opening-mode tensile fractures are a common occurrence, and these are often confined and terminated by layer boundaries. However, sometimes through-going fractures are observed which penetrate many layer boundaries (Finn et al., 2003; Gross and Eyal, 2007). The mechanisms allowing this significant pathway for fluids to develop are not well understood and are the subject of great interest to structural geologists and reservoir engineers concerned with the integrity of cap rock.

In this work the focus is on the formation of tensile fractures in layered rocks. Such multi-layer systems appear to have been subjected to direct layer parallel tensile stresses. Although intuition might suggest all three principal stresses in the ground will be compressive ($\sigma_1 < 0$, $\sigma_2 < 0$, and $\sigma_3 < 0$; it should be noted that the engineering mechanics sign convention is used in this paper, which means tensile stress is positive and compressive stress is negative), there is a range of circumstances in which this is not so and tensile stresses initiate geological structures. One example is a half-graben basin overlying a major listric, i.e. upward steepening fault (Fossen, 2010; Schlische, 1991). In such basins a roll-over anticline forms in the downward warping upper sequence, where direct tensile stresses build up in the multilayer sequence, as it is

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forced to stretch and fill the missing space. Another is the stretching of a sequence overlying an ascending diaper, e.g. a salt dome structure (Schultz-Ela et al., 1993). Also, a very common occurrence even to considerable depths in a reservoir is where, e.g. due to rapid sediment burial, the elevated fluid pressures may exceed the value of the applied maximum principal stress σ_1. Therefore, the maximum effective principal stress, i.e. accounting for pore fluid pressure and governing tensile failure, is in many respects equivalent to a direct tension.

Whereas buckle folds are associated with layer parallel compression, forced folds develop by boundary deflections at high angles to the bedding and are more readily acknowledged as facilitating stretching. There are, however, interesting analogies between forced folds and unstratified buckle folds. Two end member models for the deformation within layers folded by buckling are Tangential Longitudinal Strain (TLS) and Flexural Flow (FF) (Ramsay, 1967). Tangential Longitudinal Strain (TLS) is deformation response where the material behaves isotropically; the outer-arc stretches, and the inner-arc compresses, and the neutral surface, which will move during fold amplification, separates the material being extended parallel to the compression direction from that which is being shortened. Flexural Flow (FF) is a deformation field that would be associated with a transversely anisotropic behaviour allowing easy shear parallel to the layering. When interface slip is activated as a dominant deformation mechanism in fold amplification, the term flexural slip is used.

These various settings that are known to initiate tensile fractures perpendicular to layer boundaries, namely direct layer parallel extension and forced folding, have informed the choice of boundary conditions that have been applied to the layered models in this research. A few numerical modelling studies have also been attracted by this problem. Bai and Pollard (2000a) simulated an elastic three-layer model, where vertical fractures were inserted in the central layer as pre-existing fractures. Tang et al. (2008) modelled the entire fracture evolution until saturation using a strain-dependent finite element based degradation model. The work of Bai and Pollard (2000a) and Tang et al. (2008) used two-dimensional models with the boundary condition in which only tensile stress directed parallel to the associated layers was applied. Discussion of the fracture evolution caused by layer normal compressive stress in layered rock, e.g. induced by overburden or burial, was outside the scope of their papers. Both of their studies assumed that the two materials across the layer boundaries were initially welded together, i.e. no slip or opening was permitted along the boundary. Interestingly, Tang et al. (2008) were able to show that delamination was almost certainly occurring in their simulations. Here delamination means the two sides of an interface between two adjacent layers have relative displacement. Slip between beds and on curved sections of otherwise planar faults contributes to pull-apart structures and thus slip between opposite sides of an interface cannot be considered negligible. A better solution to numerical modelling of layered rocks is to introduce discrete surfaces as layer interfaces and use contact mechanics to simulate the interaction of neighbouring layers at interfaces.

The objective of this paper is to investigate fracture spacing and through-going fracture formation in layered rocks by two-dimensional numerical simulations using the combined finite-discrete element method. The main novelty of using this numerical method is that layer interfaces can be explicitly represented by discrete surfaces with frictional properties and governed by contact mechanics laws, which is essential for accurate understanding of this problem but has been missing in previous research. The numerical study in this paper includes two parts. The first part focuses on examining the controls on fracture spacing to layer thickness ratio in a three-layer shale-limestone-shale sequence undergoing layer normal compression. The second part models through-going fracture formation in a seven-layer limestone sequence subject to direct tension and bending conditions with the focus on the fracturing behaviour across layer interfaces. As a non-traditional numerical method is used for this research, a brief introduction and two verification examples of the method are given before presenting the numerical results of layered-rocks.

2. Numerical method

Numerical methods provide important tools for the research of fracturing behaviour in quasi-brittle materials, e.g. rock, concrete, ceramics, etc. Many models have been developed in the field of computational fracture mechanics, such as linear and non-linear elastic fracture mechanics based methods (Bittencourt et al., 1996; Ingraffea and Manu, 1980; Swenson and Ingraffea, 1988), the extended finite element method (XFEM) (Belytschko and Black, 1999; Karihaloo and Xiao, 2003; Melenk and Babuška, 1996; Sukumar and Prévost, 2003), the cohesive-zone model (Bocca et al., 1991; de Borst, 2003) and meshless methods, such as the element free Galerkin method (EFGM) (Bordas et al., 2008; Fleming et al., 1997). Moreover, discontinuum-based numerical methods that are originally used for granular materials, such as the smoothed particle hydrodynamics (SPH) method (Das and Cleary, 2010; Gray et al., 2001; Ma et al., 2011) and the discrete element method (DEM) (Cundall and Strack, 1979; Morris et al., 2004; Shi and Goodman, 1985) have also become increasingly popular in fracture modelling. In actual numerical simulations of engineering applications, the choice of modelling approach should be based on the likely failure mechanism of the material, i.e. whether it is a failure of material, discontinuity or a combination of both (Coggan et al., 2014).

The numerical method used in this paper is the combined finite-discrete element method (FEMDEM) (Munjiza, 2004). The reason to choose this method is that it is capable of modelling mechanical behaviour both in the continuum domain (e.g. deformation and stress distribution) and across discontinuities (e.g. interaction between discrete layer interfaces). In this method, the whole domain is discretised by both discrete element meshes and finite element meshes. For example, in a layered system, each layer is a discrete element, and inside each layer there is a finite element mesh associated with it; in a two-dimensional domain, 3-node triangular elements are used for the finite element mesh. The transition from continuum to discontinuum, which gives an explicit geometric realisation of fracture patterns, is modelled through fracturing and fragmentation processes and controlled by a failure criterion. An explicit time integration scheme is used to calculate the deformed configuration. In the numerical results presented in this paper, the loading is slow enough so that dynamic effects can be neglected. The details of the FEMDEM method and its fracture model can be found elsewhere (Guo, 2014; Munjiza, 2004; Xiang et al., 2009) and here only some key aspects are briefly introduced.

2.1. Pre-failure

Before fractures initiating from stress concentrations or propagating from pre-existing crack tips, the domain is in a state of continuum deformation under external loading. The algorithms of stress calculation are implemented in a standard finite element formulation. The constitutive model used for 3-node triangular elements is a neo-Hookean viscoelastic material model (Bonet and Wood, 1997), so the Cauchy stress tensor $\mathbf{T}$ can be calculated as

$$\mathbf{T}=\frac{\mu}{J}(\mathbf{B}-\mathbf{I})+\frac{\lambda}{J}(\ln J)\mathrm{I}+\eta D \tag{1}$$

where μ and λ are Lamé constants, $\mathbf{B}$ is the Left Cauchy–Green strain tensor, J is the determinant of the deformation gradient ma-