Brittle fracturing at the laboratory to outcrop scale

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Introduction

Brittle fracturing is ubiquitous in the upper crust, and is a common feature associated with ore deposits. However, prediction of its initiation, development, and evolution, and of associated properties such as dilatancy, is remarkably difficult. This is a function partly of the variability of rock properties, and partly because we cannot see into specimens to see how they behave during physical deformation experiments. This is where computer experiments can provide such valuable information. In this case we look at the opportunities provided by a particle code for exploring microstructural changes during deformation. We validate the code against physical deformation experiments, use it to improve our understanding of rock behaviour during deformation, and apply it to shear zone evolution and fracture development at outcrop scale.

The development of fracture systems, shear zones, zoned mineral alteration systems (including ore bodies), and fluid percolation networks can all be thought of as emergent phenomena in geomaterials.

Emergence is a property of large dissipative systems driven far from equilibrium (see Kondepudi and Prigogine, 1998). The term refers to the spontaneous development of structure or patterning in a system that previously had been homogeneous. In such systems, intriguing patterning and order can be generated, both in time and space, in systems that otherwise one would expect to behave in uniform manners. This can commonly be represented as a symmetry breaking phase transition (see Sethna, 1992). A characteristic of such systems is that there are first order feedback relationships between a number of processes. Another important characteristic is that the resultant patterning occurs on a number of scales so that something of a fractal nature is developed.

Emergent behaviour is associated with **bifurcation** in the system of differential equations that describes the mechanics of the system. A classical simple example of bifurcation is the behaviour of the solutions to the equation 1 $d\alpha/dt = -\alpha^3 + \lambda\alpha$ where λ is a parameter such as amount of strain. When $\lambda<0$ there is only one real stationary state, $\alpha=0$; when $\lambda>0$ two real stationary states exist, $\alpha=\pm\sqrt{\lambda}$. $\lambda=0$ is a bifurcation point (see Figure 1a). The typical stress strain curve for a rock is an example of bifurcation behaviour (see Figure 1b). Here the material behaviour departs from homogeneous deformation to localised deformation at a bifurcation point determined by the amount of strain.

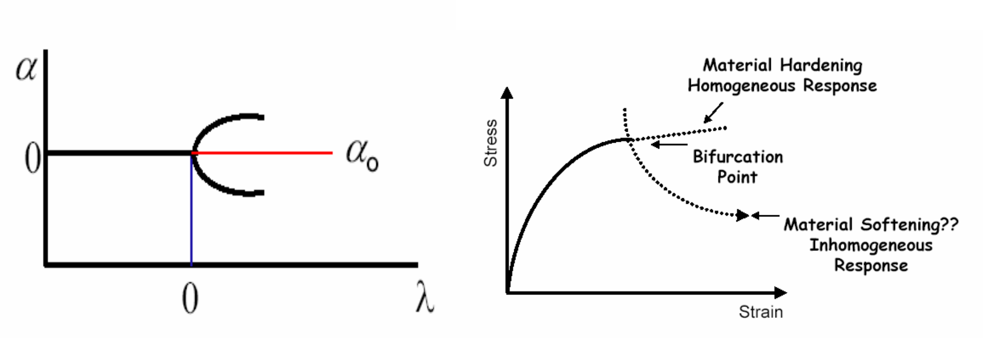

Figure 1. Bifurcation behaviour. (a) Behaviour of equation (1). (b) A typical stress strain curve showing the departure from homogeneous to localised deformation at a bifurcation point determined by the amount of strain.

The classical (engineering) description of materials is restricted to the detection of such bifurcation points in a linear stability analysis. In geology we are interested in the post failure evolution which we do by trading energy fluxes in a self-consistent particle simulation.

Fracture development at laboratory scale

In laboratory experiments, it is well known that homogeneous loading of a homogeneous specimen does not continue for ever. At some stage in the process, as noted above, the system bifurcates, and localisation of the deformation occurs. This phenomenon has been noted for various materials and environmental conditions, being observed as buckling, shearing, and the 'elephant's foot' instability. These represent emergent phenomena; which arise spontaneously from a material and loading conditions with no a priori similar structures. How can we duplicate this phenomenon *ab initio* in virtual rock experiments?

We initiated a suite of experiments for validating a particle flow code (PFC, Cundall, 2000; Cundall, 2001; ITASCA, 2003) against physical deformation experiments, in this case the triaxial experiments of Edmond and Paterson (1972), for various materials, including Gosford sandstone. The initial experiments were sufficiently encouraging for us to attempt validation of the code in a plane strain biaxial experiment against the experiments of Ord (1991). The same phenomenon, localisation of the deformation into a shear zone, emerged from a numerical specimen undergoing uniform loading (Figure 2). This behaviour is not promoted in any way through special conditions within the experiments; no notches were cut, there were no seeds of particularly weak zones.

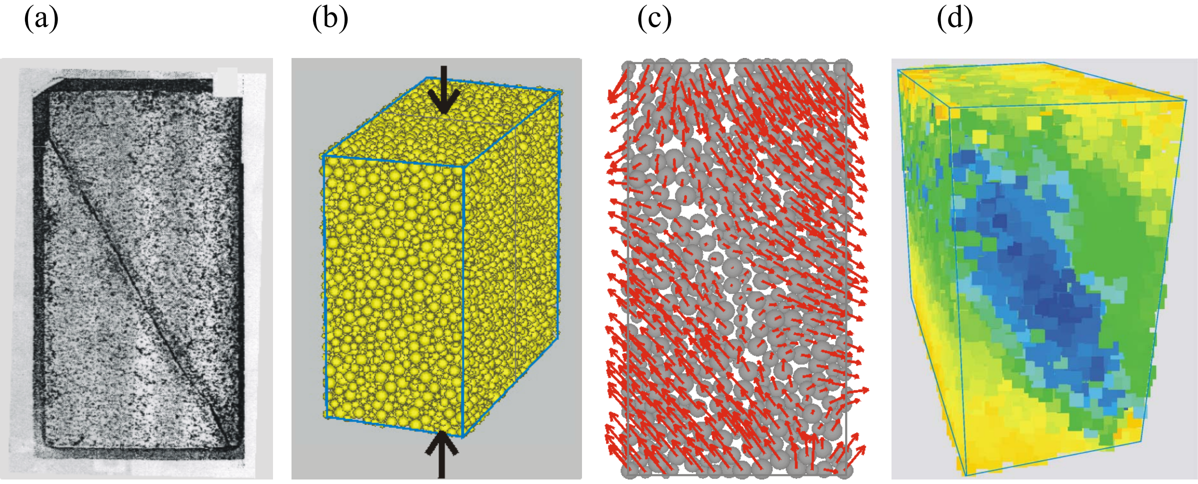

Figure 2. (a) End result of localization of deformation and failure in Gosford sandstone (Ord 1991). Dark areas either side of fracture represent dilated zone, now filled with epoxy. (b) Equivalent numerical experiments using PFC3D. (c) Displacement vectors displayed for plane in centre of the numerical models, highlighting the location of a shear zone. (d) Square root of the horizontal displacement contour (blue – minimum; yellow to orange – maximum).

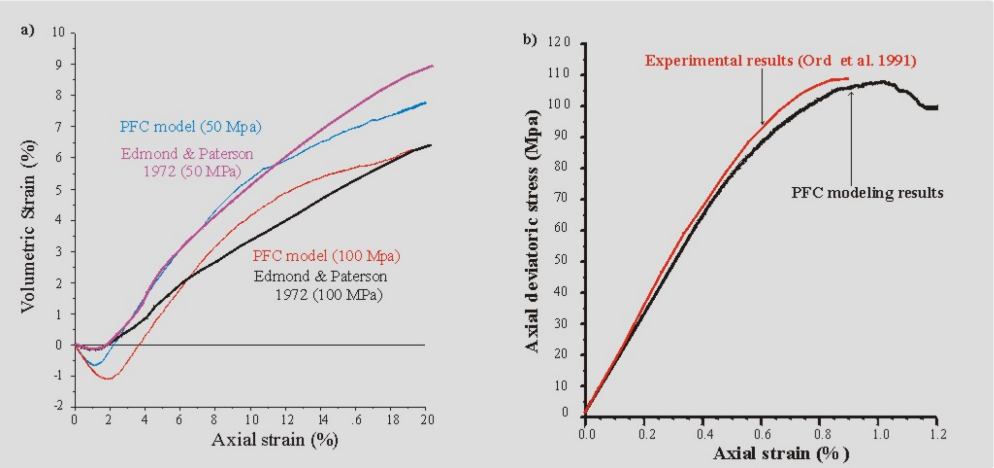

Figure 3. Comparison of numerical results with physical experimental results. (a)Volumetric strain versus axial strain. (b) Axial differential stress versus axial strain.

In geological situations, we are interested in the post-localisation behaviour of the rock. For example in a situation where a fracture, once initiated, continues to develop within the rock mass (rather than breaking it in two as shown in Figure 3a), how does the associated dilatancy evolve? How does the evolution of this system affect, and be affected by, any existing and/or developing flow regime?

The numerical particle model is a collection of rigid spheres with a distribution of sizes and contact strengths. The contacts between individual particles are described by elastic and by Coulomb style interaction laws, including Newton's Laws of Motion. In contrast, the continuum descriptions of such behaviours require non-intuitive variables in order to fit the results. The potential of particle flow codes to simulate this rich emergent behaviour of natural systems has been noted recently by Cundall (2001). We explore this potential further here for the patterning of shear zones. In addition, we spell out clearly the merits in exploring the multiscale physics and evolution of dilatancy of shear zones. In Figure 4, we see the result for shear band formation of loading the material to about 10% shortening, far beyond localization at about 0.6%. This is an excellent example of the emergence of patterned shear zones. Conjugate sets of shear bands are well developed.

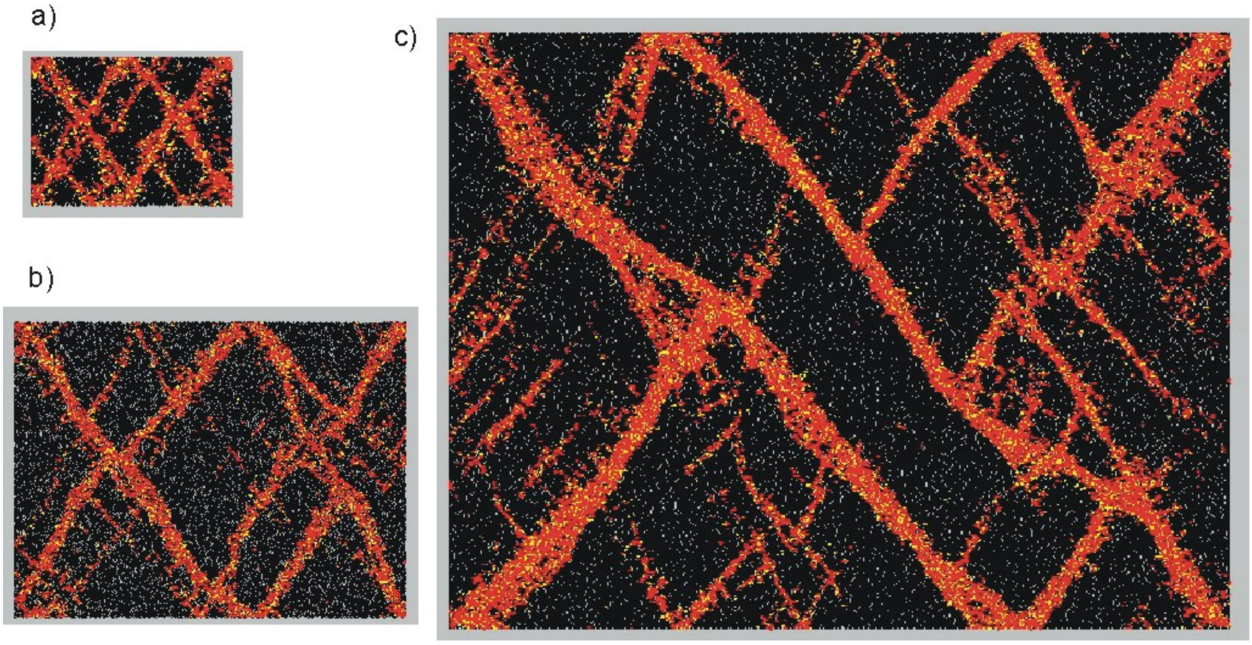

Figure 4. Development of shear bands in three numerical rock samples with different initial size (experimental scales); a) 5 x 5 cm; b) 10 x 10 cm; c) 20 x 20 cm. Shortening is in the vertical direction and confining mechanical pressure is 10 MPa. Bulk shortening of the models is about 10%.

Fracture development at an outcrop scale

Fracture development around pre-existing faults has attracted extensive attention (e.g. Reches, 1988; Zhang et al., 2003). Our outcrop scale PFC2D model examines fracture development around short isolated faults. These models are 20 metres long and 10 metres wide, containing one or two short faults, and are subject to dextral shearing. Fracture formation is represented by breakage of bonds between particles and is illustrated in red (Fig. 5a, b and c). It is noted that wing-crack type fractures developed in all the three models, in the tensile domain of shearing near the tips of pre-existing faults. It is interesting to note that in the models with two short faults, the overlapped portion is both fractured, as a result of either dilation (Fig. 5b) or contraction (Fig. 5c). These models show that a particle code can simulate fracture development consistent with observed natural fracture patterns (Fig. 5d).

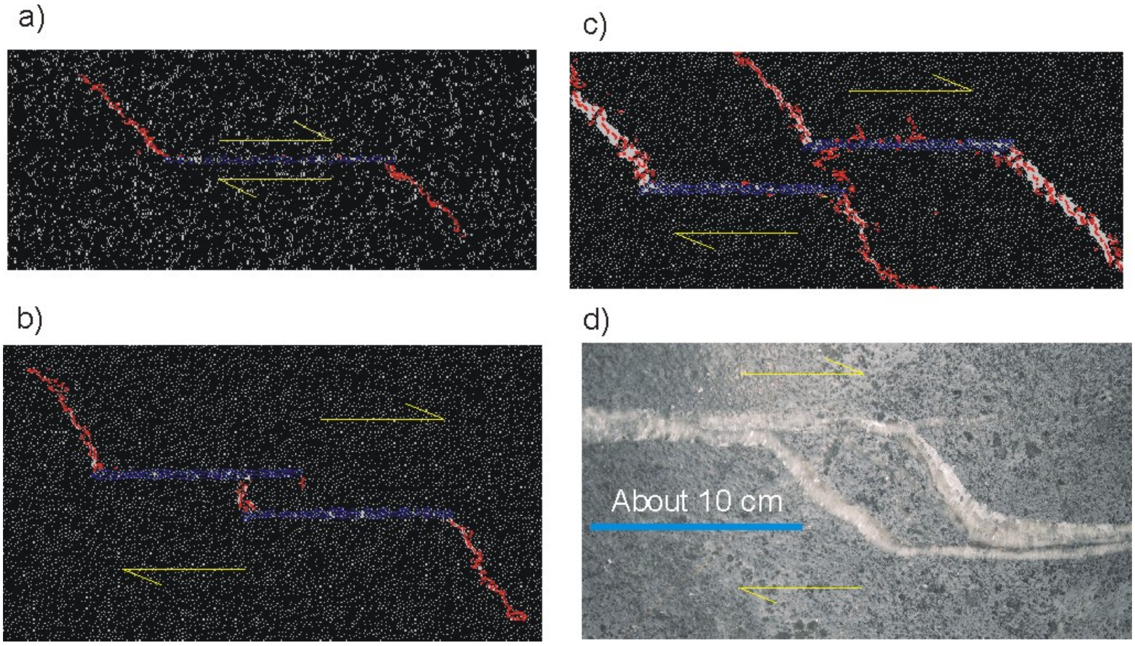

Figure 5. Wing-crack fractures (red) developed in PFC2D models with one pre-existing short fault (a); two short faults (b, dilation); and two short faults (c – contraction). Only the central part of the models around the pre-existing faults are shown. (d) A natural dilatant jog.

Conclusions

These virtual rock experiments are remarkable in their simulation of the dilatancy of rock during deformation. Such experiments offer a unique opportunity to explore a physical space scale not available through physical experiments.

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