

COMPUTATIONAL MODELING OF FAULT-RELATED FOLDS USING LARGE DEFORMATION CONTACT MECHANICS

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Summary. *In this work we present a mechanical model to study thrust fault-related folds using finite element modeling and non-linear contact mechanics. We simulate the rigid body translation and finite rotation with nonlinear kinematics; the response of the rock layers with a three-invariant elastoplastic model; and the rupturing and evolution of preexisting faults with finite deformation frictional contact mechanics.*

1 INTRODUCTION

In this paper we present a mechanical model that captures the kinematical aspects of fault related folds (Figure 1) induced by regional-scale far-field compression. We use the finite element method to model the fold and finite deformation frictional contact to model the reactivation and evolution of slip throughout preexisting faults. Our approach uses node-to-segment contact elements [1,2] to capture discontinuities in the displacement field. We quantify the perturbations in the stress field induced by slip on the fault, and show that these perturbations are enough to generate new discontinuities in the form of deformation bands. As the rock layers deform, their geometrical configurations change and the directions of the principal axes rotate. Tracking and capturing the evolving configurations of the layers and their structural features constitute a challenging aspect of the modeling and simulation. The most suitable approach to capture these geometric nonlinear effects is to adopt a Lagrangian, or material, description.

2 MECHANICAL MODEL

We implemented the constitutive models and finite deformation contact elements in a Fortran finite element code based on a fully Lagrangian description. The algorithm is fully implicit and the simulations correspond to plane strain deformation. We use a penalty

formulation to prevent interpenetration of the contacts [1,2]. Iterations for nonlinearities induced by finite deformation effects, plasticity, and large deformation contact mechanics are carried out by a full Newton–Raphson scheme under quasi-static loading conditions.

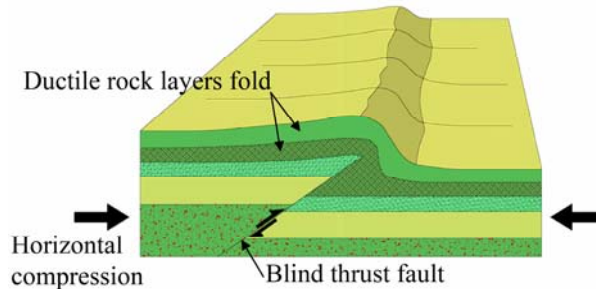


Figure 1: Schematic cross section of a thrust fault related fold.

We assume that the upper rock layers are sufficiently ductile so that they can fold when the underlying fault slip (Figure 1). Frictional sliding is allowed on a predefined fault that curves to a horizontal configuration at a prescribed depth (Figure 2). The domain is finite, so in the present analysis we assume that the two vertical boundaries in Figure 2 are sufficiently distant from the fault to represent conditions in the “far-field”.

2.1 Three-invariant plasticity model

We infer that sedimentary rock layers exhibiting excessive deformation without fracturing likely deformed in a ductile manner, and these layers are the subject of our investigation. We capture the elastoplastic response of such layers with a three-invariant Matsuoka-Nakai (MN) plasticity model [3,4]. This constitutive law considers a non-associative flow rule to control inelastic dilatancy. The MN model represents the mechanical properties of rocks more realistically than two-invariant plasticity models and is incorporated into a large deformation finite element program via multiplicative plasticity. The numerical integration of the constitutive model is done implicitly by a return mapping algorithm along the directions of the principal elastic stretches according to Borja et al. [3]. We investigate failure at each numerical integration point in the finite element model using the localization condition of Rudnicki and Rice [5]. Here we equate “failure” with the emergence of a deformation band. The localization condition entails tracking the evolution of the determinant function at each Gauss integration point. The onset of localization corresponds to the instant in the loading history at which this function becomes equal to zero, and the unit normal to the potential shear band that yields this zero determinant value defines the orientation of the band.

2.2 Finite deformation frictional contact model

Our finite element implementation considers a penalty scheme to impose the constraints along the fault. The finite element discretization of the fault is carried out with node-to-segment or node-to-point contact elements where arbitrary sliding of a node over the entire contact area is allowed. For this reason we perform a search algorithm of the contacts at each Newton-Raphson iteration to check and update the contact element connectivity if required. A

regularized Coulomb friction law is used to model the mechanical response of the fault. The contact interface has three mechanical parameters: a normal elastic stiffness, a tangential elastic stiffness, and a friction coefficient. Frictional slip is path-dependent in nature and its evolution requires the integration of the constitutive law. The integration is performed by a return mapping algorithm in a similar way to a plasticity model [2].

3 NUMERICAL EXAMPLE

In this section we present a numerical example simulating fault-related folding of elastoplastic rock layers. The finite element mesh of the problem is shown in Fig. 2. The rectangular domain, which is 120 km wide and 60 km deep, is shortened by prescribing horizontal displacements on the vertical left end. We assume a Young's modulus that increases with depth: $E = 5$ GPa for the layer above the fault tip (1 km), 10 GPa for the next 4 km, and 20 GPa for the bottom 55 km; and a Poisson's ratio $\mu = 0.25$ for all layers. Weight per unit volume for all rocks is 26 kN/m^3 ; it was applied as a downward body force prior to applying the horizontal contraction. For the plasticity model we assume that the initial and final sizes of the MN yield surface correspond to friction angles of $\phi = 15^\circ$ and $\phi = 34^\circ$, respectively, (friction hardening), and the dilatancy angle is $\psi = 12^\circ$. The ratio between the Young's modulus E and the cohesion c is $E/c = 200$ for all rock layers.

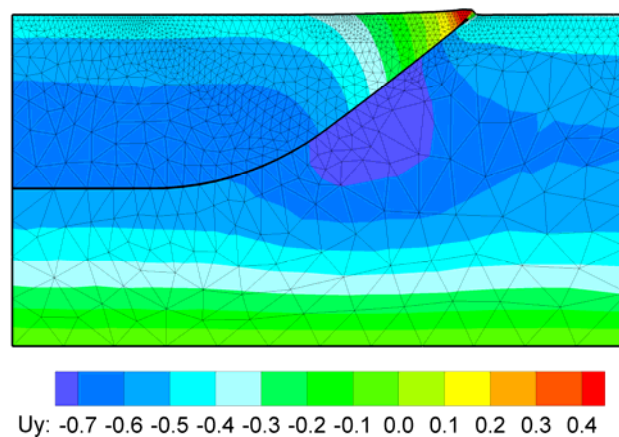


Figure 2: Deformed mesh after a horizontal contraction of 7.8 km ($\varepsilon = 6.4\%$). The fault is 1 km deep, the initial dip angle is 35° , and the coefficient of friction is 0.577. Vertical displacement bar in kilometer.

Figure 2 shows the deformed finite element meshes and contours of vertical displacement after a horizontal contraction of 7.8 km (6.4% nominal horizontal strain). The fault initially slips at the tip and the disturbance propagates downwards until it dissipates at the left vertical boundary developing an asymmetric anticline. Figure 3 shows snapshots of deformation near the fault tip and contours of the localization function. We observe that localized deformations are predicted around the tip of the fault and on the forelimb of the fold. This mechanical instability is an indication of material damage. The controlling variable in these figures is the nominal horizontal strain ε representing the ratio of the imposed horizontal displacement to

initial domain width of 120 km. A more detailed discussion of this and other fault-related fold examples can be found in Sanz et al. [6].

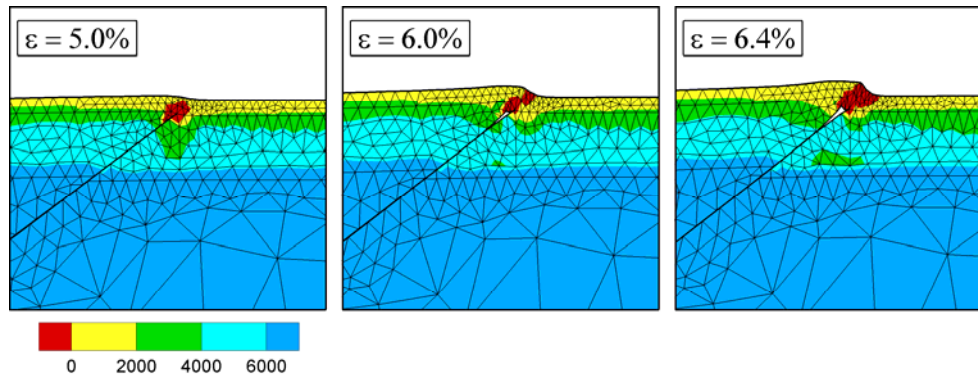


Figure 3: Snapshots of deformation. Color contours denote intensity of the localization function: red is probable zone of localized deformation, blue is probable zone of stable elastoplastic deformation.

4 CONCLUSIONS

Nonlinear finite element modeling combined with large deformation frictional contact mechanics is a powerful tool to analyze complex geological processes such as fault-propagation folds. We show that slip on a thrust fault generates an asymmetric anticline and that localized deformations may develop at the tip of the fault and on the forelimb of the fold. This work is useful to integrate mechanical and geological principles in order to formulate models constrained by available geological data.

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