Fault Response Modelling – An Overview

The new Fault Response Modelling (FRM) module in Move™ is a powerful tool that can be used to validate interpretations, identify fracture zones and calculate stress perturbations around faults and fractures by taking into account the mechanical properties of the surrounding rock volume. Fault Response Modelling uses Elastic Dislocation theory to calculate fault-related deformation, a theory that is widely used in earthquake science to quantify displacements, strains and stresses associated with ruptures (Meade, 2007). The calculated strain and stress can be used to model fracture orientations and intensities, which can then be assessed for failure potential.

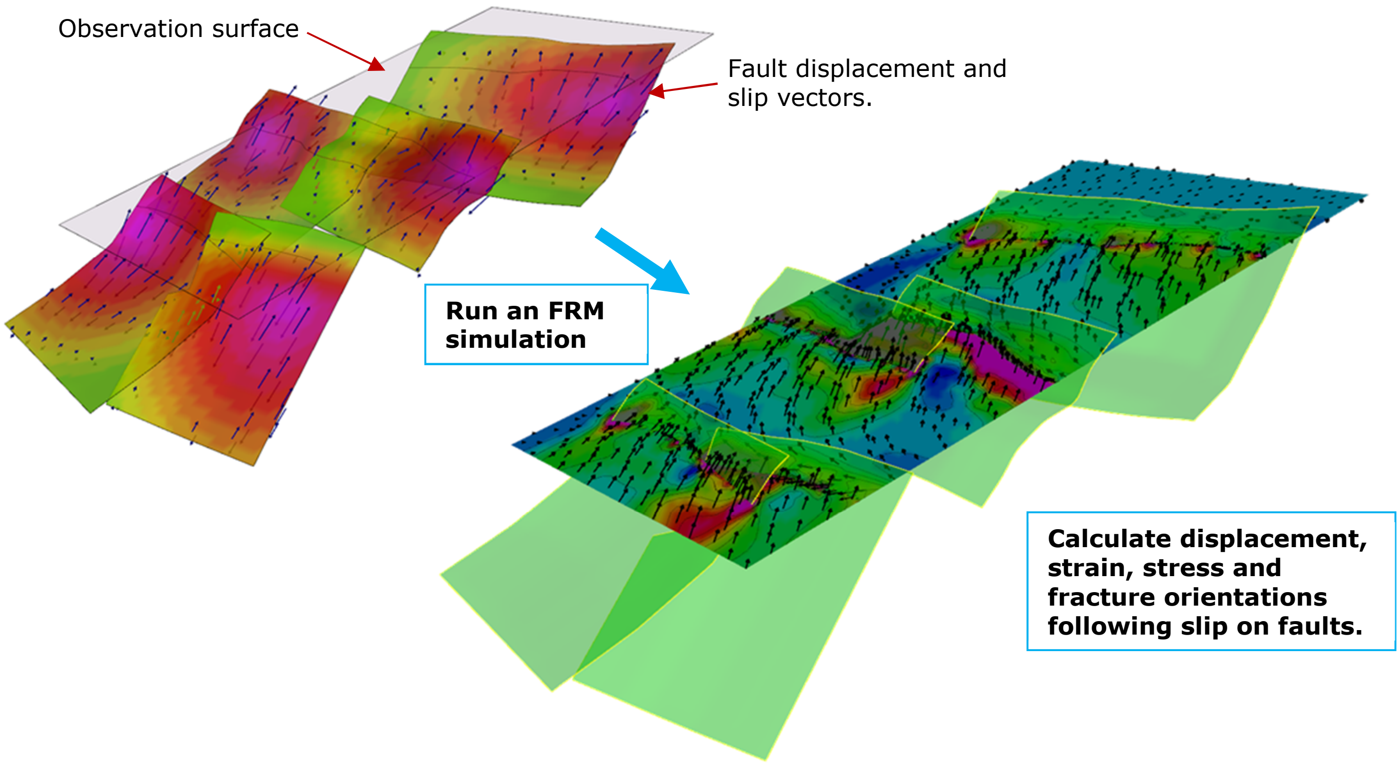

Figure 1. Example of a Fault Response Modelling simulation used to calculate the displacement, strain and stress associated with slip on reverse faults. Results of the simulation take the mechanical properties of the rock volume into account and are visualized on an observation surface. Fault displacement and slip vectors are either input or calculated from a regional stress field.

Applications

The Fault Response Modelling module is a highly versatile tool that has a wide range of geological applications across the oil & gas, mining, geothermal and geotechnical industries. Possible applications include:

- Prediction of natural fracture systems around faults to reduce risk and aid in the exploration and production of conventional or unconventional hydrocarbon resources.
- Rapid evaluation and ranking of prospects in exploration.
- Inform development and production strategies at the prospect-level.
- Exploration targeting for hydro- or mesothermal ore deposits.
- Evaluation of the risk of induced or triggered earthquakes as a result of hydraulic fracturing for enhanced geothermal systems.

- Quantification of the deformation associated with earthquakes and aftershock hazard assessment.
- Evaluation of fracture forming mechanisms based on geological evolution.

Concept of Fault Response Modelling

Fault Response Modelling is based on Elastic Dislocation theory, which describes the elastic deformation associated with dislocations in solids. It is widely used in materials science to define the deformation field surrounding defects in the crystal lattice. The implementation in Fault Response Modelling uses triangular elastic dislocation elements to model fault- or fracture-related deformation in an elastic half-space, which is bound by an upper “free” surface above which there are no opposing elastic forces. Each dislocation element corresponds to one of the triangular faces that make up the fault surface or fracture (Figure 2). Slip vectors are then assigned to each triangular dislocation and used to simulate slip on the fault surface or fracture.

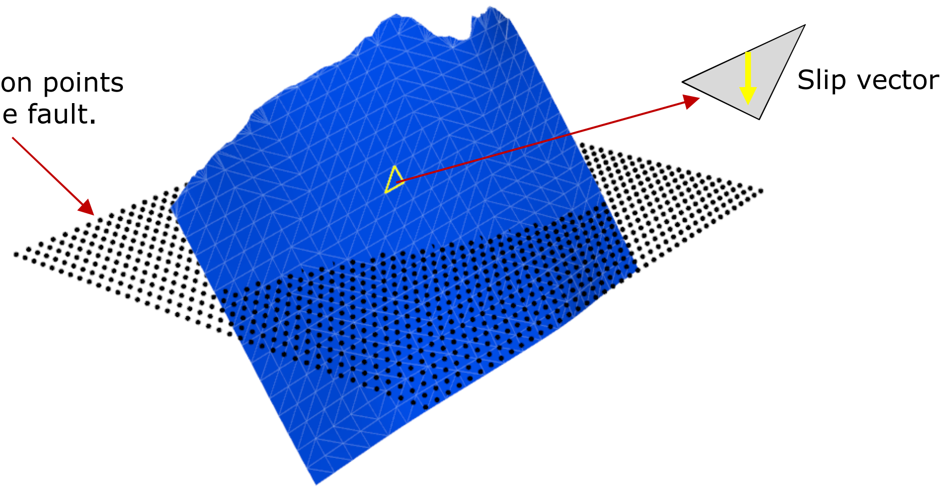

Figure 2. Illustration of a fault mesh (blue) showing the local slip vector resolved on a triangular mesh face. The implementation of triangular dislocation elements allows complex fault shapes to be modelled.

Individual slip vectors of fault triangles are superposed to calculate total displacement and infinitesimal strain for observation points in an elastic medium surrounding the fault based on the equations of Comninou & Dunders (1975). The strain tensor can then be used to determine the stress tensor assuming linear elastic behavior according to Hooke’s law. If slip is defined by a regional stress field, interaction of multiple faults can be simulated according to the mechanical properties of the intervening rock volume using the slip zone modelling approach of Jeyakumaran *et al.* (1992; Figure 3).

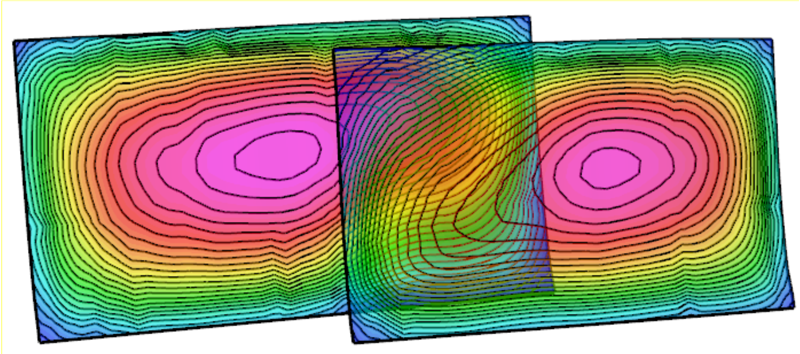

Figure 3. Slip zone modelling simulates the interaction of multiple faults in an elastic rock volume. The resulting perturbations in the local stress field are reflected in the distribution of slip on the faults.

Mechanical properties (elastic moduli, strength and friction parameters), can be defined for the entire model or varied spatially using vertex attributes. Because it uses a boundary element method, the numerical calculations in Fault Response Modelling are only run for discrete observation points of the model, which reduces computation time and improves overall performance.

Input parameters

- **Master faults/ fractures** are objects with definable fault slip that form the basis of the dislocation calculations. Each triangle on these surfaces represents an individual dislocation element (Figure 2). The front and back face of the triangles will have opposing displacement vectors. These are used to calculate the displacement, strain and stress experienced by observation points of a surrounding elastic medium.
- **Fault slip** can either be specified using a fault-parallel slip direction and magnitude, calculated as the maximum shear direction based on a remote loading using a regional or local stress field, defined by applying a specific traction, or as XYZ displacement vertex attributes. In each case, fault slip magnitude can be uniform across the fault, or it can include a component of fault slip tapering that is either user-defined or calculated based on the stress field (Figure 3). Fault slip can also be modelled with an opening or closing component, which allows slip vectors to be oblique to the fault surface.
- **Observation objects** can be specified as point clouds (Figure 2), lines, mesh or grid surfaces, fractures as well as GeoCellular or TetraVolumes.
- **Mechanical properties** that can be specified include Poisson's Ratio, Young's Modulus, Apparent Friction, Coefficient of Friction, Angle of Internal Friction, Skempton's Coefficient and Cohesion. These can be defined per object or using vertex attributes.
- **The Free Surface** defines the upper boundary of the elastic half-space that is used in the calculation. The free surface would normally represent the Earth's surface because the atmosphere provides effectively no resistance against elastic rock deformation.

Results of Fault Response Modelling

Running **Fault Response Modelling** to simulate slip on fault surfaces or fracture sets allows the displacement vector for each observation point to be calculated. The displacement vectors are then used to determine the infinitesimal strain tensor, from which the orientation and magnitude of the principal strain orientations can be obtained. Assuming linear elasticity, the stress tensor (including principal stress orientations and magnitudes) is also calculated. Note that the stress tensor can be calculated from any strain tensor (finite or infinitesimal), including those obtained from **Curvature Analysis** and using **Strain Capture** during **3D Kinematic Modelling** or **Geomechanical Modelling** modules. Displacement, strain and stress axes can be visualized and attached to the model for further analysis.

From the stress tensor, various relationships between shear and normal stress can be analysed in more detail. These include the Coulomb Stress change, which provides a measure of how likely a fracture or fault is to fail following slip on the master fault. On a Mohr-Coulomb diagram, this is represented by the relative change of a fault or fracture's plotted proximity to the failure envelope compared to its plotted location for the initial stress regime: positive (negative) Coulomb Stress changes indicate that a fault or fracture is more (less) likely to fail. The Maximum Coulomb Shear Stress can be used as a proxy for the intensity of shear fractures (Mode II or III); if the Maximum Coulomb Shear Stress exceeds the cohesive strength of the rock, the fracture is expected to be in failure (Figure 4). Other properties that are calculated and saved as vertex attributes on observation objects are a range of slip, dilation, leakage and stability parameters that are also available in the **Stress Analysis** module.

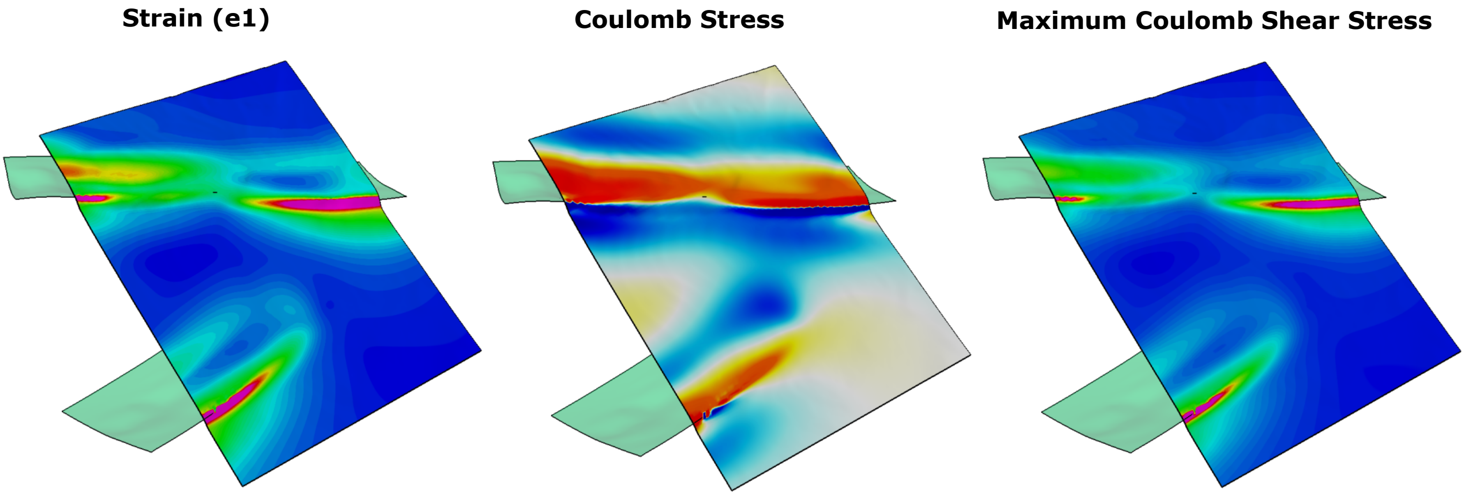

Figure 4. Reverse-slip Fault Response Modelling simulation showing a selection of the available strain and stress properties visualized on the observation surface. Warm colours correlate to high values, cold colours to low values.

Strain and stress fields can be used to calculate fracture orientations, with attribute magnitudes providing information on fracture intensities. Strain-based fractures that are calculated include joints, cross-joints, and conjugate shear planes 1 & 2. In addition, optimal fracture orientations can be obtained by searching the available orientation space for fractures with the highest possible Coulomb Stress Change. Fractures can be colour mapped for any of the calculated stress or strain attributes and relationships, as well as filtered for brittle failure or fracture stability, which are calculated using frictional rock properties and cohesion (Figure 5). Predicted fracture systems can then be compared to observed fracture orientations by calculating the angular misfit and fracture properties can be used as an input to create a Discrete Fracture Network (DFN) in the **Fracture Modelling** module.

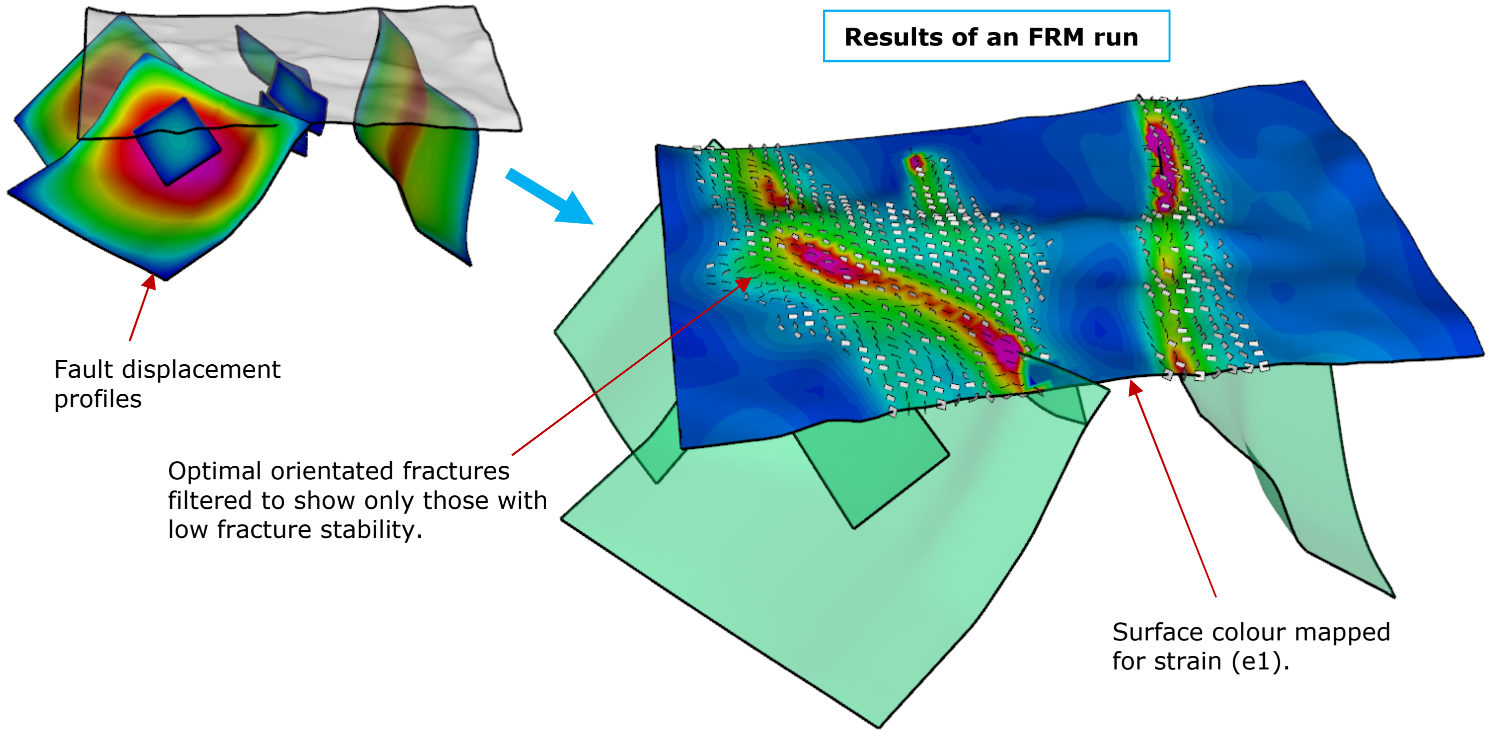

Figure 5. Example of a Fault Response Model run to calculate optimal fracture orientations and stability.

References

Comninou, M. & Dundurs, J. 1975. The angular dislocation in a half space. *Journal of Elasticity* **5**, 203-216.

Meade, B.J. 2007. Algorithms for the calculation of exact displacements, strains, and stresses for triangular dislocation elements in a uniform elastic half space. *Computers & Geosciences*, **33**, 1064-1075.

Jeyakumaran, M., Rudnicki, J.W. & Keer, L.M. 1992. Modeling slip zones with triangular dislocation elements. *Bulletin of the Seismological Society of America*, **82**, 2153-2169.

If you require any more information about Fault Response Modelling in Move, then please contact us by email: enquiries@mve.com or call: +44 (0)141 332 2681.