2D and 3D Finite Element Restorations of Geological Structures with Sliding Contact Along Faults

Martin Guiton, Chokri Zammali

2D and 3D finite element restorations of

M.L.E. Guiton[1], C. Zammali[1]

[1] IFP Geology-Geochemistry-Geophysics Division

1. Abstract

A fully implicit finite element method is developed for the restoration of sedimentary basins. Internal deformation is distributed with a linear hyper-elasticity constitutive law. Deformation is also accommodated by large sliding along faults. This mechanism is represented by a frictionless bilateral contact algorithm between deformable bodies. Application are shown with 2D forward or backward models of thrust related folding with multiple intersecting discontinuities. An example demonstrates how this restoration algorithm enables to detect misinterpretation in the structural model. One advantage of the method is to allow 3D modeling, as shown by the restoration of a Miocene anticline in the Iranian Zagros thrust belt. The main interest of this method will be to facilitate the coupling between restoration and forward modeling.

2. Principles of the method

A restored state (i.e. faults are healed on a given horizon which is unfolded), is calculated by honoring the mechanical equilibrium of elastic rock continuums with implicit finite element Code_Aster, like in Moretti et al (2006).

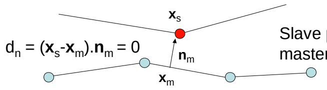
$$\text{Find } (u,\lambda) \quad \int_{\Omega_0} \mathbf{S}_{(u)} : \delta\mathbf{E}_{(v,u)} d\Omega = \int_{\Gamma_c} \chi.(\lambda - \rho d_{n(u)})[[v_n]] d\Gamma,$$

$$\forall v, \lambda^* \quad \int_{\Gamma_c} \frac{1}{\rho}\big(\lambda - \chi(\lambda - \rho d_{n(u)})\big)\lambda^* d\Gamma = 0$$

1st line : internal work (left) balanced with contact contributions (right)

2nd line: bilateral contact condition (see figure below).

χ is a contact indicator, ρ a conditioning scalar and $[[v_n]]$ the normal virtual displacement jump



Slave point projection to master surface

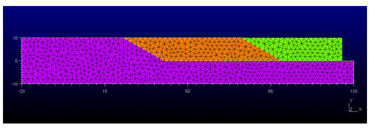
The originality of the method is to represent the large continuous sliding along faults during the deformation history. Both penetration and separation of deformable rock masses are prohibited. This is achieved through a frictionless bilateral adaptation of Ben Dhia et al (2000) hybrid contact algorithm.

To account for finite rotations, constitutive law is linear hyperelasticity relating second Piola Kirchhoff stress tensor **S** to Lagrangian deformation tensor **E**. Material is defined by elasticity modulus E and Poisson's ratio ν.

The implicit scheme of the present method should enable greater deformation increments than other explicit restoration methods (Rodrigues de Santi & Martha, 2005; Maerten & Maerten, 2006).

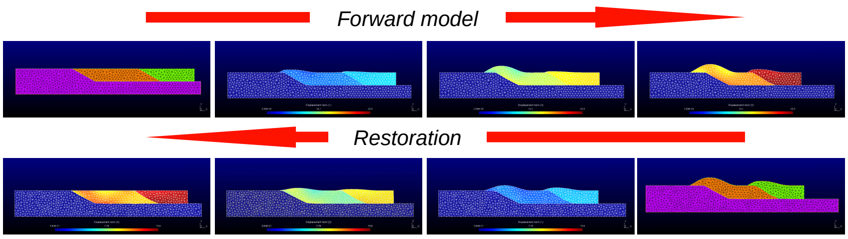
3. Forward modeling and restoration of a duplex

A forward 2D model of thrust sheet formation shows accommodation of fault related folding by sliding of two less competent thrust units on a basement and along a reverse fault separating them.



The initial mesh with a basement (b) and two thrust units (w)

$E_b = 5\, E_w$ and $\nu = 0.3$



Boundary condition

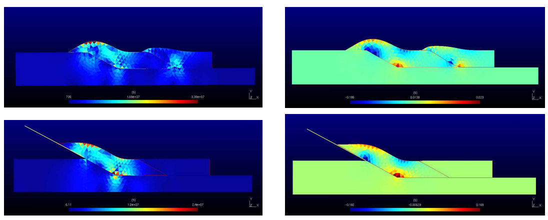
- **forward model :** 20 km leftward uniform displacement is applied on the vertical right side of the green thrust unit
- **restoration** : flattening of top horizon

Sliding contact is enforced on faults

Deviatoric Cauchy stress norm | Trace of deformation

Contact with basement flat

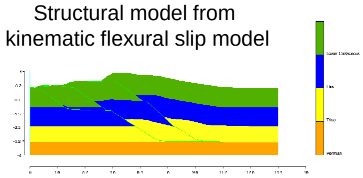
Transfer along extended fault



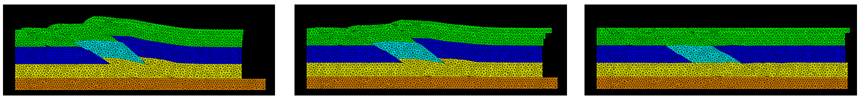
Without bending of left trust unit on the basement flat, the right fold is inhibited

4. Sensibility on geometrical misinterpretation in deformed structural model

Structural model from kinematic flexural slip model

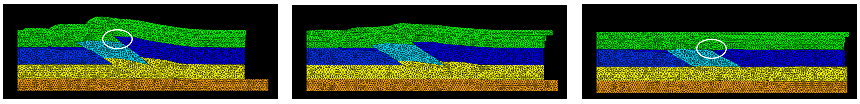


Initial finite element mesh | Intermediary state | Restored state



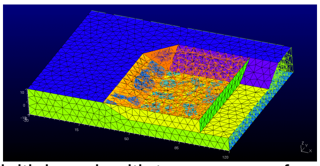
the model below, one horizon has been misinterpreted (see circle in initial mesh). Comparison of the restored state with respect to the above correct model shows that the misinterpretation is highlighted by the offset of a bedding plane inside the circle of the restored state.

Restoration is computed with sliding along faults and horizons



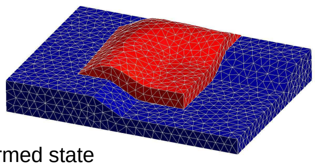
5. 3D applications

Forward model of fold on a thrust fault with a lateral ramp



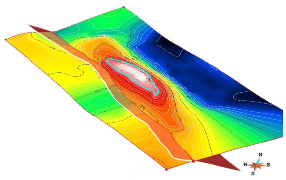
The initial mesh with transparency for hanging wall (h) and footwall (f)

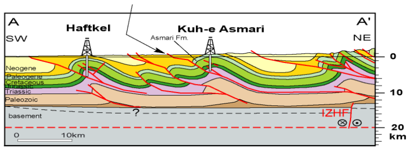
- $E_f = 10^5 E_h$ and $\nu = 0.3$
- 22.5 km thrust displacement is applied on back sides of hanging wall.



Deformed state

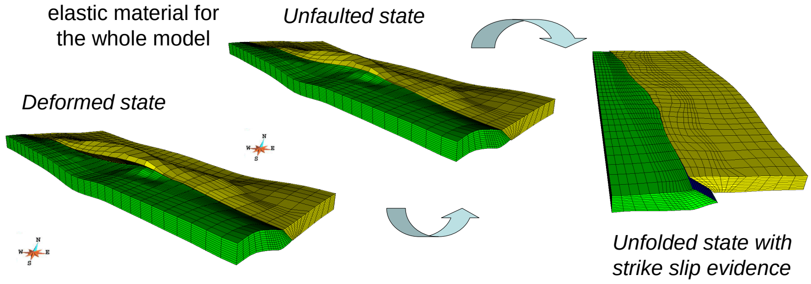
Restoration of a thrust related anticline from Zagros, Iran





A mesh is constructed from a structural model (left) of Miocene Asmari anticline in Zagros thrust belt (right from *Sherkati et al, 2005*).

Incompressible elastic material for the whole model



6. Conclusion and perspectives

This new 2D or 3D numerical approach for the restoration of sedimentary basins enables both forward or backward kinematic modeling. Its particular originality is to account for possible large sliding along discontinuities, thanks to a bilateral contact algorithm in a fully implicit Finite Element framework.

Elaborating on this method, ongoing works include:
- coupling with an erosion or decompaction calculator with an efficient mesh updating,
- coupling with an inverse method to improve the geometry of the initial structural model,
- coupling with a thermal and fluid flow solver,
- forward mechanical basin modeling with non-linear internal constitutive laws and frictional contact.

EdF R&D is thanked for helpful discussions and exchanges on Code_Aster development. Code_Aster is distributed by EDF with GPL license. Gmsh GNU GPL software has been used in this work as a pre- and post-processor with Code_Aster. H. Ben Dhia of LMSSMat at the Ecole Centrale Paris is acknowledged for a pioneering collaboration on contact algorithm. The authors are grateful to J-M. Daniel, J-L. Rudkiewicz, J-L. Faure and I. Moretti from IFP for help and comments.
The method presented in this poster might be available in next version of Kine3D-3, the IFP volumetric restoration plugin in gOcad™.

References

Maerten, L. and F. Maerten, (2006). Chronologic modeling of faulted and fractured reservoirs using geomechanically based restoration: Technique and industry applications. AAPG Bulletin, pp. 1201-1226.

Ben Dhia, H.; Vautier, I. and M. Zarroug, (2000). Problème de contact frottant en grandes transformations : du continu au discret. Revue Européenne des Eléments Finis, 9, pp. 243-261.

Moretti, I.; Lepage, F. and M. Guiton, (2006). KINE3D: a New 3D Restoration Method Based on Mixed Approach Linking Geometry and Geomechanics. Oil&Gas Science and Technology – Rev. IFP, 61, No. 2, pp. 277-289.

Santi, M.R.; Campos, J.L.E.; Martha, L.F., (2003). 3D Geological Restoration using a Finite Element Approach. Proceedings of 23rd GOCAD Meeting Nancy, France, pp. 1-12.

Sherkati, S.; Letouzey, J. and D. Frizon de Lamotte, (2006). Central Zagros fold-thrust belt (Iran) : New insight from seismic data, field observation and sandbox modeling. Tectonics, 25.

Contact name : Dr. M.L.E. GUITON, *martin.guiton@ifp.fr*

Innovation Energy Environment