

2006 SCEC Progress Report: Demonstration of elastic finite element models for fault systems studies and meshing the Community Block Model*Bradford H. Hager (PI), Massachusetts Institute of Technology**Carl Gable (co-I), Los Alamos National Laboratory**Charles A. Williams (co-I), Rensselaer Polytechnic Institute***Introduction**

The primary goals of this project were to develop computational meshes for southern California using realistic fault geometry provided by the Community Fault Model (CFM), and to use these meshes to investigate the effects of fault geometry and material property inhomogeneities on the predicted surface deformation field. The Unified Structural Representation (USR) group has been in the process of creating topologically closed volumes based on the CFM, resulting in an initial version of the Community Block Model (CBM). The CBM is a GoCAD T-surf representation of the surfaces bounding a number of blocks representing the southern California fault system. The interaction with USR has been active and informative, resulting in the resolution of problems in going from GoCAD representation of the CBM to meshing the CBM via the LaGRIT meshing package [<http://lagrit.lanl.gov>]. Large amounts of effort are expended in creating the realistic geometrical representations of the CFM and CBM, and much additional effort is required to create computational meshes suitable for quasi-static finite element computations. One of the goals of this project was to determine the amount of geometrical complexity required to adequately represent the fault systems in southern California. As a first step in this direction, we decided to compare finite element results for a small portion of the CBM with those of an analytical model based on a simpler rectangular fault system geometry (CFM-R). This is a first step in determining the importance of detailed fault geometry, and it also serves as a check on the finite element calculations. Using this same mesh, we have also begun examining the effects of material property inhomogeneities using the same mesh, which will allow us to determine the importance of these effects for purely elastic models.

While the scientific goals of this project are important, the workflows and methodologies developed to accomplish the scientific tasks are of equal or greater importance, since these will pave the way for future work that makes use of the resources involved in this project (CFM, CFM-R, CBM, LaGriT, PyLith finite element code, analytical block modeling code). As mentioned above, much work has already been done toward resolving the issues related to going from the GoCAD version of the CBM to creating a mesh of the CBM using LaGriT. There are similar problems involved in providing mesh information from LaGriT in a form that can be used by the PyLith finite element code. We have also made some headway in simplifying the comparison between PyLith results and those of the analytical block model. We believe that the methods we have developed thus far are fairly powerful and should be flexible enough to handle a range of problem types.

LaGriT to PyLith Workflow

We are using the LaGriT mesh generation package [<http://lagrit.lanl.gov>] to create the meshes needed for our numerical modeling. To perform the modeling itself, we are using the PyLith finite element code [<http://www.geodynamics.org>], which is an outgrowth of previous SCEC-funded work and is still under active development. A simplified view of the workflow is shown in Figure 1, which shows the steps involved in going from the CFM to the CBM to a finite element mesh produced by LaGriT that may be used for computations. We have developed

codes to translate UCD (Unstructured Cell Data) format produced by LaGriT to a format suitable for PyLith; however, the most problematic portion of this step is dealing with faults. The difficulties lie primarily in how to deal with intersecting faults. In most cases it is difficult to determine which faults get ‘priority’ at nodes that lie on more than one fault. In our case the person producing the meshes does not generally know how to assign slip on nodes along fault intersections, and in many cases the user of the meshes may not know either. It may be necessary to try more than one option. To get around this problem, we devised a method for defining auxiliary fault files, where fault segments are defined in terms of different ‘colors’ on either side of the fault. To define a fault system, we need a number of such files, each representing a different color pair. Each file contains information such as coordinates, vertices defining each fault face, and the fault-normal direction at each node on the fault. The use of colors is also useful in conjunction with the file naming scheme, since this tells us which color is associated with the outward-directed fault normal direction.

LaGriT has now been modified to automate the process of creating auxiliary fault files, and we have developed several codes that can accept the auxiliary file input and produce ‘split node’ input files for PyLith. For the block problem, we use a code that assigns fault slip based on rotation poles for the different blocks. We now have a system that is relatively easy to use, and should be flexible enough to deal with a range of problem types.

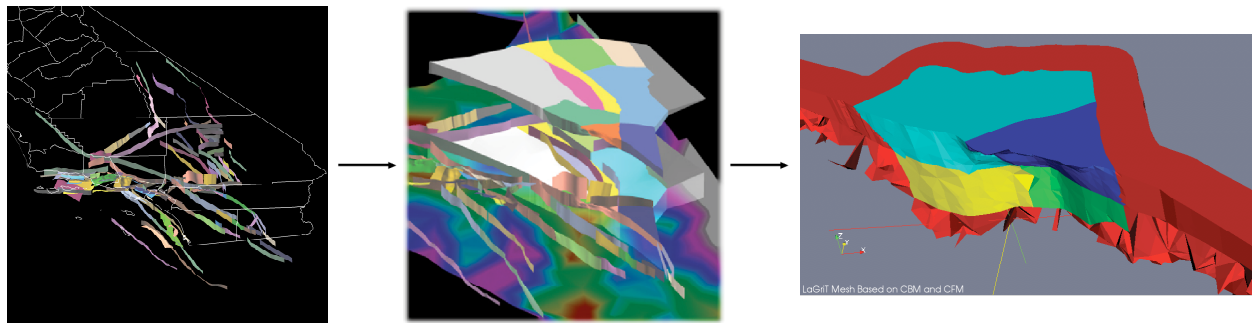
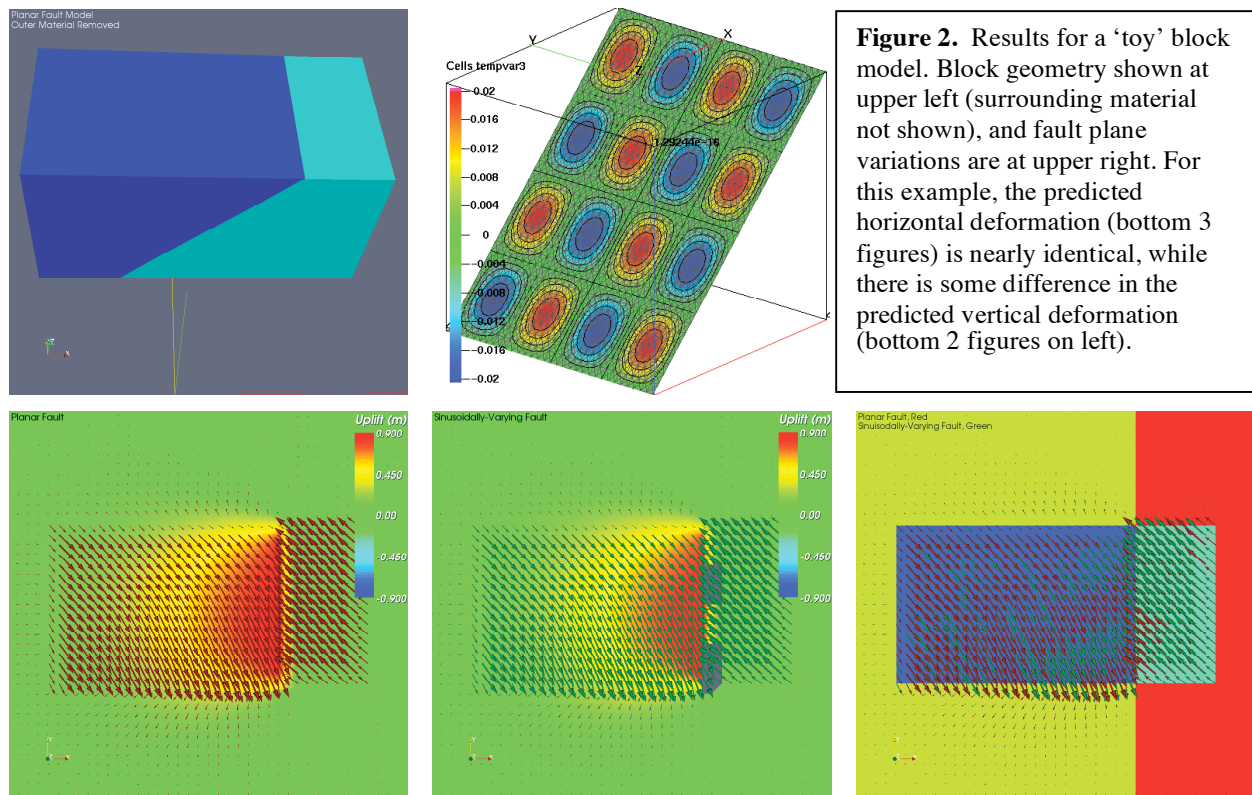


Figure 1. Simplified depiction of the steps involved in going from the CFM [<http://structure.harvard.edu/cfm>] (left) to the CBM [<http://structure.harvard.edu/cfm>] (center) to a finite element mesh of a 4-block subset of the CBM [<http://meshing.janl.gov>] (right).

Effects of Fault Geometry

We have begun our investigations into the effects of fault geometry using two different approaches. The first approach involves simple ‘toy’ block models composed of planar fault segments (Figure 2). Backslip corresponding to specified block rotations are imposed such that the slip on the fault has approximately equal amounts of strike-slip and dip-slip motion. We then apply sinusoidal variations to the geometry of the dipping fault plane to determine the effects on the predicted surface deformation field. The ‘toy’ models represent the first step in an ongoing project to quantify the effects of fault geometry variations on the predicted surface deformation field, and they have also been quite useful in refining our workflow.

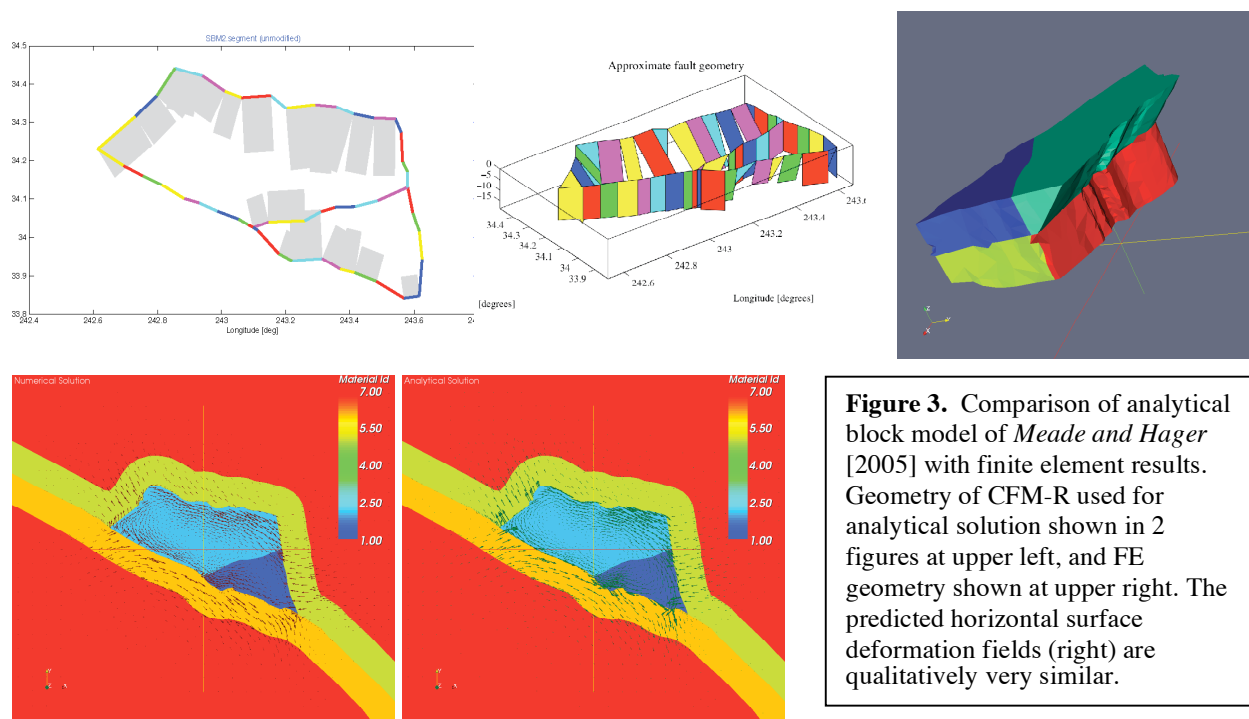
In our second approach (Figure 3), we compare finite element results for a 4-block subset of the CBM to those produced by the analytical block model of *Meade and Hager* [2005] using a coarser mesh as defined by CFM-R. This serves both to validate the finite element computations and allows us to begin our investigation into the effects of fault geometry in a realistic geological setting. Due to the limited availability of GPS observations in this region, we do not attempt an



inversion. Instead, we use the same rotation pole for the two inner blocks in Figure 3, and we do not apply North America – Pacific motion. This means that there is no motion across the Pinto Mountain fault (between the two blue blocks), and the only motion on the San Andreas is along the boundary with the blue blocks. Motion occurs across the San Bernardino frontal fault (northwest) and the Eastern California Shear Zone (northeast and east). We find reasonable agreement between the analytical and numerical solutions, although we have not yet quantified the misfit. We are attempting to quantify the model misfit in an ongoing project where we progressively coarsen the finite element mesh and determine the minimum fault geometry resolution required to match the analytical solution to a precision less than typical GPS data uncertainties. In the course of our studies, we have refined the workflow needed to compare the analytical and numerical results.

Effects of Material Property Variations:

One of the primary advantages of finite element solutions for elastic models is the ability to represent material property variations, and it is important to determine the potential effects of these variations on our predicted results. If we find that the effects are likely to be relatively minor, for example, then analytical solutions may suffice for many studies. The actual material property variations in southern California are quite complex, and could be at least partially constrained by estimates based on the Community Velocity Model (CVM). As a starting point, however, we chose to examine the effects when material properties are constant within each block (Figure 4). The model setup is similar to that for comparing the finite element solution with the analytical block model solution, but we used slightly more complex boundary conditions, allowing movement on both the main part of the San Andreas fault as well as along the Pinto Mountain fault. The effects of variations in the material properties are most clearly seen in the strain patterns (left two columns). Decreasing the strength of the block material



concentrates the strain within the blocks, while strengthening the block material moves the majority of the strain just outside the boundaries of the blocks. We plan to perform a more detailed sensitivity study to determine the range of gradients in the elastic properties that preclude an adequate representation with a homogeneous (analytical) block model.

Presentation and Dissemination of Results

We have presented the results of our work to date at the 2006 SCEC Annual Meeting [Williams *et al.*, 2006a] and at the AGU Fall Meeting [Williams *et al.*, 2006b]. In addition, the software created specifically for this project is now publicly available in both LaGriT [<http://lagrit.lanl.gov>] and as part of the PyLith package [<http://www.geodynamics.org>]. The additions to the software will also be discussed and demonstrated at the next CFEM workshop (Golden, CO, in June of 2007). We are continuing our investigations into the effects of both fault geometry and material property variations, and this should result in two publications completely supported by this SCEC project. This project has laid the groundwork for a number of future SCEC projects, including our own plans for much larger-scale models of southern California block dynamics as well as those of other investigators.

References

- Meade, B. J., and B. H. Hager, Block models of crustal motion in southern California constrained by GPS measurements, *B. J. J. Geophys. Res.*, *110*, B03403, doi: 10.1029/2004JB003209, 2005.
- Williams, C. A., C. W. Gable, and B. H. Hager, Numerical and analytical computations of surface deformation in southern California using the Community Block Model, *SCEC Annual Meeting*, 2006a.
- Williams, C. A., C. W. Gable, and B. H. Hager, Numerical and analytical computations of surface deformation in southern California using the SCEC Community Block Model, *AGU Fall Meeting*, 2006b.

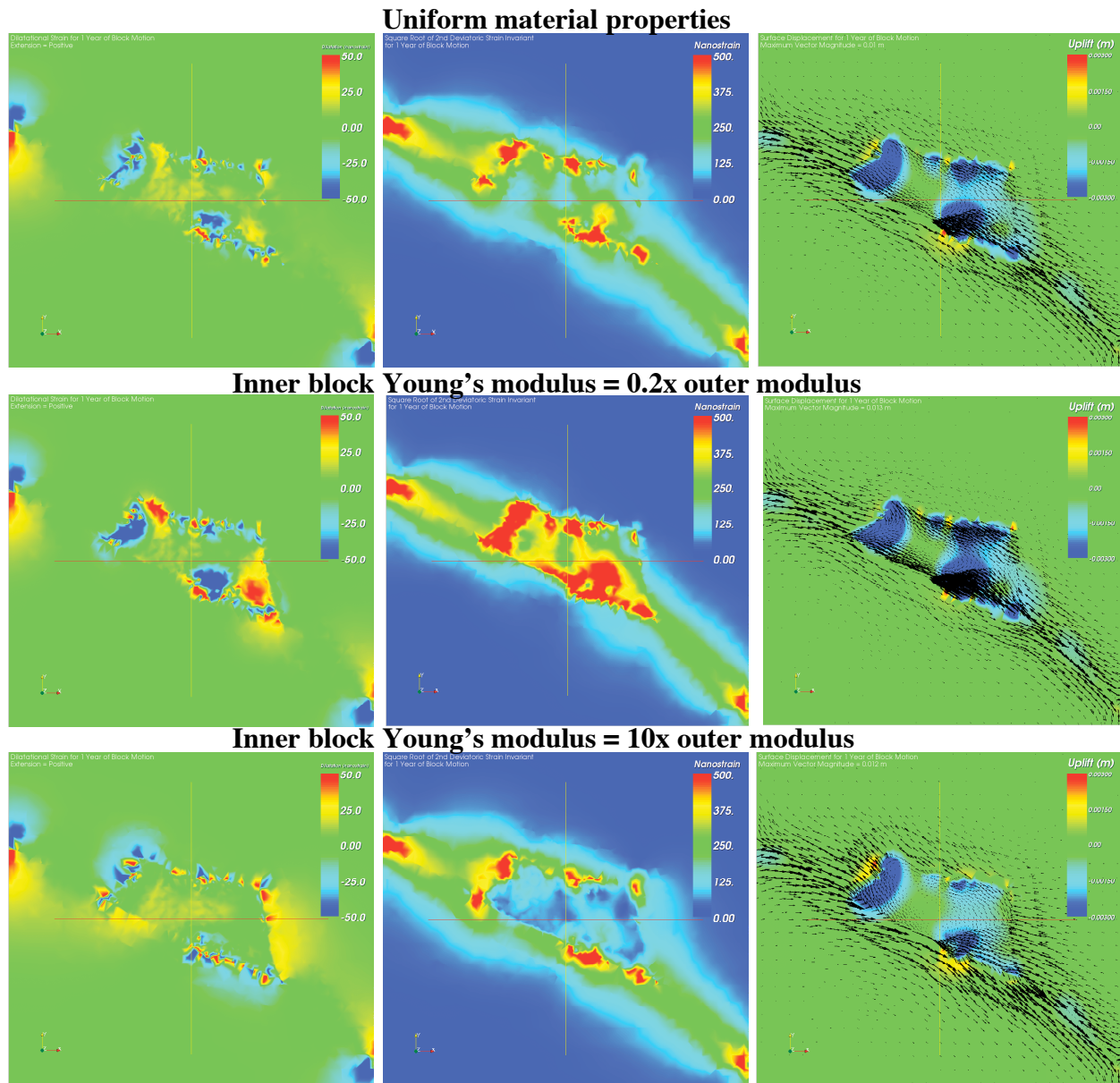


Figure 4. Effects of varying the material properties within the blocks with respect to the surrounding material. Results at top are for constant properties throughout the mesh. Results in center are for the case where the Young's modulus of the inner blocks is 0.2x that of the surrounding material. Results at bottom are for the case where the Young's modulus of the inner blocks is 10x that of the surrounding material. Left column shows dilatational strain, center column shows square root of the second deviatoric strain invariant (related to distortional strain energy), and right column shows horizontal and vertical deformation fields. Results clearly show how decreasing the strength of the blocks concentrates strain within them, while increasing the strength concentrates the strain just outside the block boundaries.