

Progress Report

Collaborative Research: Development of Community Finite Element Models and Community Block Model-A (CBM-A) for Fault Systems Studies

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Development of Community Finite Element Models: This is the second year of a 5-yr effort to coordinate development and validation of 3D quasi-static, finite-element codes capable of simulating crustal deformation in coordination with SERVO, GeoFEM, ACES, and other modeling efforts; develop deformation models of Southern California consistent with observed topography, fault geometries, rheological properties, geologic slip rates, geodetic motions, and earthquake histories; and use these models to infer fault slip, rheologic structure, and fault interactions through stress transfer. Part of our strategy for community building, as well as building software, is to have a series of workshops to involve the SCEC Crustal Deformation Modeling (CDM) community in this process. Last year the CDM workshop focused on assessing the accuracy, speed, and ability to modify software in use by members of the community. At the workshop the CDM Group developed its *Mission Statement*: 1) Build tools to understand the response to single earthquakes, and make geodetic comparisons, infer rheology, and constrain structures; 2) Build tools to simulate fault system interaction, regional strain and stress field evolution and produce results that assist in the estimation or modeling of fault slip and constrain physics; 3) Develop understanding of transient stress interaction among faults; and 4) Determine realistic predictions of geologic features (e.g., topography, fault slip). (Workshop reports, benchmark descriptions, and useful links are on the CDM web site: <http://geoweb.mit.edu/fe> or <http://www-gpsg.mit.edu/fe>.)

In August, 2003, Simons and Hager (with Carl Gable) organized and ran the second annual workshop of the Crustal Deformation Modeling (CDM) subset of the Fault Systems Working Group. The workshop was hosted by Los Alamos National Laboratory, with the locale chosen to enable SCEC scientists to benefit from attendance by Lab experts, particularly those with expertise in meshing. It also introduced SCEC Fault Systems efforts to LANL physics/computational groups, sowing the seeds for future collaborations. By leveraging SCEC, NASA, and LANL support, we were able to increase the number of students and senior researchers attending, as well as meet for a longer time. Because members of the NASA-sponsored Quakesim group participated in the workshop, there was significant interchange of ideas and codes. Part of the group effort is aimed at verifying code accuracy, so significant effort was spent on refining the preliminary benchmark problems that were developed at last year's workshop. Efficient and accurate meshing of complex geologic structures is a very high priority, and meshing tutorials from scientists from LANL (LAGrit) and Sandia (Cubit) were very informative.

One of the important outcomes, discussed more below, is that we are now reevaluating whether the GoCAD/t-surf approach used by the USR group will be used to produce “final” tetrahedral meshes or will be an intermediate step in developing hexahedral meshes for use in FEM calculations.

Another highlight of the workshop was intense discussion of Computational Frameworks. One of the high priorities of the Crustal Deformation Modeling subgroup is to develop a quasi-static, parallelized finite element code that will eventually be able to represent the deformation and stress fields due to all major faults in southern California as provided by the Community Block Model, using realistic rheologies and fault behavior. The code should also be relatively easy to use and should integrate well with other modeling codes as well as visualization and meshing packages. Charles Williams (RPI) has been leveraging SCEC, NSF ITR, and Caltech resources to upgrade Tecton into a SCEC Community code. The top priority has been the integration of the code into the Pyre framework (Caltech), which immediately adds several new capabilities to the code, while easing the process of adding new features. The initial version of the code is now available as a dynamic shared library, callable via python (Pyre) function calls. The groundwork has also been laid for the addition of tetrahedral elements, since it is relatively easy to mesh geological structures with such elements. Work is progressing to integrate “Tecton,” Charles Williams’ community code for the Fault Systems Group, and “eqsim,” Brad Aagaard’s source physics and strong ground motion code, via the Pyre Framework. In addition, the Quakesim code “GeoFEST” (JPL) was impressive; a stronger integration of this project with the SCEC effort was initiated.

At MIT, we used the commercial finite element software Adina, which has a variety of element types and solvers, to address the cost vs. accuracy trade-off for linear and quadratic tetrahedral and hexahedral (brick) elements. We used the SCEC CDM Benchmark 4, a finite strike-slip fault in a finite domain, as our test case. Convergence tests (Figure 1) showed that 27-node hexahedral elements (with quadratic basis functions) are the most accurate we tested; we used the finest such mesh we could solve to define “truth.” We compared accuracies of solutions on coarser grids with nodes that were a subset of those in our most accurate mesh. (Caveat: this strategy led us to use rule-based, rather than free-form tetrahedral elements.) Important results include: 1) Elements with quadratic outperform elements with linear basis functions in cost vs accuracy; 2) Hexahedral elements outperform tetrahedral elements in cost vs accuracy; 3) Relative accuracies for elastic and viscoelastic solutions are comparable; 4) Performance of linear, rule-based tetrahedral elements is unacceptable; and 5) Iterative solution via conjugate gradient has solution time increasing as the (number of nodes)^{4/3}, regardless of element order or shape.

In view of the apparent computational advantages of hexahedral elements, it is prudent to examine whether the triangular/tetrahedral t-surf meshes that are natural for the Gocad-based CFM and CBM are the only practical choice of mesh. The presentation of the capabilities of Sandia’s Cubit meshing package at the LANL workshop pointed to a potentially fruitful approach to the problem. Cubit has the capability to generate hexagonal meshes of triangular regions (Figure 2a), as well as a scheme for converting from tetrahedral to hexahedral meshes (Figure 2b). We plan to investigate this further next year.

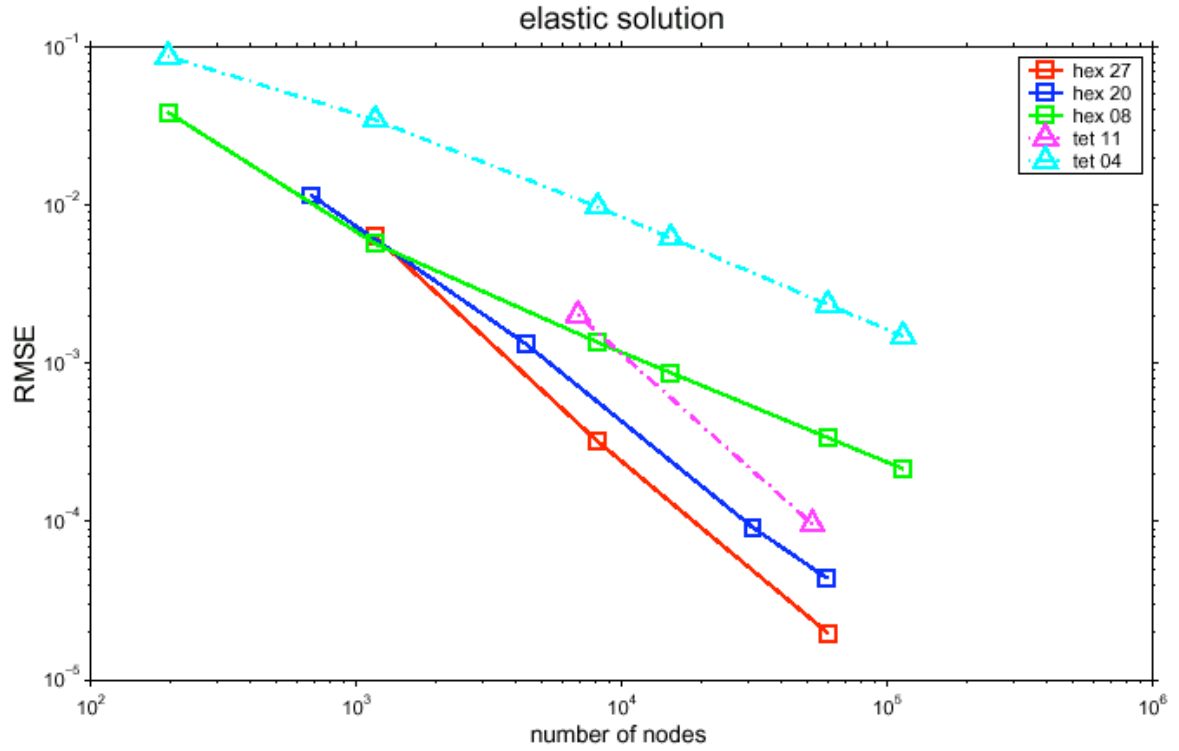


Figure 1: Log-log plot of root mean square error (RMSE) as a function of number of nodes for 27-node quadratic hexahedral elements, 20-node quadratic serendipity hexahedral elements, 8-node linear hexahedral elements, 11-node quadratic tetrahedral elements, and 4-node linear tetrahedral elements. For the same number of nodes, quadratic elements are more accurate than linear, and hexahedral elements are more accurate than tetrahedral.

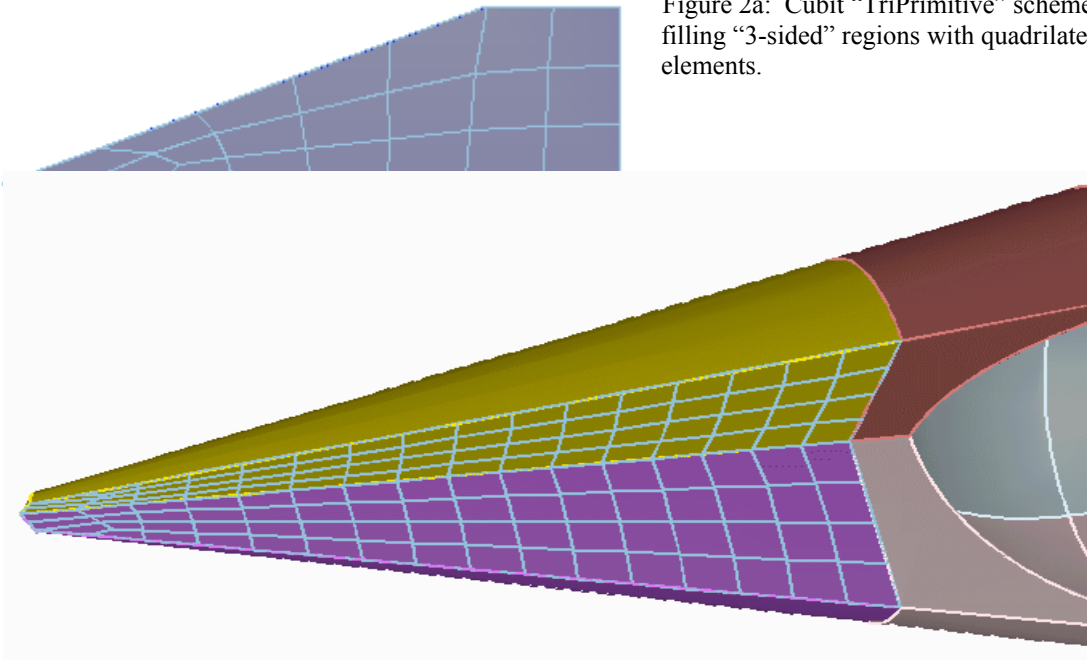


Figure 2a: Cubit "TriPrimitive" scheme for filling "3-sided" regions with quadrilateral elements.

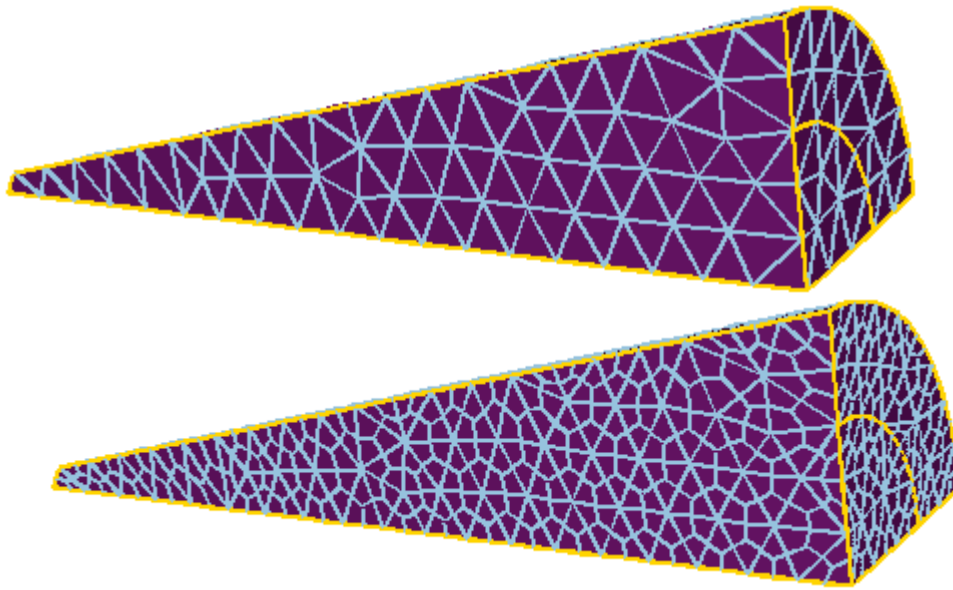


Figure 2b: Cubit scheme “thex” for tet -> hex mesh conversion

Community Block Model (CBM): Elements of SCEC’s Fault Systems studies require a three dimensional description of major fault blocks in southern California, the Community Block Model (CBM). The CBM will provide closed volumes that can be readily meshed, and used by 3D quasi-static codes for simulating crustal motions, and by codes that simulate earthquake catalogs over multiple rupture cycles. Unlike the community fault model (CFM), where faults can terminate laterally or at depth in free space, all “fault surfaces” in the CBM must extend to connect with other faults or the model boundaries. Extending fault surfaces requires both careful consideration of geology and meshing issues in order to produce meaningful block representations with topologies that are not too complex. Because most of the effort is being done by Shaw and Plesch at Harvard, the CBM effort is described in more detail in their report. However, Hager’s contribution is still substantial, so a brief summary is included here.

To get started on this iterative procedure, last year we developed a “□block” model of the northwestern LA basin (Figure 3). Blocks are bounded by faults and other surfaces, including topography and the base of seismicity surfaces extracted from the CFM. The completed blocks are defined by closed triangulated surfaces (t-surfs) that must fit together precisely without gaps or overlaps. Testing of the results by Carl Gable (LANL) has been crucial to debugging the process. The first attempt at block generation included: 1) collecting surfaces which bound a given block; 2) extending those surfaces such that they intersect; and 3) cross-cut mutually all intersecting surfaces. This process results in satisfactory block geometries that enclose completely a volume, with neighboring blocks sharing faces. Besides geometry, however, node connectivity and the topology of the triangles which comprise a given block need to respond to requirements of modeling software. The first requirement is that a block have no unconnected edges, a topology equivalent to a (deformed) sphere. Unfortunately, repeated cross-cutting using the Gocad modeling software of one face with several adjacent faces created connectivity problems. The unconnected nodes are difficult to connect or eliminate without completely

regenerating the block (e.g., by using LAGrid). Fortunately, the Gocad block generation process could be modified to allow the software to determine an optimal cross-cutting sequence. The modified process is much more successful in producing improved, albeit not perfect triangle connectivity, with only minor manual editing required.

Carl Gable has used LAGrid to start with the closed surfaces of the \square block model and generate a volume-filling tetrahedral mesh of the region. This mesh is available for use in testing FEM codes used by the CDM.

We are now extending the region covered by the block model to include the entire region included in the USR. The initial coarse model, CBM-A, includes a subset of 52 faults selected from the more than 120 faults currently comprising the CFM. Faults were selected based on size, slip rate, and continuity. We will provide this product by the end of the current funding period.

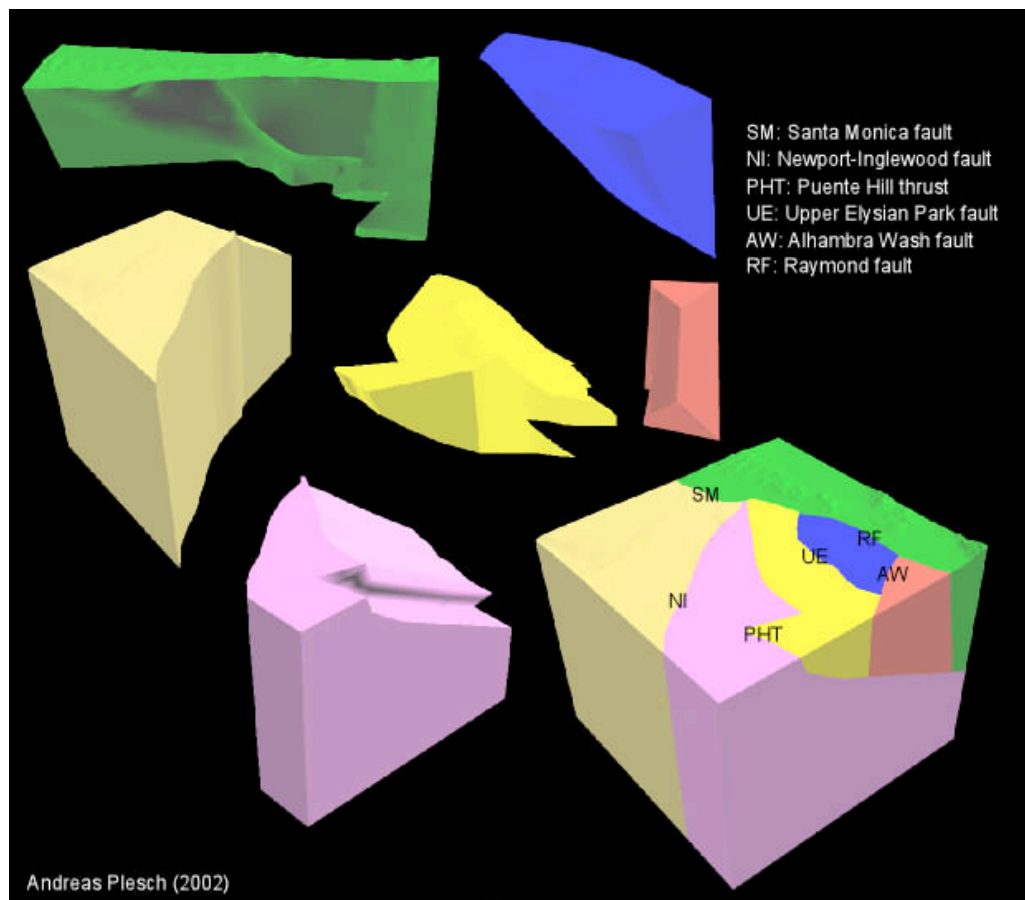


Figure 3: \square block model of the northwestern Los Angeles basin. Discontinuous faults in the CFM are connected with interpolated and extrapolated surfaces to form closed volumes (aka “blocks”). These closed volumes allow for efficient mesh generation for FEM with arbitrary rheologies and can also be used directly in models that assume block-like motions.