Scan of Shelley Kenner's Presentation - ABAQUS

SCEC Crustal Deformation Modeling Workshop

Caltech, June 10-12, 2002

ABAQUS Capabilities

Analysis Types

- Linear and nonlinear static stress-displacement analysis
- Linear dynamic stress-displacement analysis, including:
  - Time history response
  - Steady-state response due to harmonic loading
  - Dynamic response to random loadings
- Transient nonlinear dynamic stress-displacement analysis
- Transient and steady-state heat transfer analysis
- Fully coupled temperature-stress analysis
- Fully coupled thermoelectric analysis
- Coupled pore-fluid and stress analysis
- Mass diffusion analysis
- Fracture mechanics analysis
- Hydrostatic fluid filled cavities
- Etc.

Material Types

- Linear and nonlinear elasticity
- Poroelasticity
- Elastoplasticity
- Plasticity
- Viscoelasticity/Creep
- Etc.

Other Features

- User defined materials and creep laws
- [illegible]
- [illegible]
- [illegible]
- [illegible] boundary conditions
- [illegible] conditions

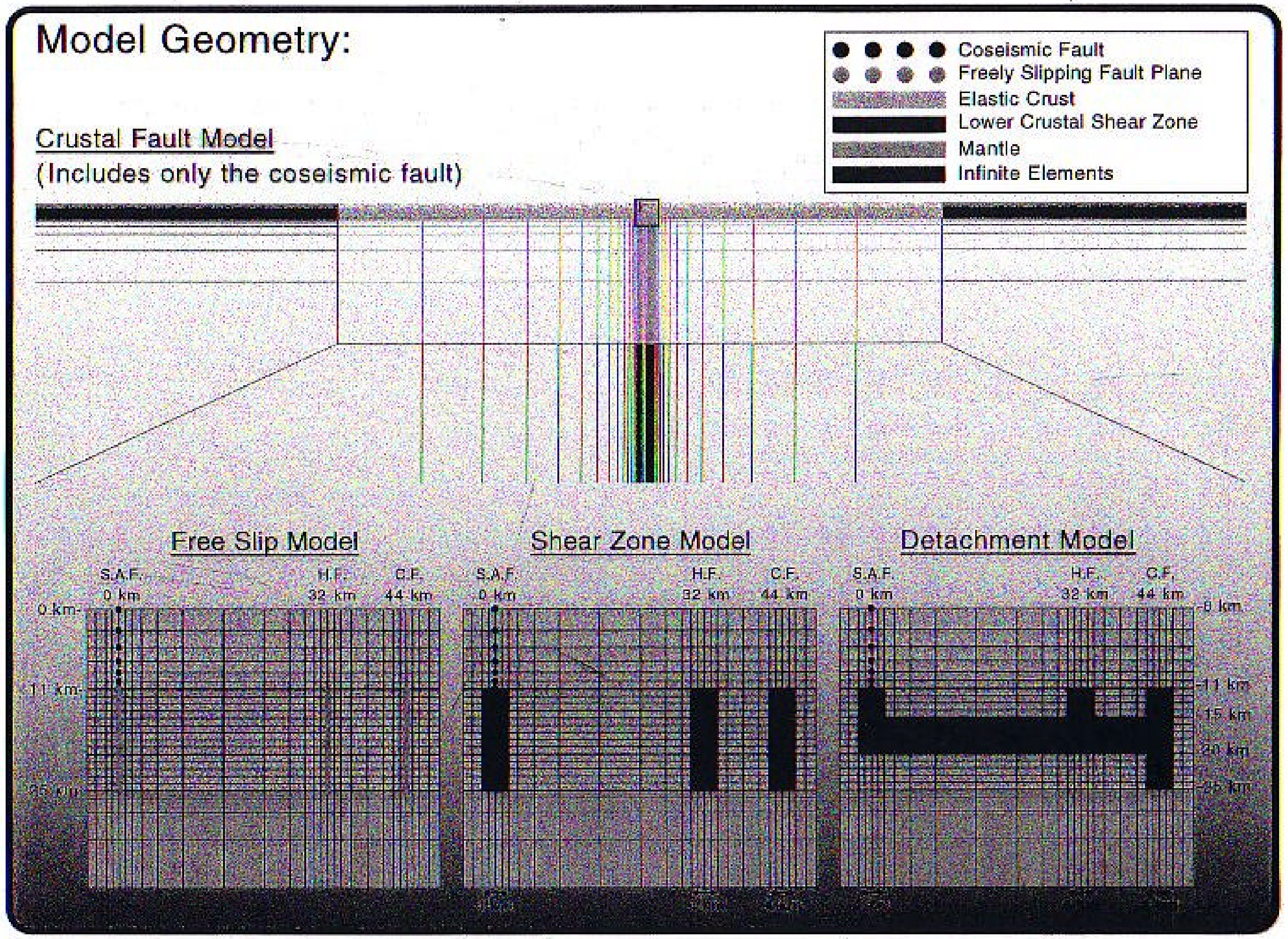
ABAQUS CAPABILITIES

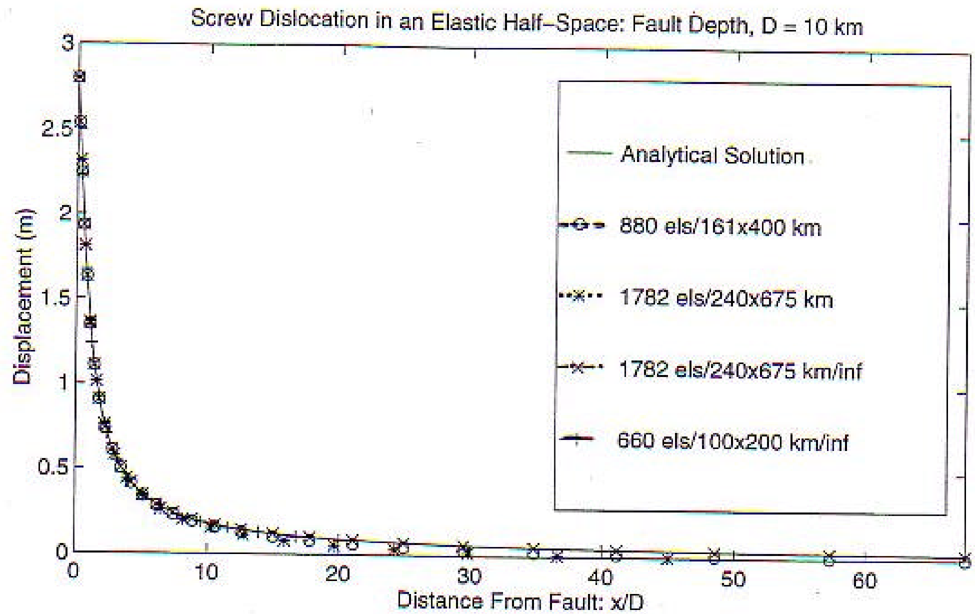
ELEMENTS

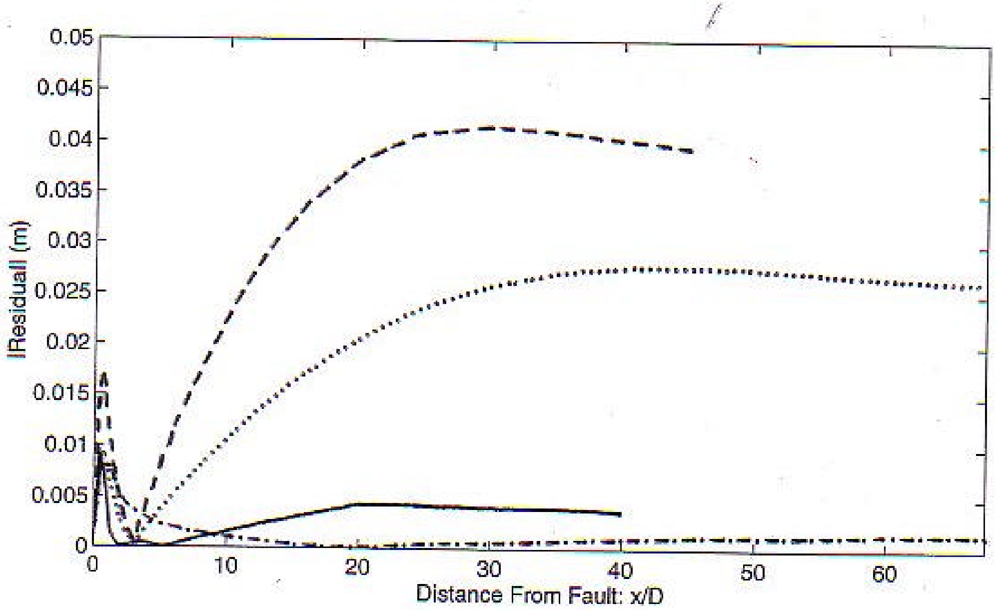
- **Continuum Elements** (Plane Stress, Plane Strain, Axisymmetric, 1D, 2D, 3D)
  - Triangles (2D), quadrilaterals (2D), tetrahedral, triangular prisms, hexahedra, structural elements (1D)
  - 1rst and 2cnd order elements
  - Full and reduced integration elements with hourglass control
  - Modified triangular and tetrahedral elements for contact problems
  - Hybrid elements for compressible or nearly incompressible problems
  - Incompatible model elements for improved bending behavior
  - Variable node elements
- **Structural Elements**
- **Connector Elements** (e.g. Springs, Dashpots)
- **Hydrostatic Elements**
- **Infinite Elements** (allow realistic half-space models)

SOLVERS AND SOLUTION CONTROLS

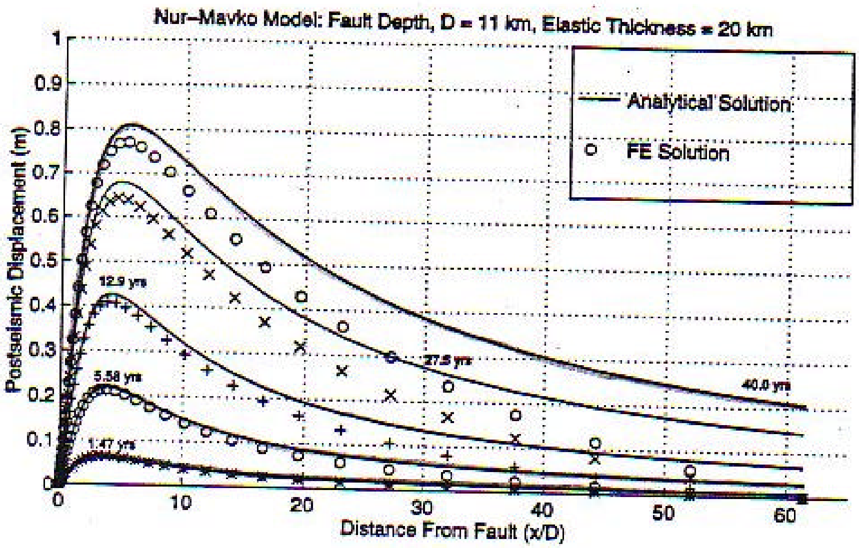
- **Sparse Solver** (multifront)
- **Wavefront Solver** with wavefront minimization for repeat jobs
- **Convergence Criteria:** automatic or user-specified
- **Time-Integration Criteria:** automatic or user-specified


Model Geometry:
Crustal Fault Model
(Includes only the coseismic fault)
Coseismic Fault
Freely Slipping Fault Plane
Elastic Crust
Lower Crustal Shear Zone
Mantle
Infinite Elements
Free Slip Model
Shear Zone Model
Detachment Model
S.A.F.
0 km
H.F.
32 km
C.F.
44 km
0 km
11 km
15 km
20 km
25 km


Screw Dislocation in an Elastic Half-Space: Fault Depth, D = 10 km
Analytical Solution
880 els/161x400 km
1782 els/240x675 km
1782 els/240x675 km/inf
660 els/100x200 km/inf
Displacement (m)
Distance From Fault: x/D


|Residual| (m)
Distance From Fault: x/D

(A)



(B)

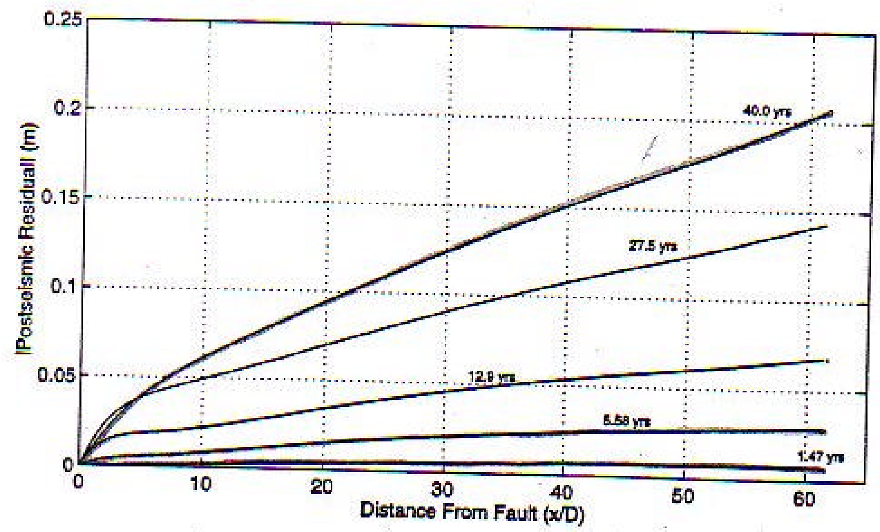
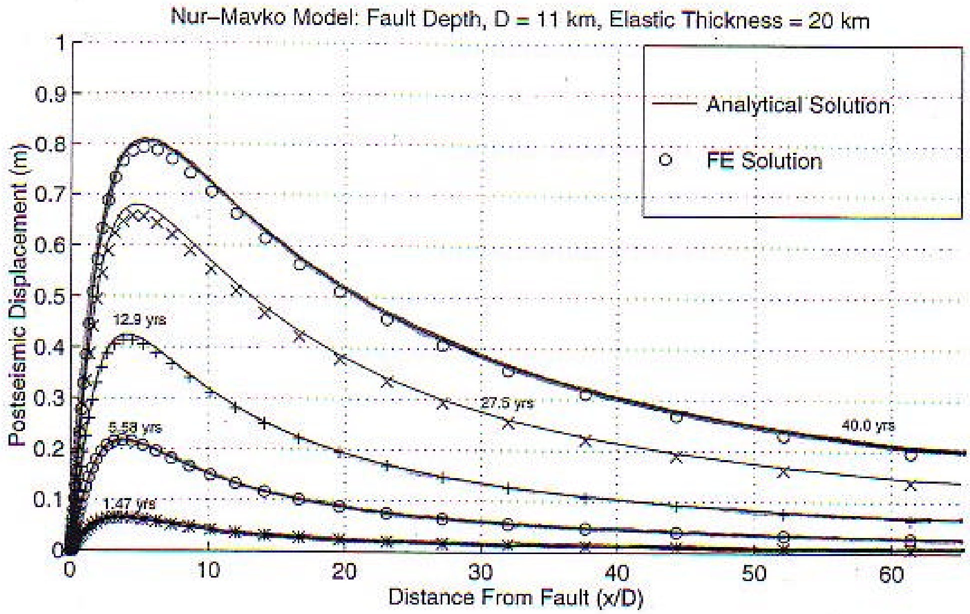
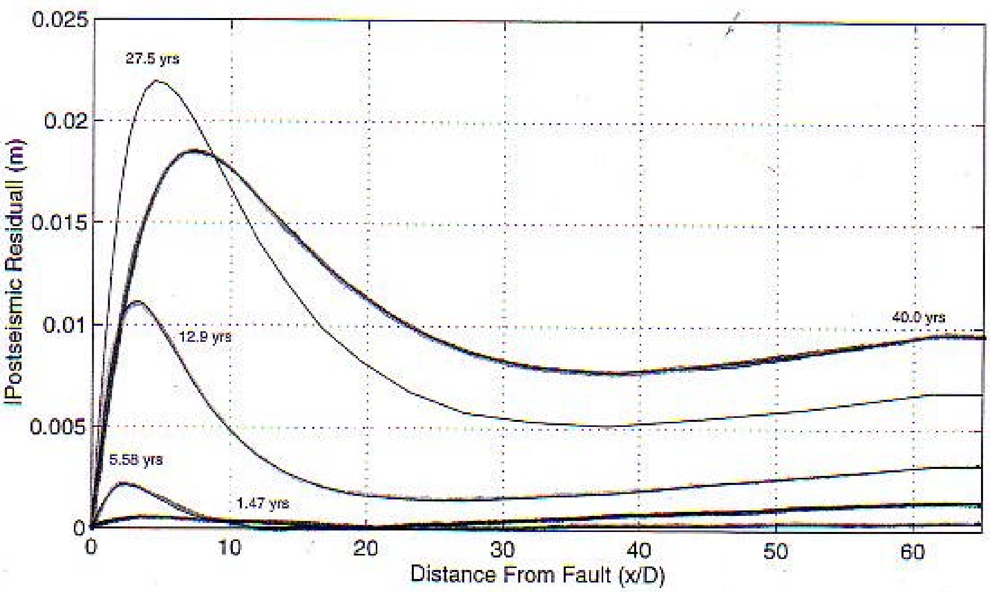


Figure 14: The benchmarking results for the anti-plane elastic plate/viscoelastic half-space model. The outer edges of the finite element model are fixed and uniform slip is imposed on the fault surface from 0 - 11 km. The finite element model is a 38 x 75 element mesh with dimensions of 675 km x 300 km. The shear modulus is 3.5×10^4 MPa. The relaxation time is 10.9 yrs. (A) The cumulative postseismic displacement. (B) The difference between the analytical and finite element solutions at each time.


Nur–Mavko Model: Fault Depth, D = 11 km, Elastic Thickness = 20 km
Analytical Solution
FE Solution
Postseismic Displacement (m)
Distance From Fault (x/D)
12.9 yrs
27.5 yrs
40.0 yrs
5.58 yrs
1.47 yrs


|Postseismic Residual| (m)
Distance From Fault (x/D)
27.5 yrs
12.9 yrs
40.0 yrs
5.58 yrs
1.47 yrs

ABAQUS CAPABILITIES

PRESCRIBED CONDITIONS

- **Initial Conditions**
  - Velocity
  - Stress
  - Temperature
  - Fluid Pressure
  - Pore Fluid Pressure
  - Void Ratio
  - Geostatic Stress (elevation dependent)

- **Kinematic Boundary Conditions**
  - Pinned
  - Built-in
  - Rollers
  - Displacement
  - Velocity
  - Acceleration

  - Can be added, altered, or removed during any step
  - User-specified amplitude variation is possible during any step

- **Load Boundary Condition**
  - Concentrated Loads (at nodes)
  - Distributed Pressures
  - Hydrostatic Pressure
  - Gravity

  - Can be added, altered, or removed during any step
  - User-specified amplitude variation is possible during any step

- **Temperature Loads and Fluxes**
- **Pore Fluid Flow**
- **Etc.**

KINEMATIC CONSTRAINTS

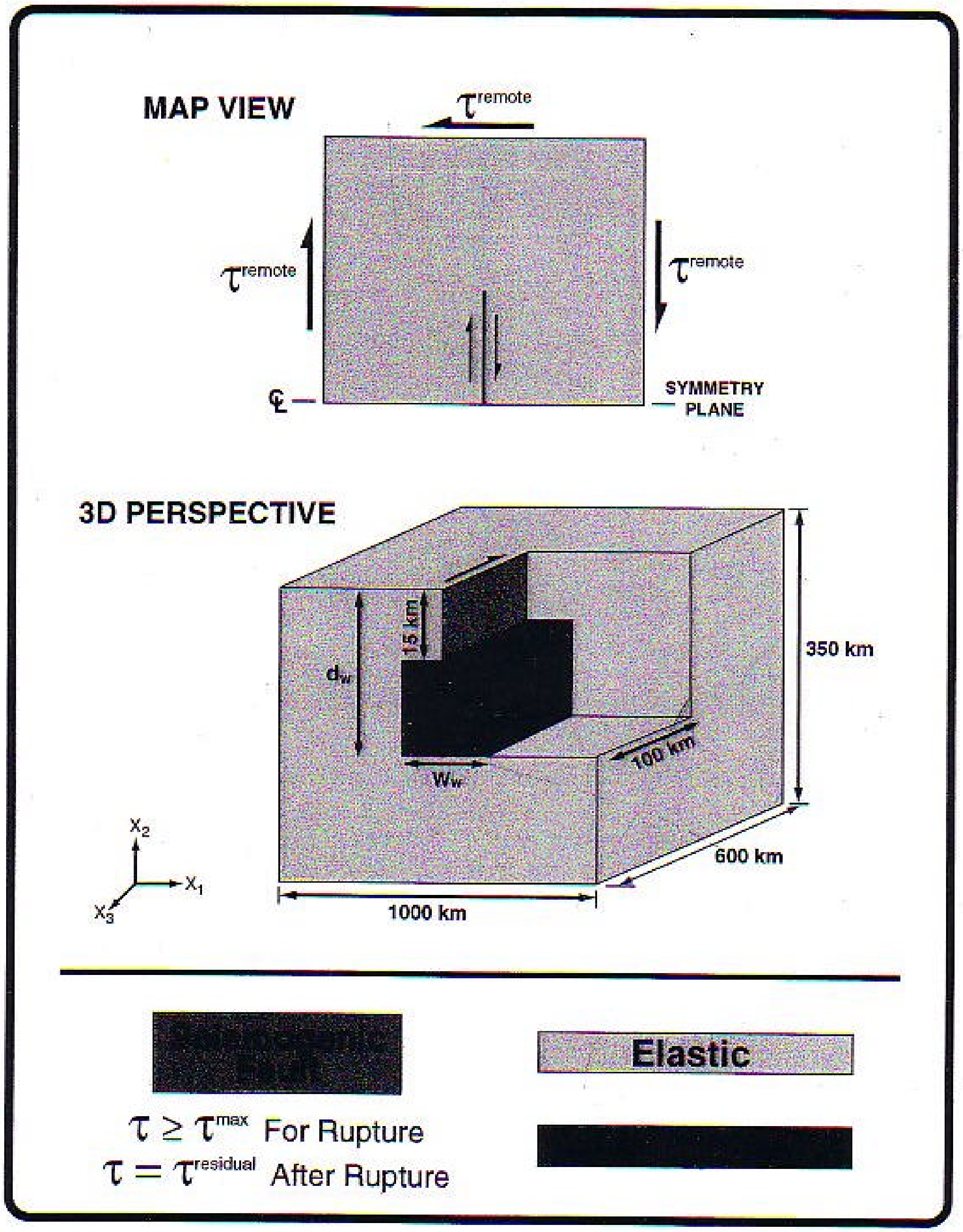
- **Linear Constraint Equations**

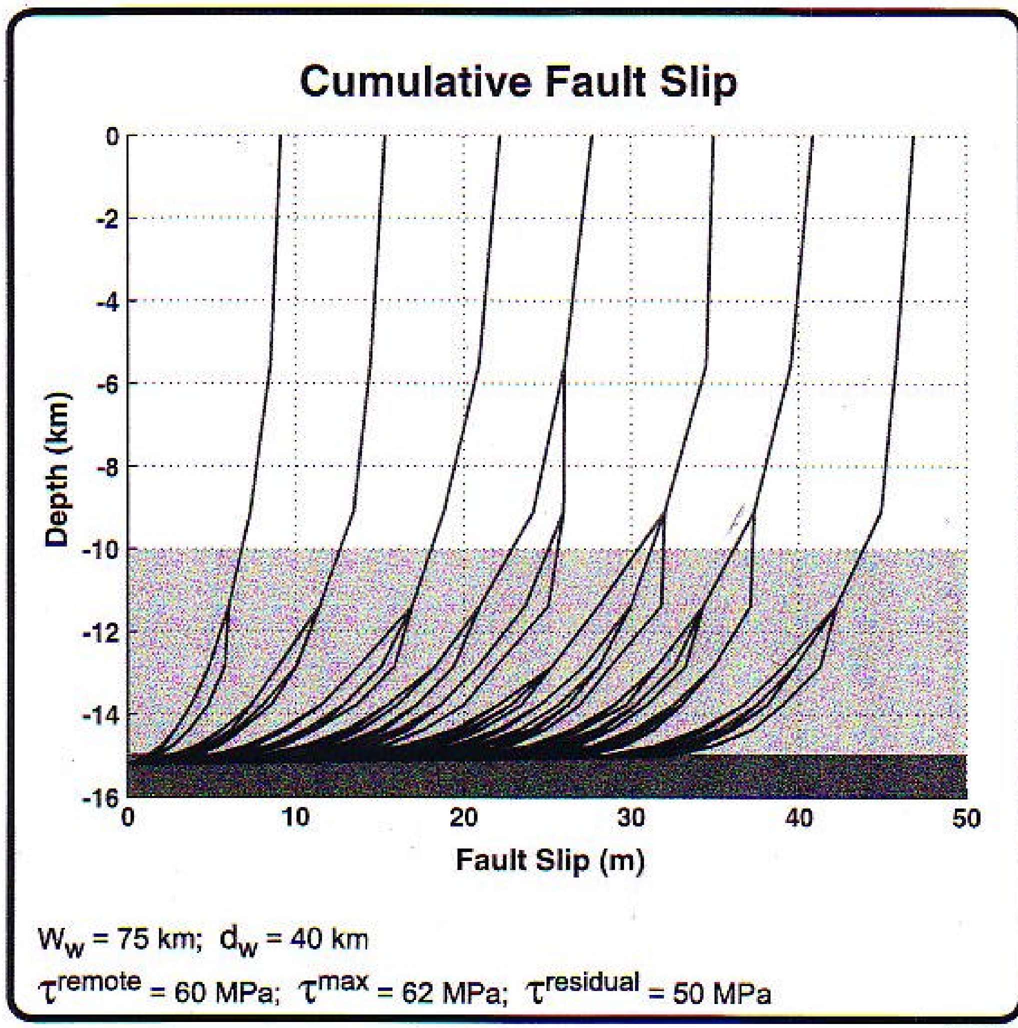
$$\text{e.g.,}\quad A_1 u_i^P + A_2 u_j^Q + \ldots\ldots\ldots\ldots + A_N u_k^R = 0,$$

  where i, j, k, etc. denote degree of freedom and P, Q, R, etc. denote individual nodes or node sets.

  - Useful for constraining fault motions, internal constraints when applying stress boundary conditions

- **Multi-Point Constraints**
  - Used in mesh refinement, sliding, kinematic coupling, tying nodes, etc.


MAP VIEW
τ^remote
τ^remote
τ^remote
SYMMETRY PLANE
℄
3D PERSPECTIVE
15 km
d_w
W_w
100 km
350 km
600 km
1000 km
X_2
X_1
X_3
[redacted]
Elastic
τ ≥ τ^max For Rupture
τ = τ^residual After Rupture


Cumulative Fault Slip
Depth (km)
0
-2
-4
-6
-8
-10
-12
-14
-16
0
10
20
30
40
50
Fault Slip (m)
W_w = 75 km; d_w = 40 km
τ^{remote} = 60 MPa; τ^{max} = 62 MPa; $\tau^{residual}$ = 50 MPa

mxshrA2

ABAQUS CAPABILITIES

USER-DEFINED SUBROUTINES

- **Available User-Defined Subroutines** (via FORTRAN codes)
  - **Constitutive Laws**
    - Creep Laws
    - Friction
    - Yield Surface Size and Hardening Parameters for Isotropic Plasticity and Combined Hardening Models
    - Equivalent Pressure-Stress Conditions
    - New Constitutive Laws – Mechanical
  - **Temperature Dependent Problems**
    - Heat Transfer Parameters for Convection, Diffusion, Cavity Radiation, etc. (non-uniform film coefficients, heat sinks, mass flow rate conditions, etc.)
    - Prescribed Temperature Distributions
    - Internal Heat Generation
    - Non-Uniform Gap Conductance (heat, electric)
    - Non-Uniform Flux (Heat or Mass)
    - Incremental Thermal Strains
    - New Constitutive Laws - Thermal
  - **Poroelastic Problems**
    - Initial Pore Fluid Pressure Distributions
    - Initial Pore Fluid Velocity Distributions
    - Initial Void Ratios
    - Non-Uniform Fluid Flux
    - Non-Uniform Mass Diffusion
    - Non-Uniform Seepage Coefficients/Sink Pore Pressures
    - Fluid Density/Compliance
  - **Initial and Boundary Conditions, Kinematic Constraints**
    - Non-Uniform Displacement Boundary Conditions
    - Non-Uniform Distributed Loads
    - Initial Stress Field
    - Initial Equivalent Plastic Strain
    - Multi-Point Constraints
  - **Input/Output**
    - Read/Write Information from/to External Databases
    - External Database Design and Management
    - Generate Element Output
  - **Miscellaneous**
    - Define Solution Dependent State Variables
    - Predefine/Redefine Field Variables at Material Points
    - New Element Definitions
    - Define Local Coordinate Systems
    - Rigid Surfaces
- **State variable** dependencies allowed within subroutines
- **Field variables** can be defined by user: Subroutine calculations can depend on and/or update the field variables

ABAQUS CAPABILITIES

CONTACT PROBLEMS

- Defined using **master surface/slave surface** technique

- **Capabilities**

  - **Repeated removal and reactivation of contact pairs**

  - Tied contact

  - Extension of master surface

  - **User-specified pressure clearance relation**

  - **Control strike-slip, dip-slip, and opening components of motion independently**

  - Default friction relations
    - Frictionless
    - Coulomb friction
    - Kinematic and static coefficient of friction
    - Maximum shear stress (does not relock)
    - Changing friction values during analysis
    - User-defined friction subroutines

  - **User-defined friction relations allow**
    - Fault locking after slip events
    - State variable dependencies in constitutive relation allowed
    - Field variables can be included in friction relation (e.g., allows calculation of average stresses)
    - Field variables can be a function of the surface state
    - User-specified dependence on shear and normal stresses across surface

- **Stiffness Method or Lagrange Multiplier Method**

- **Thermal Interactions Allowed Across Surface**

- **Pore Fluid Interactions Allowed Across Surface**

Implementation of the Maximum Shear Stress Fault Constitutive Relation

For each node at each time increment:
What is the magnitude of τ^{out} ?

Allowable τ^{out} for Initial Rupture

If Other Nodes **NOT** Rupturing ...
- Cutback Time Step
- Restart Increment

If Other Nodes **ARE** Rupturing ...

If $\Delta t > (\Delta t)_{max}$ for multi-node rupture ...
- Cutback Time Step
- Restart Increment

If $\Delta t \leq (\Delta t)_{max}$ for multi-node rupture ...
- Allow Rupture
- Continue Equilibrium Iterations Until [illegible]

ABAQUS CAPABILITIES

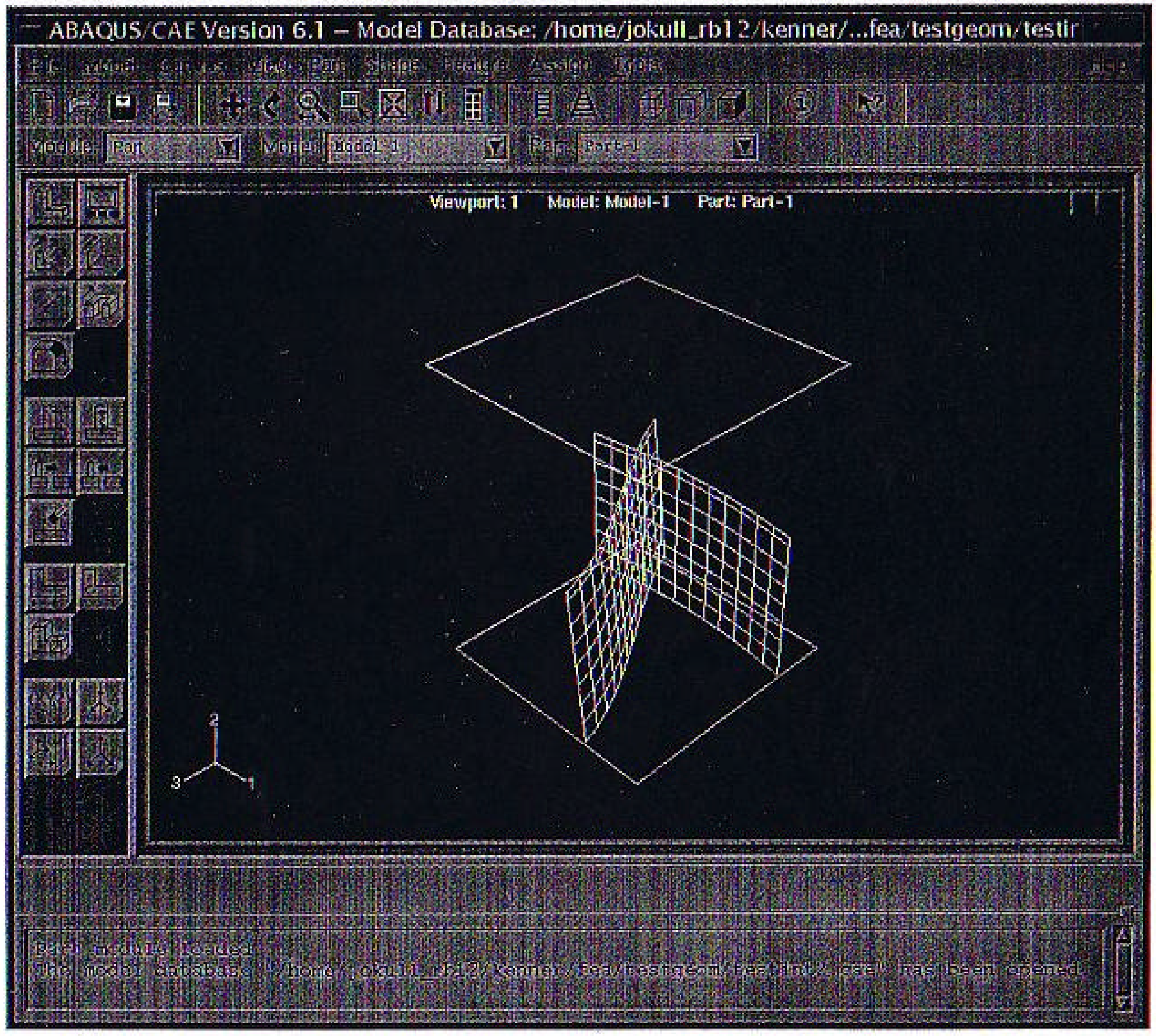
PRE- AND POST-PROCESSING

- **ABAQUS CAE**
  - Interfaces directly with ABAQUS STANDARD and ABAQUS EXPLICIT
  - Packaged with ABAQUS license
  - Scripts written in PYTHON
  - Not all ABAQUS capabilities supported at this point (mostly esoteric commands needed for faulting problems and geologically realistic BC's)
  - Kludgy geometry generation, surface definition, etc.
  - Mesh generation capabilities
  - Designed for engineering purposes

- Other commercially available pre- and post-processors (e.g. **I-DEAS**, **PATRAN**, **HyperMesh**, etc.)
  - Write/Read ABAQUS input/output files
  - Generally more user-friendly pre-, post-processors
  - Much better geometry generation
  - Mesh generation capabilities
  - Additional cost
  - Designed for engineering purposes

- In-house codes written in MATLAB (e.g., **APMODEL**), FORTRAN, C++, etc.
  - Can be designed especially for fault and tectonic problems
  - Can be designed to interface with a variety of finite element codes
  - Bookkeeping can get complex (need to keep track of geometry, mesh, IC's, BC's, input/output, solutions controls, rheologies, etc., etc., etc.)
  - Large investment of time required to generate/code/debug reasonable pre-, post-processor
  - Mesh generation issues – need to appeal to the experts for non-uniform meshing capabilities
  - Once the code has matured, probably the most efficient and easy to use option for geoscientists who have no background in CAD, CAM, or CAE

> In finite element studies, the vast majority of skilled person hours are spent during pre-processing, especially geometry and mesh generation. This is particularly true as models become more complex. Thus, the success of this project requires the development of efficient, user-friendly and numerically robust pre- and post-processor capabilities.


ABAQUS/CAE Version 6.1 – Model Database: /home/jokull_rb12/kenner/...fea/testgeom/testir
Viewport: 1 Model: Model-1 Part: Part-1

ABAQUS
Pros and Cons

- **Pros**
  - Extremely user adaptable/modifiable (e.g., user-subroutines, ability to specify various numerical criteria, etc.)
  - Allows user to push the envelope of typical engineering applications to deal with specific tectonic and fault modeling problems (especially non-kinematic contact problems)
  - Allows user to model almost any tectonics scenario they might imagine (e.g., contact, thermal, poroelastic, hydrostatic pressures, creep, depth-dependence, lateral rheological variations, etc., etc.)
  - Robust convergence and time-stepping (automatic or user-specified), especially for non-linear problems
  - Extensive element library with elements designed to minimize numerical errors under a variety of conditions (bending, contact, incompressible limit, etc.)
  - Extensively benchmarked and tested with a variety of example and verification problems

- **Cons**
  - Not open source
  - Not a particularly fast solver
  - Does not run on distributed memory machines
  - Can run in parallel on shared memory machines, but not very efficiently
  - No obvious pre-, post-processor choice (industry users purchase commercial pre-, post-processors which interface directly with ABAQUS).

Coseismic, Postseismic, & Interseismic Fault Modeling Problems

Potential Technical Issues

- Geologically appropriate BC's: stress vs. velocity BC's – which work best, when, and how best to implement them
- Implementation of stress BC's: initial equilibrium, specification of distributed normal stresses, application with time-dependent rheologies.
- Model cycle-up: is model cycle-up important, methods for efficiently preconditioning model stresses
- Specification and numerical characterization of complex, potentially continuous rheologic definitions (viscoelastic, depth-dependent, strain-rate dependent, temperature-dependent, etc.)
- Generation of time-dependent numerical models that do not include unrealistic, model induced temporal deformation transients
- Pros and cons of infinite elements in large scale tectonic models
- Geologically reasonable, numerically efficient, non-kinematic fault friction relations
- Mechanisms that naturally concentrate stress and deformation, especially in the seismogenic crust
- Topographically complex, potentially intersecting 3D surface generation