Branched Fault Benchmarks
TPV24 and TPV25

Michael Barall
Invisible Software, Inc.

SCEC Dynamic Rupture Code Validation Workshop
March 15, 2013
TPV24-25 Summary.

**Benchmark** | **Dimension** | **Rupture Type** | **Material Properties**
---|---|---|---
TPV24 | 3D | Right-lateral, releasing branch. | Linear elastic. |
TPV25 | 3D | Left-lateral, restraining branch. | Linear elastic. |

Requested resolutions: 100 m and 50 m.

Although these are linear elastic benchmarks, they are constructed like plastic benchmarks.
The boundary condition is that slip on the branch fault goes to zero at the junction point.

The picture shows a possible implementation for a finite-element code that uses split nodes. The junction point behaves as an ordinary split-node on the main fault. Other types of code may implement the junction point in different ways.
Issues in the Design of Branched Fault Benchmarks
Loss of Numerical Precision.

This is an extreme example of loss of numerical precision on the branch fault.

The 50 m and 100 m results begin to diverge in the part of the branch fault where stresses are close to the minimum needed for the rupture to propagate.

(Figure shows a right-lateral case that differs from TPV24 in initial stress tensor and other ways.)
Loss of Numerical Precision.

Finite Element (FaultMod) 100 m
Finite Element (FaultMod) 50 m

This is another example of loss of numerical precision on the branch fault.

Divergence occurs where there is just barely enough stress, or just barely not enough stress, to sustain the rupture.

(Figure shows a left-lateral case that differs from TPV25 in initial stress tensor and other ways.)
Nucleation
Day Radius and the Problem of Nucleation.

Day (1982) obtained the following formula, which gives the minimum radius $R_D$ that a circular rupture must have, such that it is energetically favorable for the rupture to expand.

$$R_D = \frac{7\pi \mu (\tau_s - \tau_d) D_c}{24(\tau - \tau_d)^2}$$

For typical parameter values used in spontaneous rupture simulations, the Day radius is about 3 to 4 km.

The nucleation problem is that, somehow, we must impose an artificial mechanism to get the size of the rupture up to the Day radius, at which point the rupture can be self-sustaining.
Pros and Cons of Two Nucleation Methods.

Overstress Method: Apply high initial shear stress in the nucleation zone.

- Pro: Simple to implement.
- Pro: Nucleation zone can be small, by making the initial stress high enough.
- Con: Small changes in the nucleation process affect the entire fault.
- Con: Injects a lot of excess energy into the rupture.
- Con: Much higher slip in nucleation zone than elsewhere on the fault.
- Con: Not compatible with a regional stress tensor (and so not usable with plasticity).

Forced-Rupture Method: Reduce the friction in the nucleation zone.

- Pro: Small changes in the nucleation process tend not to affect the entire fault.
- Pro: Does not produce higher slip in the nucleation zone.
- Pro: Does not require alteration of stress (and so compatible with a regional stress tensor and with plasticity).
- Con: More complicated to implement.
- Con: Requires large nucleation zone, at least the size of the Day radius.
Decay time = 0 s, Constant $V_R$.
(Original method)

Nucleation Methods Considered For Benchmarks TPV22-25.

Plots show horizontal slip rate at the hypocenter.

Decay time = 0.50 s, Constant $V_R$.
(Final method)
Nucleation Parameters.

Radius of nucleation zone \( r_{\text{crit}} = 4000 \text{ m} \)

Time of forced rupture

\[
T = \begin{cases} 
\frac{r}{0.7 V_S} + \frac{0.081 r_{\text{crit}}}{0.7 V_S} \left( \frac{1}{1-(r/r_{\text{crit}})^2} - 1 \right), & \text{if } r < r_{\text{crit}} \\
1.0E+9, & \text{if } r \geq r_{\text{crit}}
\end{cases}
\]

Forced rupture decay time \( t_0 = 0.50 \text{ s} \)

Speed of forced rupture \( V_R/V_S \).
TPV24-25 Design
Friction Parameters.

\[
\begin{align*}
\mu_s &= 0.18 \\
\mu_d &= 0.12 \\
d_0 &= 0.30 \text{ m} \\
C_0 &= \begin{cases} 
0.30 \text{ MPa} + (0.000675 \text{ MPa/m})(4000 \text{ m} - \text{ depth}), & \text{if depth} \leq 4000 \text{ m} \\
0.30 \text{ MPa}, & \text{if depth} \geq 4000 \text{ m}
\end{cases}
\end{align*}
\]

Friction coefficients are low because of the high initial normal stress, which is lithostatic.

Cohesion tapers from 3.0 MPa at the earth’s surface, to 0.3 MPa at depths of 4000 m or greater.

Cohesion in the upper 4 km suppresses free surface effects.
Initial Stress Tensor and Fluid Pressure.

\[ P_f = (1000 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(\text{depth in meters}) \]

\[ \sigma_{11} = -(2670 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(\text{depth in meters}) \]

\[
\sigma_{22} = \begin{cases} 
 b_{22} (\sigma_{11} + P_f) - P_f, & \text{if depth } \leq 15600 \text{ m} \\
 \sigma_{11}, & \text{if depth } > 15600 \text{ m}
\end{cases}
\]

\[
\sigma_{33} = \begin{cases} 
 b_{33} (\sigma_{11} + P_f) - P_f, & \text{if depth } \leq 15600 \text{ m} \\
 \sigma_{11}, & \text{if depth } > 15600 \text{ m}
\end{cases}
\]

\[
\sigma_{23} = \begin{cases} 
 b_{23} (\sigma_{11} + P_f), & \text{if depth } \leq 15600 \text{ m} \\
 0, & \text{if depth } > 15600 \text{ m}
\end{cases}
\]

\[ \sigma_{13} = \sigma_{12} = 0 \]

<table>
<thead>
<tr>
<th>Initial Stress Tensor Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>( b_{22} )</td>
</tr>
<tr>
<td>( b_{33} )</td>
</tr>
<tr>
<td>( b_{23} )</td>
</tr>
</tbody>
</table>
On-Fault Stations.

Modelers are asked to submit slip, slip rate, and stress as a function of time, for 8 stations on the main fault (top) and 6 stations on the branch fault (bottom).

In addition, modelers are asked to submit the time at which each point on the fault begins to slip, from which we construct rupture contour plots.
Off-Fault Stations

Modelers are asked to submit displacement and velocity as a function of time, for 8 stations on the earth’s surface.
TPV24 Results — 50 vs. 100 Meters
Main Fault

Branch Fault

Hypocenter

branchst090dp100

Hypocenter

barall (Michael Barall - Finite Element - FaultMod - 100 m)

barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
Main Fault

Branch Fault

Hypocenter

branchst090dp100

Horizontal slip rate (m/s)

Time (s)

soma (Surendra Somala - Spectral Element - SESAME (100m))

somala.2 (Surendra Somala - Spectral Element - SESAME (50m))
Main Fault

Branch Fault

Hypocenter

branchst090dp100

Comparison between 200 vs. 100 m
TPV24 Comparisons
(Right-Lateral, Releasing Branch)
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
Main Fault

5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
Comparision of Final Slip on Main and Branch Faults

- Faults:
  - faultst020dp000
  - faultst090dp000
  - faultst020dp100
  - faultst090dp100

- Branches:
  - branchst020dp000
  - branchst090dp000
  - branchst020dp100
  - branchst090dp100

- Graphs show horizontal slip over time for both main and branch faults.

- Main Fault Slip:
  - Graph indicates initial slip, followed by a steady state.

- Branch Fault Slip:
  - Graphs show initial slip, then a peak and finally a steady state.

- Diagrams illustrate the faults and their slip patterns.
TPV25 Comparisons
(Left-Lateral, Restraining Branch)
Branch Fault

Distance along strike (m)

Distance down-dip (m)

- aagaard.2 (Brad Aagaard - PyLith v1.9.0a - Tet4 100m)
- barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
- duan.2 (Benchun Duan - Finite Element - EQdyna - 50 m)
- ma (Shuo Ma - Finite Element - MAFE (100 m))
- somala (Surendra Somala - Spectral Element - SESAME (100m))
Branch Fault

Distance down-dip (m)

Distance along strike (m)

- aagaard.2 (Brad Aagaard - PyLith v1.9.0a - Tet4 100m)
- barall.2 (Michael Barall - Finite Element - FaultMod - 50 m)
- duan.2 (Benchun Duan - Finite Element - EQdyna - 50 m)
- ma (Shuo Ma - Finite Element - MAFE (100 m))
- somala (Surendra Somala - Spectral Element - SESAME (100m))
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
branchst010dp100

5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
Zero slip at this location, for all codes.

5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
5 Hz low-pass filter applied to all time series.
Conclusions

Our branched-fault benchmarks are:
TPV24 = Right-lateral, releasing branch.
TPV25 = Left-lateral, restraining branch.

The benchmarks are linear elastic but are designed like plastic benchmarks, with gravitational loading, fluid pressure, and an initial stress tensor specified throughout the medium.

These multi-fault benchmarks are designed to avoid loss of numerical precision, which may occur if there is a significant part of the branch fault where shear stress is near the minimum required to sustain a rupture.

We nucleate by gradually reducing the friction within the nucleation zone, to create a forced rupture with variable speed.

With selected parameters, the releasing case ruptures the entire branch fault, while the restraining case ruptures only a small part of the branch fault.

Comparison of 50 m and 100 m results shows good agreement, indicating the benchmarks are well resolved at the requested resolutions.

Comparison between different codes shows good agreement.