a) Summary of Research Highlights

Significant experimental results:

1) A rupture propagating in a fracture damaged medium travels at a velocity below that expected based solely on the associated reduction in the elastic moduli, even if the rupture does no new damage. The implication for fault mechanics models is that it is not sufficient to simply account for the reduction in moduli associated with fracture damage.

2) A rupture propagating along the edge of a damaged fault zone propagates at a higher velocity in the direction that puts the compressive lobe of the crack tip field in the damaged material. In some cases the propagation is unilateral in this direction and may even jump to supershear. This is the opposite direction from that expected based on the reduction in modulus and is observed to dominate the velocity effect.

Significant theoretical results:

1) Expansion of the Ashby and Sammis damage mechanics to include the physics of high-speed crack propagation and incorporation of this new dynamic damage mechanics as a user defined rheology in the ABAQUS dynamic finite element code.

2) A verification of the dynamic damage mechanics by accurately prediction the failure envelope of marble over 14 orders of magnitude in loading rate.

3) Prediction of the damage pattern and elastic waves generated by an explosion in a “candy-glass” plate. This is a further test of the dynamic damage mechanics code in a geometry that is a bit simpler than a propagating rupture. We are currently working to generate dynamic fractures on a frictional interface in candy glass. We have switched from photoelastic polymers (Homalite and polycarbonate) to candy-glass because we were unable to generate new damage in the polymers by either stick-slip events or explosions. Explosions in candy-glass generated extensive fracture patterns. We have identified the difference by measuring the critical stress intensity factor in the candy glass which turned out to be only 0.04 MPa $m^{1/2}$ as compared to 1 MPa $m^{1/2}$ in the polymers.

b) Technical Report

The primary objective of this research has been to identify the dynamic processes that produce fault zone structures observed in the field and to understand the effect of fault zone structure on the dynamics of an earthquake rupture. The approach has been a combination of experiments in Professor Ares Rosakis’ high-speed digital photography lab at Caltech and a theoretical expansion of the Ashby and Sammis (1990) quasi-static micro-mechanical damage mechanics to include the physics of high-speed fracture propagation.

Having demonstrated that our dynamic damage mechanics accurately predicted the failure strength of Carrera marble at loading rates spanning 14 orders of magnitude (see last year’s annual SCEC report), we spend the past year using the ABAQUS implementation to begin to model earthquakes and underground explosions.

In our previous laboratory studies, we documented strong effects of off-fault damage on rupture propagation (beyond the effects due to the associated reduction in elastic moduli), but we were unable to generate new damage. Last year, we concentrated on finding a material that would allow us to generate new damage during stick-slip sliding events thus allowing us to simulate the dynamic development of a fault zone.

We settled on a material used in the film industry called break-away glass or candy-glass, which allows actors to safely fly through plate glass windows or hit each other on the head with beer bottles. As is evident in Fig.1A, an exploding wire in the center of a plate of this material produced an extensive fracture pattern. The same explosion produced no fractures in the Homalite or Polycarbonate plates that we previously used. Randy Martin at New England Research measured the P and S waves velocities in candy glass, which were comparable to those in Homalite and Polycarbonite. We then used four-point bending to measure the critical stress intensity factor which turned out to be a factor of 25 times smaller than that in the polymers (which explains why it is so fragile).

Figure 1B shows an ABAQUS simulation of the explosion, which uses our dynamic damage mechanics. Figure 2 shows a recording of the elastic waves generated by the explosion recorded using laser velocimeters. We are currently comparing this radiation with that predicted by the ABAQUS simulation.

Figure 3 shows a simulation of an earthquake rupture propagating on the edge of a damage zone. Note the asymmetry in the damage zone and the fact that is broadens as the rupture progresses. This is because it is a crack-like rupture. We are currently working to generate pulse-like ruptures so we can relate the width of the damage zone to characteristics of the rupture pulse. The problem is that ABAQUS does not deal well with the rate and state-dependent friction required to generate slip pulses, and we may need to implement our dynamic damage mechanics in a spectral element or other formulation.

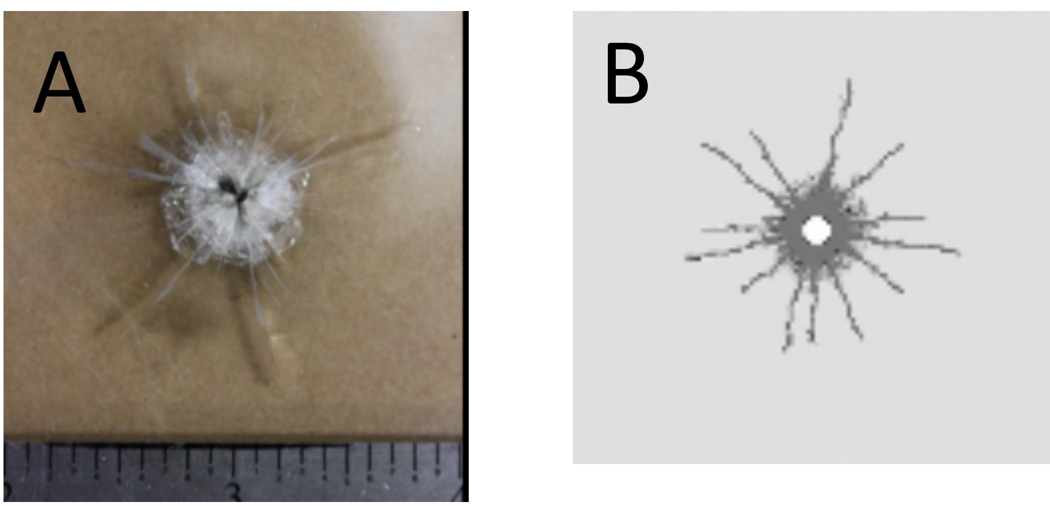

Figure 1. Panel A shows the damage resulting from an exploding wire. Panel B shows an ABAQUS simulation using the dynamic damage mechanics.

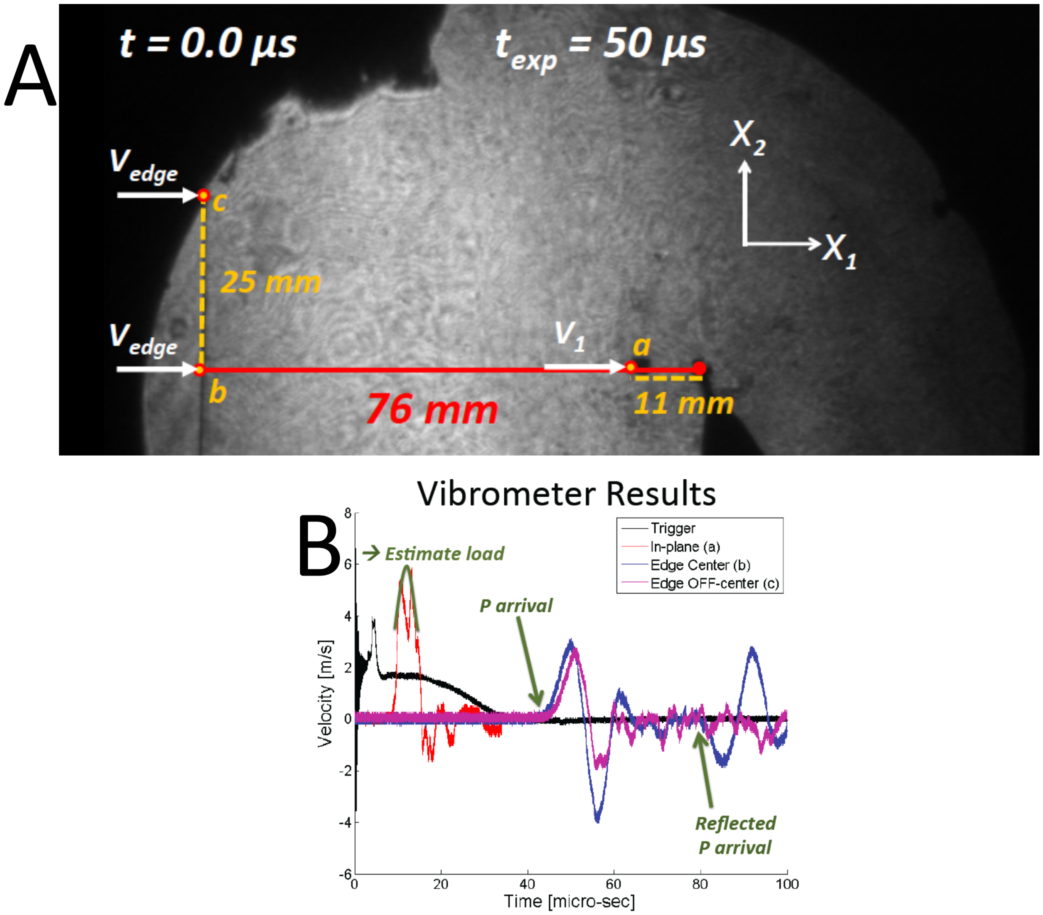

Figure 2. Panel A shows the location of the laser vibrometer sensors. Panel B shows the velocity seismograms written by the laser vibrometers. Not that the initial pulse can be used to estimate the time history of the explosion pressure.

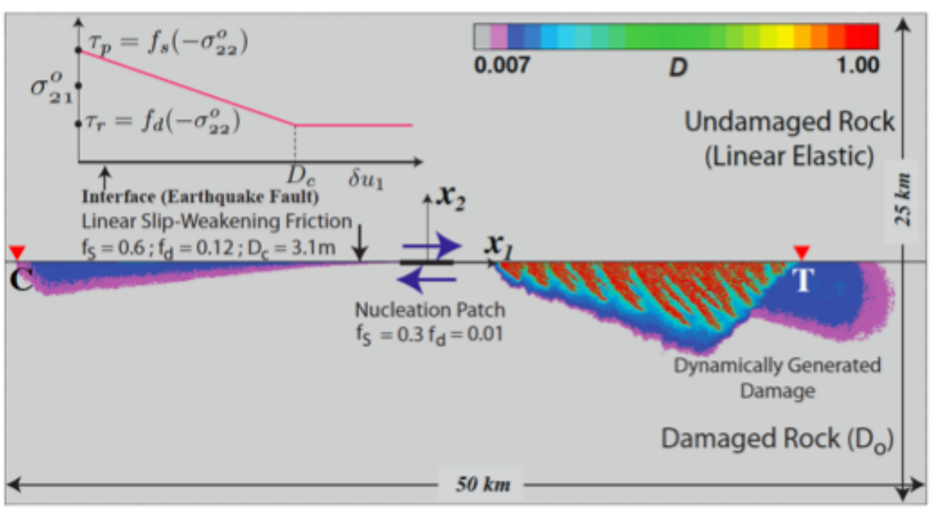

Figure 3. Simulation of an earthquake rupture on the boundary of a damage fault zone. Note the asymmetry in damage and rupture velocity.

d) Intellectual merit

A major objective of the SCEC research program is to model the source mechanics of an earthquake with enough physical reality to predict the resultant seismic waves in the near and far field. The micro-mechanical damage mechanics being developed and tested in this project is the most physically based approach to study the effects of the generation of on- and off-fault fracture damage during an earthquake.

e) Bibleography

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Sammis, C. G., A. J. Rosakis, and H. S. Bhat (2009), Effects of Off-Fault Damage on Earthquake Rupture Propagation: Experimental Studies, PAGEOPH, 166 (2009) 1629–1648 Doi: 10.1007/s00024-009-0512-3