Abstract
Large earthquakes propagate on faults, which are generally meters wide zones of crushed rock. The primary objective of this ongoing project is to understand how this fault zone is created and modified by successive earthquakes, and how it affects the propagation and seismic coupling of an individual event. Toward this goal, we have developed a fully dynamic micromechanical damage mechanics, which we have used to simulate earthquake ruptures. We have demonstrated strong asymmetries in damage generation and propagation direction associated with fault zone structure. We are currently carrying out a set of laboratory experiments to validate the theory. In order to generate off-fault damage in the laboratory, we have had to use "candy glass", the extremely fragile material used in movie stunts. Preliminary studies using small explosions have shown that we can generate damage at the correct spatial scale to test our model. Although we have yet to generate a laboratory earthquake in this material (because it is so fragile) we have measured its elastic moduli, its critical stress intensity factor, and the size and density of its dominant flaws, all of which are required inputs to the mode. We have also perfected a laser technique to produce broadband velocity seismograms at selected points on the sample surface. We are continuing our efforts to generate spontaneous ruptures in this material.

Technical Report

The objectives of this project are to explore the application of dynamic damage mechanics to the propagation of earthquake ruptures and the generation of cataclastic fault zone rocks. Figure 1 shows our most recent simulation of a rupture on the interface between damaged rock below and undamaged rock above. This simulation uses our fully dynamic micromechanical damage mechanics (Bhat et al., 2012) and the material properties of granite from Ashby and Sammis (1990). Note the strong asymmetry in both the damage (most damage ocurrs where the damage rock is in tension) and propagation velocity (ruptures run more slowly in the direction that puts the tensile lobe of the rupture tip field in the damaged material).

Although we are able to simulate off-fault damage during an earthquake rupture, the question arises, how much confidence can one put in the results? To answer this question, our efforts this year have been directed toward producing shear ruptures on the interface between plates of "candy-glass" and modeling the resulting off-fault damage. Candy-glass is a polymer material used to simulate glass in movie stunts. It is very fragile, which is why it breaks without causing injury. We are using candy-glass because we have not been able to produce dynamic damage in either Homalite or polycarbonate by propagating ruptures or by point explosions. Homalite and polycarbonate are the two photo-elastic polymers we have used in prior experiments.

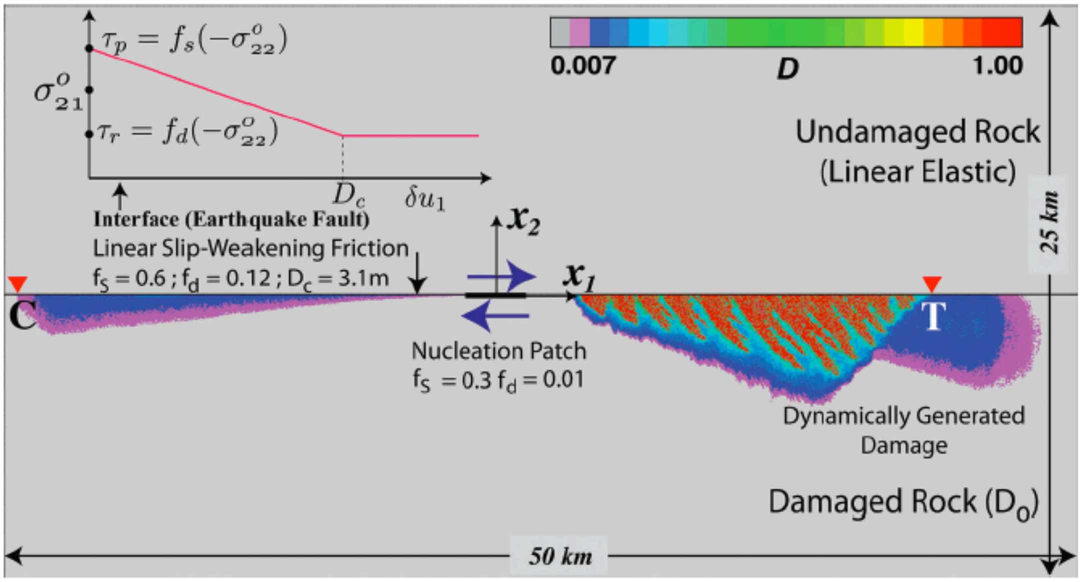

Figure 1. Snapshot of a bilateral rupture propagating on the boundary between damaged and undamaged rock. Note the generation of dynamic damage in the tensile lobe of the right rupture tip and its slower propagation. Rupture tips are denoted by the inverted triangles.

The idea is that if we can successfully model the lab experiments, then there will be reason to believe the results for earthquake ruptures - once the material properties of candy-glass are replaced with those of rock. Our major achievement this year was to measure the material properties of candy-glass that are required as inputs to the micromechanical damage mechanics. We are using the quasi-static micromechanical damage mechanics developed by Ashby and Sammis (1990) and recently extended to a fully dynamic form by Bhat et al. (2012). The required input parameters are the elastic moduli, the critical stress intensity factor, and the size and density of the dominant initial flaws.

The elastic properties of candy-glass

The elastic properties of candy-glass were measured by Randy Martin at New England Research as a personal favor. Velocities V_P and V_S were measured ultrasonically at three different locations on a plate of candy-glass. The data are given in Table 1. The density was also measured and used together with the velocities to calculate Young's modulus and Poisson's ratio. Average values are:

Vp = 2162 ± 18 m/s	Young's Modulus = 3.26 ± 0.07 GPa
Vs1 = 1116 ± 7 m/s	Poisson's Ratio = 0.332 ± 0.00
Vs2 = 1051 ± 21 m/s	

The two different S wave velocities in orthogonal directions evidence a slight anisotropy in the material.

Table 1. Elastic properties of candy-glass measured at New England Research.

Sample	Thickness (mm)	Density (gm/cm3)	Vp (m/s)	Vs1 (m/s)	Vs2 (m/s)	Young's (GPa)	Poisson
1	4.80	1.041	2173	1127	1075	3.35	0.327
2	4.78	1.041	2156	1113	1057	3.26	0.330
3	4.47	1.041	2179	1110	1048	3.24	0.338
4	4.47	1.041	2138	1115	1024	3.17	0.333

The mode I critical stress intensity factor of candy-glass

We measured the mode I critical stress intensity factor K_{IC} using four-point bending tests as illustrated in Fig. 2. Results are summarized in Table 2.

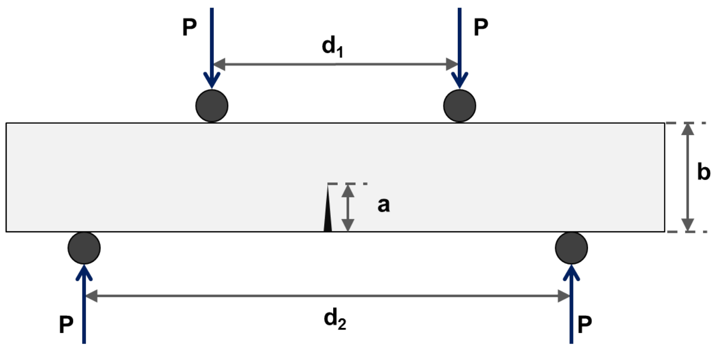

Figure 2: Four point bending geometry used to measure the critical stress intensity factor K_{IC} in candy glass.

Compare K_{IC} = 0.015 MPa*m$^{1/2}$ measured here in candy glass with K_{IC} = 1 MPa*m$^{1/2}$ typical of glass (and most oxides and silicates). The fact that the fracture toughness of candy glass is a factor of 67 times smaller explains why candy glass fractures so easily – in movies and in our experiments.

Table 2. Test data and measured values of K_{IC} for the five test specimens.

	Crack length a [mm]	a/b	P_{fail} [N]	K_{IC} [Pa*m$^{1/2}$]
Specimen 1	11.9	0.650	13.52	32,885
Specimen 2	11.1	0.606	12.59	25,297
Specimen 3	5.4	0.294	22.03	**16,384**
Specimen 4	4.8	0.265	20.86	**15,116**
Specimen 5	6.5	0.353	16.97	**15,300**

The initial flaw size and density in candy-glass

In order to determine the initial flaw size and density we ran a series of uniaxial compression tests on small prisms of the candy glass that we are using for our experiments (Fig. 3). The flaw size a is determined by the initiation of damage (first non-linearity in the stress-strain curve) using the expression

$$\sigma_1^* = \frac{\sqrt{3}}{(1+\mu)^{1/2} - \mu} \frac{K_{IC}}{\sqrt{\pi a}}$$

where σ_1^* is the stress at which nonlinearity is first observed, μ = 0.6 is the coefficient of friction, and K_{IC} is the critical stress intensity factor (which we measured to be $K_{IC} = 1.56\text{x}10^4$ Pa $m^{1/2}$). Note that the stress strain curve is linear up to the failure stress in Fig. 4. This implies that the samples fail as soon as damage nucleates, which implies a relatively high initial flaw density. The above equation gives a = 8.2 microns.

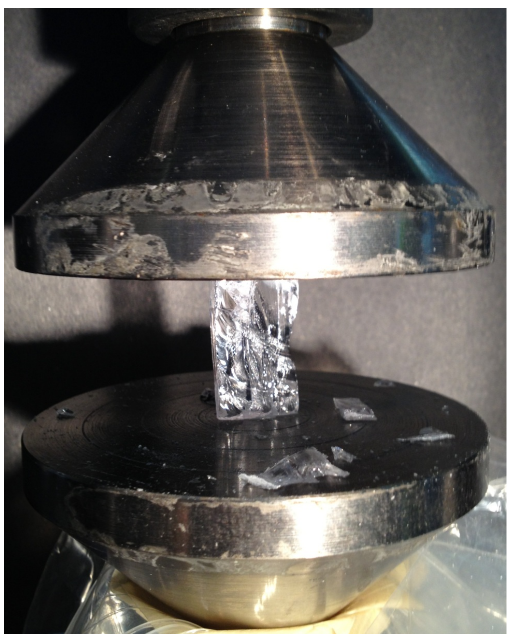

Figure 3. Experimental geometry used to measure the uniaxial strength in candy glass.

The initial damage is defined as $D_0 = \frac{4}{3}\pi N_V (\alpha a)^3$. It is determined by fitting the uniaxial strength in Fig. 3. Since we know a from damage initiation, we can calculate the initial flaw density N_V. Both a and D_0 are inputs required by our numerical model.

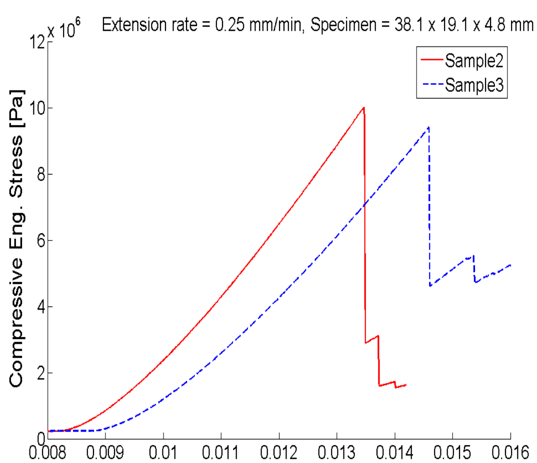

Figure 4. Uniaxial stress-strain curves for candy glass used to determine a and D_0 as described in the text.

Experimental Seismograms

Although we have not yet succeeded in generating a spontaneous rupture on an interface in candy-glass, we have successfully recorded seismograms generated by point explosions. We obtain a velocity seismogram by reflecting laser light from a 1mm reflector on the sample using a vibrometer. Figure 5. below is an example. We are thus in a position to analyze secondary radiation in the near field generated by off-fault damage as soon as we solve our experimental problems in loading the extremely fragile material.

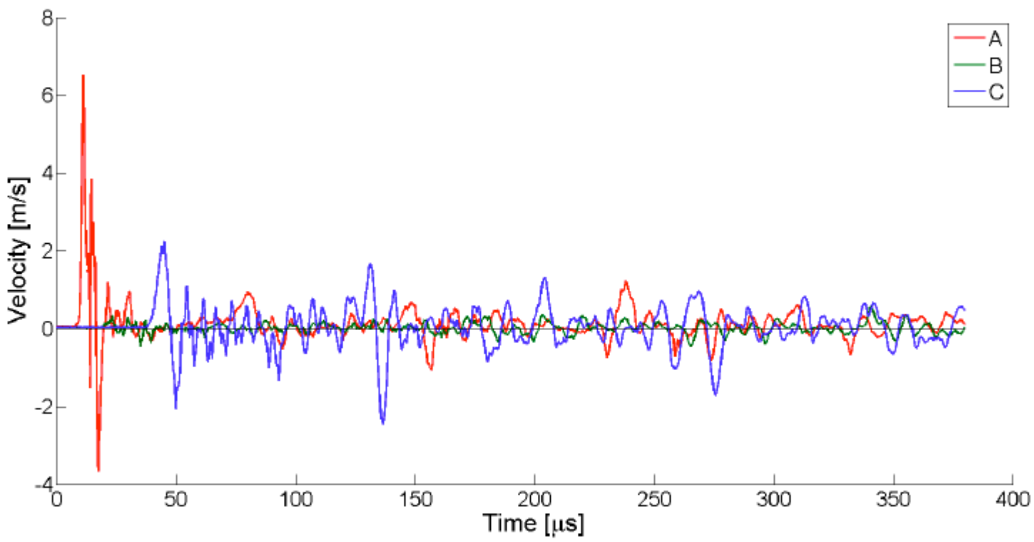

Figure 5. Velocity seismograms measured at three locations following a laboratory explosion.

References

Ashby, M. F., and C. G. Sammis, 1990: The damage mechanics of brittle solids in compression, *Pure Appl. Geophys.,* **133**(3), 489–521.

Bhat, H. S., A. J. Rosakis, and C. G. Sammis, 2012: A micromechanics based constitutive model for brittle failure at high strain rates, *J. Appl. Mech.,* **79**(3), 031016, doi:10.1115/1.4005897.

Intellectual Merit & Broader Impacts

This work is at the cutting edge of theoretical damage mechanics and laboratory fracture mechanics. We have combined the quasi-static micromechanical model developed by Ashby and Sammis (1990) with recent theoretical and experimental advances in dynamic fracture propagation to produce model based damage mechanics that has been shown to correctly predict the strength of marble over 10 orders of magnitude in loading rate (Bhat et al., 2012). The Rosakis high-speed digital photo lab at Caltech was the first to produce high-speed movies of dynamic mode II ruptures in photoelastic plates and to observe the interaction of these ruptures with off-fault fracture damage. As soon as we solve our current experimental problems, we will be the first to observe the generation of off-fault damage in the process zone of a dynamic mode II rupture.

The postdoctoral fellow supported and trained on this project is now on the faculty at IPGP Paris. This work has impact beyond earthquake mechanics. Other problems in the Earth Sciences that involve the generation of fracture damage at high loading rates include the seismic coupling in underground explosions (chemical and nuclear) and the modeling of meteorite impact. Many engineering problems also required high-speed damage mechanics including the design of armor and hardening satellites against impact from micrometeorites and space debris.

Publications

Bhat, H. S., A. J. Rosakis, and C. G. Sammis, 2012: A micromechanics based constitutive model for brittle failure at high strain rates, *J. Appl. Mech.,* **79**(3), 031016, doi:10.1115/1.4005897.