An Experimental Study of the Effect of Off-Fault Damage on the Velocity of a Slip-Pulse

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Summary of Research Accomplishments

During the past year we have achieved the following objectives:

1. We have developed a technique for introducing isotropic damage into the Homalite samples that we use to measure rupture speed in our experiments at Ares Rosakis Lab at Cal Tech. The technique involves scoring the surfaces of the Homalite plates and immersing them into liquid Nitrogen for about 15 to 30 seconds. The initial scoring controls the crack density and is important for producing an isotropic homogeneous distribution of off-fault cracks.

2. We have shown that this off-fault damage can slow the rupture speed of a propagating dynamic rupture. This reduction is greater than that expected by a reduction of the limiting Rayleigh speed corresponding to the lower shear wave velocity in the damaged Homalite. This reduction is probably due to Coulomb slip on the off-fault cracks. We observed no crack extension in any of our experiments.

3. In order to determine the spatial extent of the interaction between the crack tip and the off-fault damage, we prepared samples with damaged bands of various widths surrounding the fault. The speed of the rupture decreased as the width of the damaged band increased up to a width of about 1 cm in width and was then constant for all wider bands.

4. We also prepared samples with undamaged bands of various widths surrounding the fault plane, where the rest of the sample was damaged. The rupture speed increased as the width of the undamaged band increased up to about 1 cm and was constant for wider bands.

5. The interaction distance of about 1 cm found in (3) and (4) above is consistent with that predicted by the dynamic slip-pulse model of Rice et al. (2006).

6. Preliminary experiments on samples where the fault plane separates damaged and undamaged plates found asymmetric propagation effects that differed from those predicted for elastic bimaterials, but which can be understood in terms of asymmetric anelastic off-fault losses.

7. We built a loading frame to hold our larger (12 in. x 12 in.) marble samples for use in future experiments.

This work has resulted in two publications,

"Interaction of a Dynamic Rupture on a Fault Plane With Short Frictionless Fault Branches" Biegel, R.L., Sammis, C.G., Rosakis, A. J., *Pure and Appl. Geophys.* (in press), 2007a.

"An Experimental Study of the Effect of Off-Fault Damage on the Velocity of a Slip-Pulse", Biegel, R.L., Sammis, C.G., Rosakis, A. J., *Jour. Geophys. Res.* (in prep), 2007b.

Experimental Results

In this section, we present the tables and figures from the paper being prepared for publication in JGR (Biegel et al., 2007b).

Undamaged and All-damage samples

Experiments were carried out with undamaged and all-damaged samples to test if rupture speed would be affected by damage in the sample. Digital images like Figure 1b were used to measure rupture speed v_r and shear wave velocity v_s. Table 1 shows that v_r and v_s were close to the Rayleigh limit 0.92 v_s in the undamaged samples. In all-damage samples (Figs. 1a, b) we observed the rupture speed slow significantly below the Rayleigh limit which suggest that additional energy was being dissipated by Coulomb slip on off-fault cracks

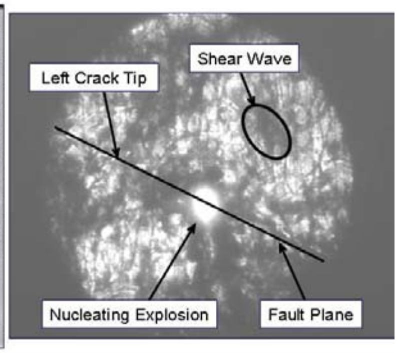


Figure 1a. (Lower left) A digital scan of the all-damage sample used in Experiment H-70. The image shows the top and bottom pieces of the sample with their dense fracture network. The faint vertical and horizontal parallel lines on the surface were made by scoring with a knife before immersion in liquid Nitrogen. The dark traces in the center along the fault are from the nucleating explosion.

Figure 1b. (Upper right) A digital image from Experiment H-70. The rupture tips from the bilateral ruptures appear as dark spots on the fault surrounded with transient fringes and propagating to the left and right from a central nucleation point. The shear wave can be seen as a dark ellipse propagating toward the upper right of the field of view. Sense of motion along the fault is right lateral.

Table of Experiments

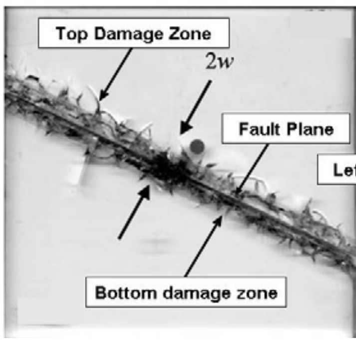
Experiments	V_r (m/s)		V_s (m/s)	V_r/V_s
No Damage				
C-13	left	1150	1280	0.90
	right	1150		0.90
H-43	left	1110	1220	0.91
	right	1090		0.90
All Damage				
H-50	left	900	1030	0.87
H-53	left	830	---	---
H-70	left	720	970	0.74
HH-7	left	820	1000	0.84
HH-7	right	860		

Table 1. Table of experiments classified by the extent of damage in the sample. The columns give the experiment name, direction of rupture propagation (left or right), rupture speed v_r, shear wave velocity v_s, and ratio of v_r/v_s. All experiments were run at 12 MPA, the remote uniaxial stress not the normal stress resolved onto the fault.

Damage bands

Experiments were done to measure the spatial extent of interaction of the off-fault stress field with the damage. Bands of varying widths of damaged Homalite were made which surrounded the fault. Rupture speeds were measured as a function of band half-width and are shown in Table 2.

Figure 2a. (Lower left) Digital scan showing damage bands of half-width w_d = 0.5 cm made by dipping the edges in liquid nitrogen. The dark dot above the explosion site is for scaling and has a diameter of 0.95 cm.



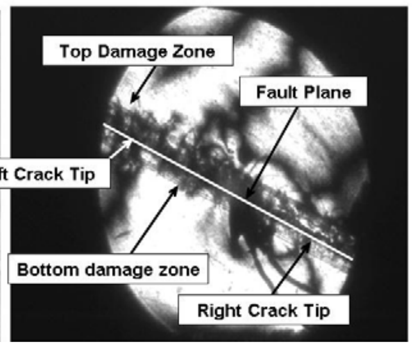
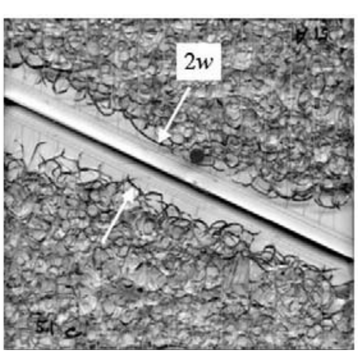


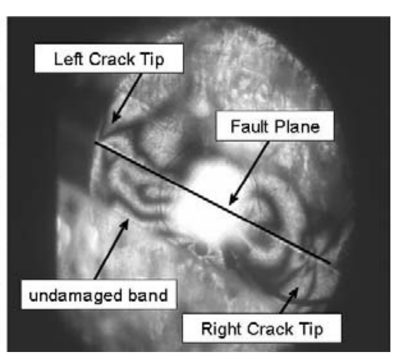
Figure 2b. (Right) A digital image from an experiment with damage bands. A rupture tip from the bilateral rupture appears as a dark spot on the fault surrounded with transient fringes and propagating to the left and right from a central nucleation point. The shear wave in this experiment has propagated out of the field of view. Sense of motion along fault is right lateral.

Samples with Damage Bands		
Experiments	**Crack Propagation**	**V_r (m/s)**
Damage Half-Width = 1/2 cm		
H-54	left	930
H-55	left	1000
	right	930
H-58	left	880
	right	830
Damage Half-Width = 1 cm		
H-59	left	680
	right	660
H-62	left	830
	right	710
Damage Half-Width = 2 cm		
H-61	left	910
	right	900
H-66	---	---
H-67	left	880
HH-10	right	850

Table 2. Table of experiments classified by the half-width of the damage band w_d, in the sample. The columns give the experiment name, direction of rupture propagation (left or right), and rupture speed v_r. All experiments were run at 12 MPA.

Undamaged bands





Bands of varying widths of undamaged Homalite were made which surrounded the fault. Rupture speeds were observed as a function of band half-width (see Table 3).

Figure 3a. (Previous page, lower left) A digital scan of the sample with undamaged bands of half-width $w_d = 0.5$ cm made by dipping all of the sample in liquid nitrogen except the edges. The dark dot at the center and above the fault has a diameter of 0.95 cm.

Figure 3b. (Previous page, lower right) A digital image from experiment H-52 with sample having undamaged bands of half-width $w_u = 2$ cm. The rupture tips from the bilateral ruptures clearly appear as dark tips on the fault surrounded with transient fringes propagating to the left and right from a central nucleation point. The shear wave in this experiment has propagated out of the field of view. Sense of motion along fault is right lateral.

Samples with Undamaged Bands		
Experiments	**Rupture Direction**	**V_r (m/s)**
Undamaged Half-Width = 0.5 cm		
H-51	left	1000
	right	1030
Undamaged Half-Width = 2 cm		
H-52	left	1010
	right	1050

Table 3. (Left) Experiments classified by the half-width of undamaged band w_u, in the sample. The columns give the experiment name, direction of rupture propagation (left or right), and rupture speed v_r. All experiments were run at 12 MPA.

Spatial Extent of Interaction between the crack-tip stress field and off-fault damage.

We plotted the rupture speed as a function of the sample damage or undamaged band half-width (see Figure 4). We interpret the interaction distance (W_I) to be the half-width at which the rupture speed stops changing with additional increases in band half-width.

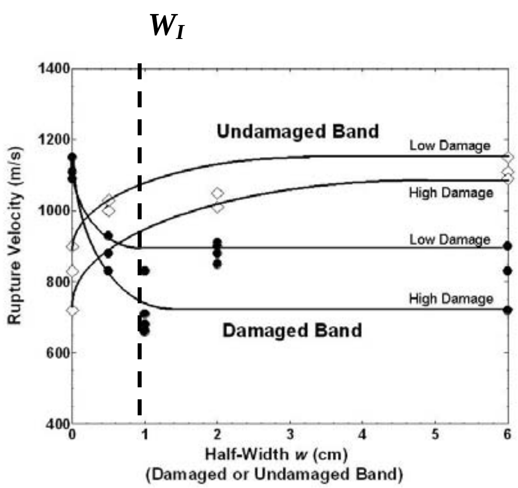


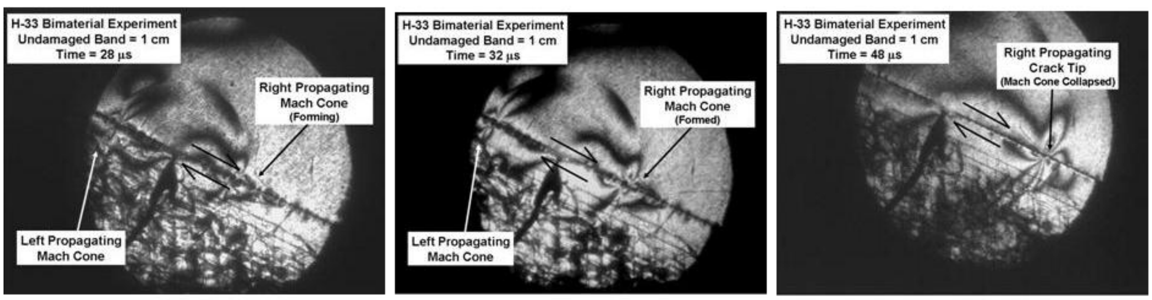
Figure 4. (Left) A plot of the rupture speed v_r and half-width w of the band. Undamaged samples are considered to have an undamaged band half-width comparable to the size of the sample - or a damage band of zero half-width. All-damage samples are considered to have a damage band comparable to the width of the sample - or an undamaged band of zero width. These samples are plotted on the right and left sides of the graphs. Samples with damage bands show a decrease in v_r with an increase in damaged half-width w_d. Samples with undamaged bands show an increase in v_r with an increase in undamaged half-width w_u. Note that v_r decreases for damaged bands less than ~1 cm, reaching a stable rupture speed for larger values. Similarly, v_r increases for undamaged bands less than ~1 cm, and reaches a stable rupture speed for larger values.

Figure 4 shows an interaction distance W_I of about 1 cm consistent with that predicted by the dynamic slip-pulse model of Rice et al. (2006).

Anelastic Bimaterials

Preliminary rupture experiments were performed using bimaterials of undamaged and all-damage Homalite plates. Supershear Mach cones were observed propagating along the fault. As shown in Figure 5 only those crack tips whose extensional side propagated through the undamaged plates continued to propagate at supershear rupture speed. If the extensional side of a crack tip propagated through the damaged Homalite plate then it either slowed and collapsed soon after formation or it did not form a Mach cone at all.

Figure 5. (Below) Bimaterial of undamaged/all-damage Homalite with higher velocity material moving to the right (right lateral). As a Mach cone forms and propagates to the



left another cone forms and propagates to the right but then the right propagating cone contacts the damaged Homalite and collapses. The left cone continues to propagate.

We hypothesize that in a bilateral rupture, the extensional side of one crack tip must propagate through the all-damage plate so it loses energy due to frictional sliding on off-fault cracks. For that reason, this crack tip cannot achieve supershear rupture speed in that direction. But, the opposing crack tip has an extensional side that propagates through the undamaged material which does not dissipate energy and so can reach and maintain supershear rupture speeds. (see Fig. 6)

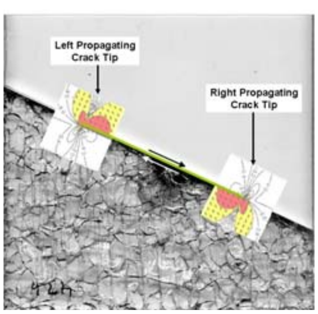


Figure 6. (Left) A possible explanation for Mach cones forming more readily at the left crack tip than at the right tip. Note that for the left propagating tip, the extensional side propagates through the undamaged Homalite so that no Coulomb slip can occur to dissipate energy from the left crack tip. For the right propagating tip, it is the extensional side that propagates through damaged Homalite triggering Coulomb slip on crack surfaces which dissipates energy from the right crack tip.