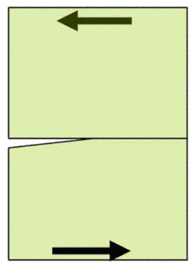
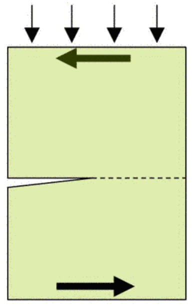
Dynamic Rupture along Interfaces:
1. Dynamic frictional sliding modes along interfaces between identical materials
2. Shear-dominated fracture

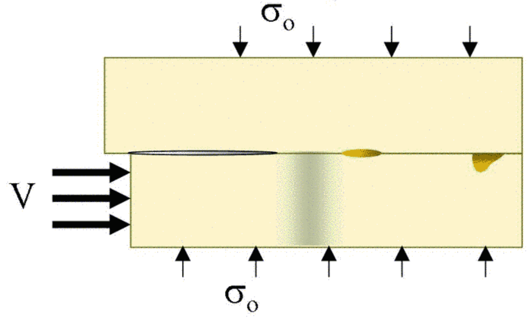
Demir Coker
Mechanical and Aerospace Engineering
Oklahoma State University

Collaborators:
E. Ennis, Oklahoma State
A. Needleman, Brown University
G. Lykotrafitis, Caltech
A. J. Rosakis, Caltech

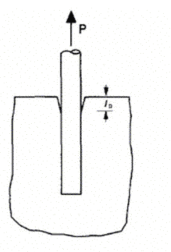
Rupture= Shear failure along weak interfaces: Friction and Fracture


Fracture: Coherent Interface
(with cohesion)

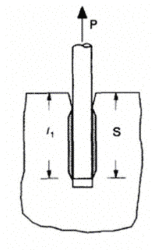

Friction: Incoherent Interface
(without cohesion)



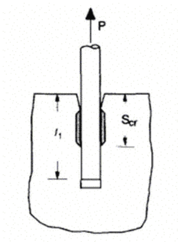
Frictional sliding modes observed in fiber pull-out experiments (Tsai & Kim, 1996)



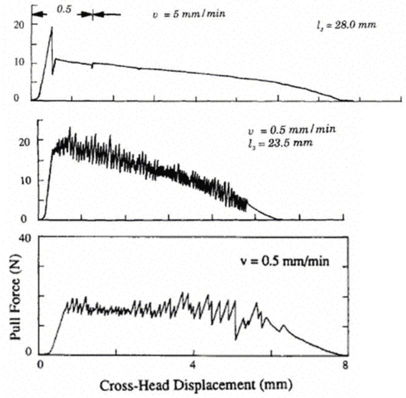
(i) Precursor of fiber pull-out: Semi-brittle debonding.



(iii) Fiber pull-out with full active sliding zone. ($S_{cr} > l_1$)



(ii) Fiber pull-out with limited active sliding zone. ($S_{cr} < l_1$)



Steady-state

Global stick-slip

Local stick-slip

Issues that will be discussed:

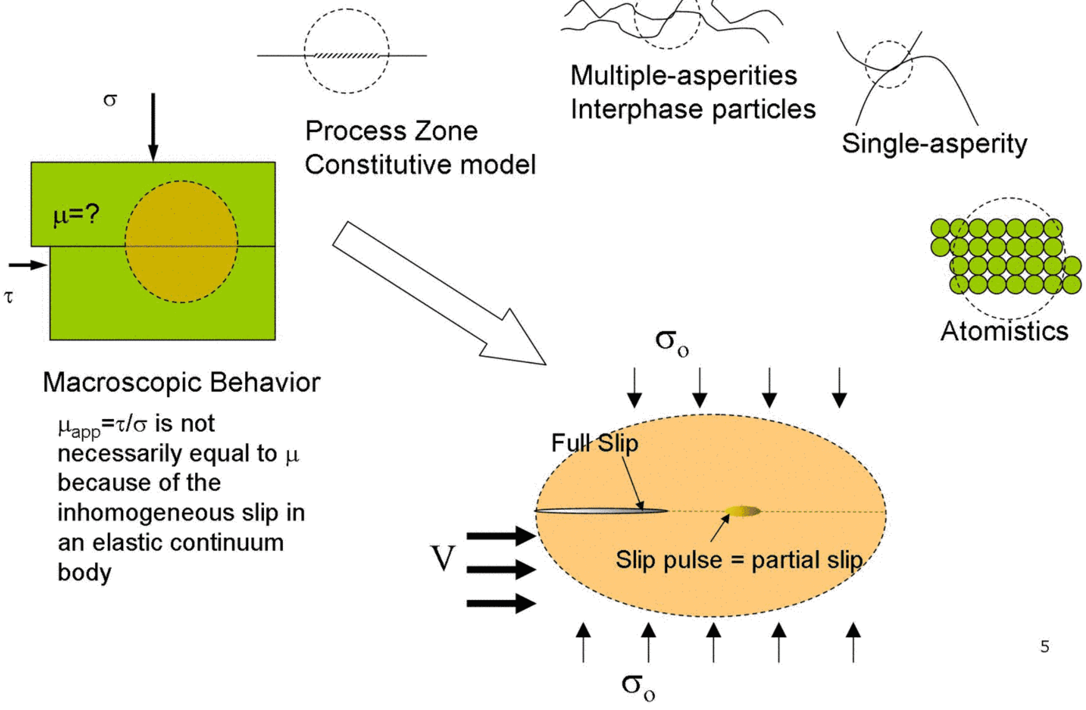
Some local complex behavior of interest:

- Super-shear rupture front
- Sliding modes: self-healing pulse and crack-like expanding modes and a train of periodic self-healing pulses.
- Hot spots and localized stress concentrations (pinching)
- Sub-Rayleigh to Supershear rupture transition
- Opening pulses (even at high temperatures)
- Supersonic front propagation

Numerical and experimental approach:

- Identical materials
- Straight interface with no kinks
- Smooth interface
- Elastic materials
- No heterogeneity: interfacial or bulk
- Rate/State constitutive law used for computations

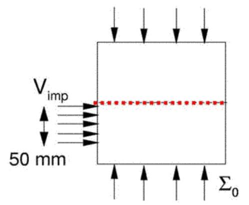
Modeling friction at different length-scales



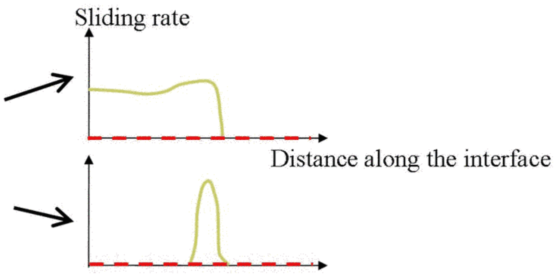
Macroscopic Behavior

$\mu_{app}=\tau/\sigma$ is not necessarily equal to μ because of the inhomogeneous slip in an elastic continuum body

Frictional Sliding Modes



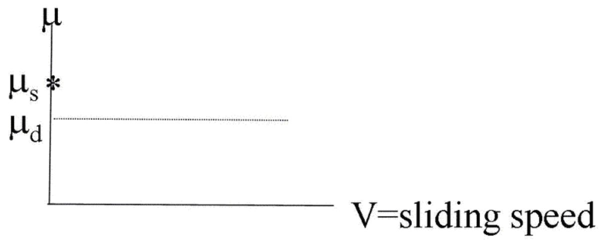
- Case I: Crack-like
- Case II: Slip pulse



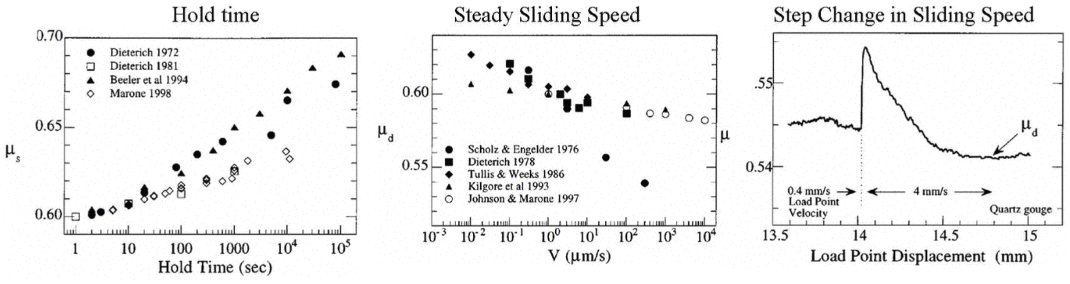
- Case III: Quasi-periodic train of slip pulses
- Case IV: Mixed modes
  - Compare with experiments

History and sliding speed affect the apparent coefficient of friction

Amontons-Coulomb law: $\tau = \mu\,\sigma$



Experiments



→Amontons-Coulomb friction law is not adequate to capture these phenomena.

Rate and State Laws

- Frictional sliding between rapidly deforming solids arises in a variety of contexts.
- The classical Amontons-Coulomb friction law is inadequate because:
  - Not consistent with observed experimental behavior.
  - Leads to ill-posed boundary value problems.
- Rate and state friction laws regularize the ill-posedness.
- Experimental and numerical work carried out to investigate frictional sliding between identical elastic plates.
- Questions
  - What is the mode of sliding?
  - How does it depend on loading?
  - What is the propagation speed of the sliding tip?

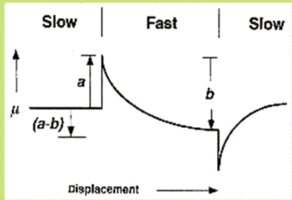
Friction Interface Law:
Rate- and state-dependent with variations in normal stress

$$T_s = \mu(\theta_o, \Delta\dot{u}_{slip})\theta_p(T_n)$$

where $\mu(\theta_o, \Delta\dot{u}_{slip}) = g(\theta_o)(\frac{\Delta\dot{u}_{slip}}{V_o}+1)^{1/m}$ $\quad g(\theta_o) = \frac{\mu_d + (\mu_s - \mu_d)\exp\left[\left(\frac{L_o/\theta_o}{V_o}\right)^p\right]}{\left[\frac{L_o/\theta_o}{V_o}+1\right]^{1/m}}$

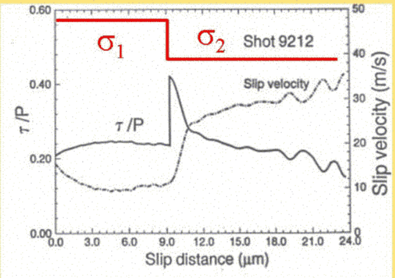
Povirk and Needleman, 1993

$$\dot{\theta}_o = A_o\left\{1 - \frac{\theta_o \Delta\dot{u}_{slip}}{L_o}\right\}$$



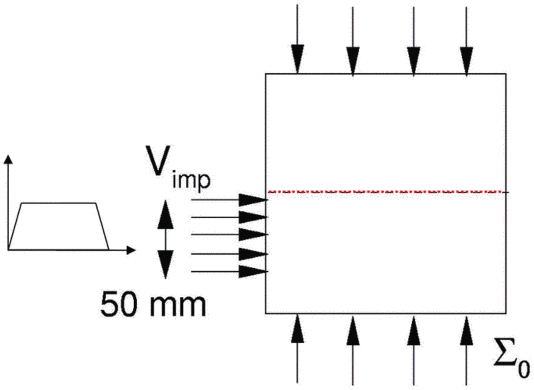
Dieterich, 1979; Ruina, 1983; Rice and Ruina; 1983

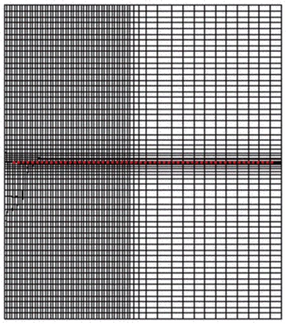
$$\dot{\theta}_p = -\frac{1}{L_p}(\theta_p - DT_n)\Delta\dot{u}_{slip}$$



Prakash and Clifton, 1993; Prakash, 1993

Finite element model with friction interface elements in a cohesive framework

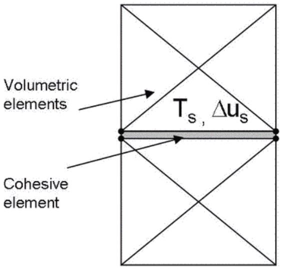




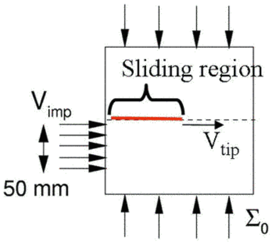
$$\int_V \mathbf{S} : \delta\mathbf{E}dV - \int_{S_{int}} \mathbf{T}\cdot\delta\Delta\mathbf{u}dS = \int_V \mathbf{T}\cdot\delta\mathbf{u}dV - \int_V \rho : \frac{\partial^2\mathbf{u}}{\partial t^2}\cdot\delta\mathbf{u}dV$$

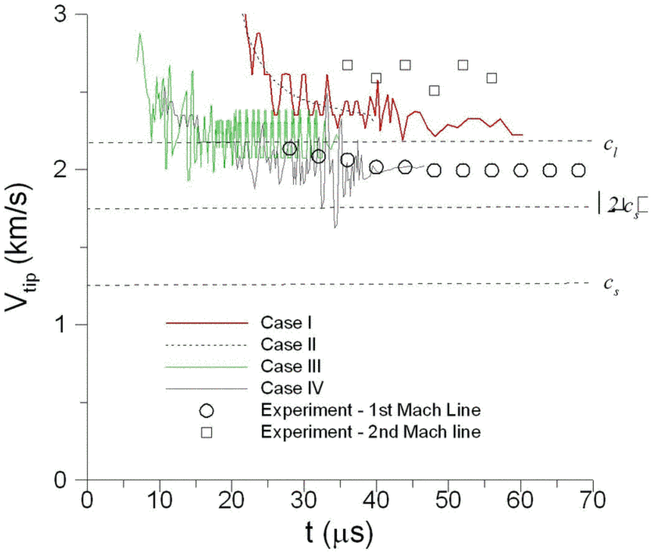
$$\dot{T}_n = C_n\Delta\dot{u}_n$$
$$\dot{T}_s = C_s(\Delta\dot{u}_s - \mathrm{sgn}(T_s)\Delta\dot{u}_{slip})$$

(Povirk and Needleman 1993)

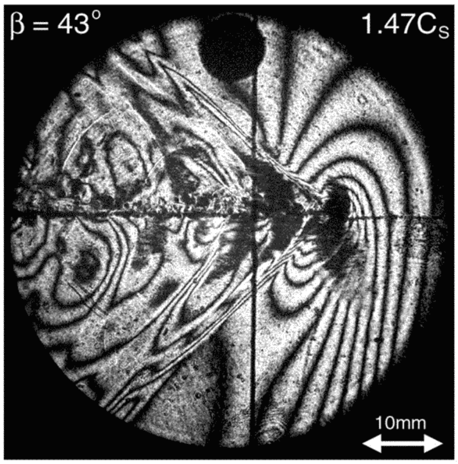


Frictional sliding tip propagation speed

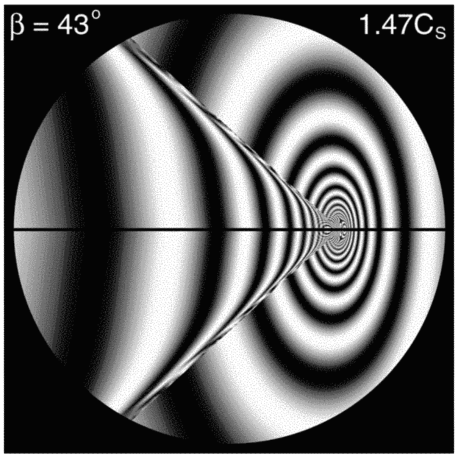




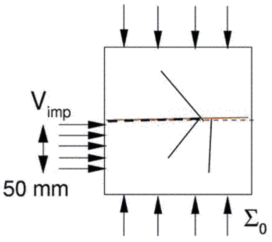
INTERSONIC MODE-II CRACK PROPAGATION ISOCHROMATIC FRINGE PATTERN



Experiment
(Rosakis, Samudrala & Coker)
(*SCIENCE*, May '99)

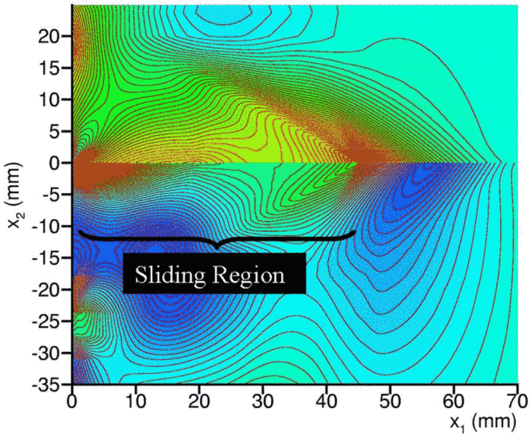


Theory
(Freund '79)



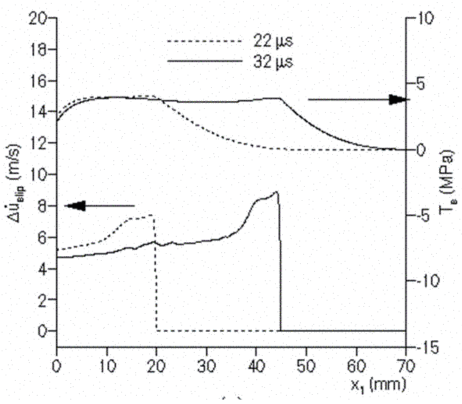
Case I: Results for Σ_o =6 MPa, V_{imp}=2 m/s

At low compressive stress →
Expanding crack-like frictional sliding

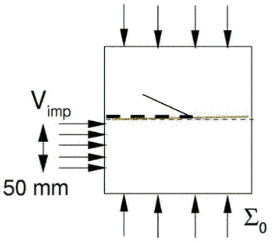


Isochromatic fringe patterns

$$\dot{T}_s = C_s(\Delta\dot{u}_s - \mathrm{sgn}(T_s)\Delta\dot{u}_{slip})$$

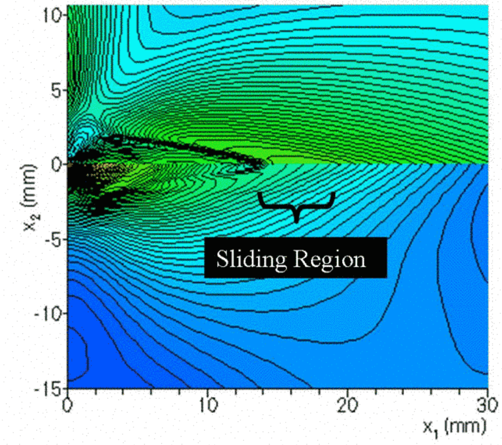


Sliding rate and shear traction



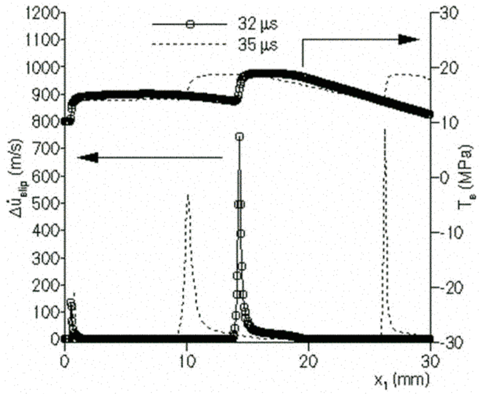
Case II: Results for Σ_o =30 MPa, V_{imp}=2 m/s

High compressive stress →
Self-healing slip-pulse

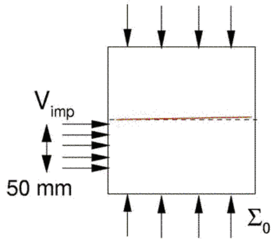


Isochromatic fringe patterns

$$\dot{T}_s = C_s(\Delta\dot{u}_s - \mathrm{sgn}(T_s)\Delta\dot{u}_{slip})$$



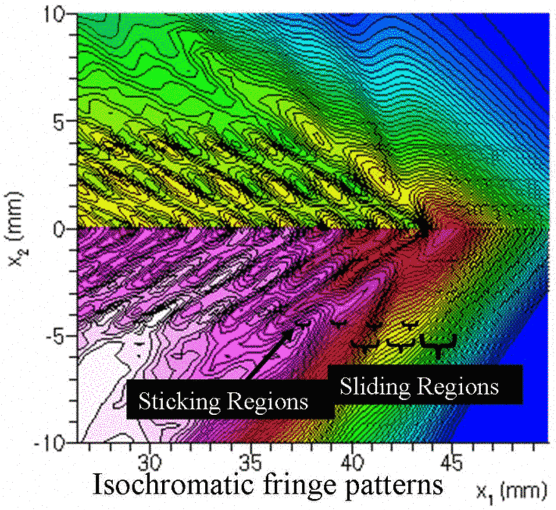
Sliding rate and shear traction



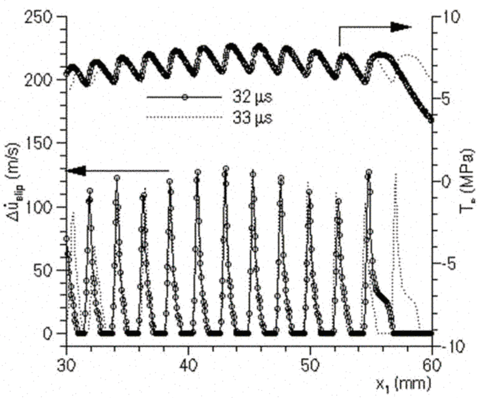
Case III: $\Sigma_o = 10$ MPa, $V_{imp} = 20$ m/s

Intermediate compressive stress and high impact speed
→ Quasi-periodic slip-pulses

$$\dot{T}_s = C_s(\Delta\dot{u}_s - \mathrm{sgn}(T_s)\Delta\dot{u}_{slip})$$

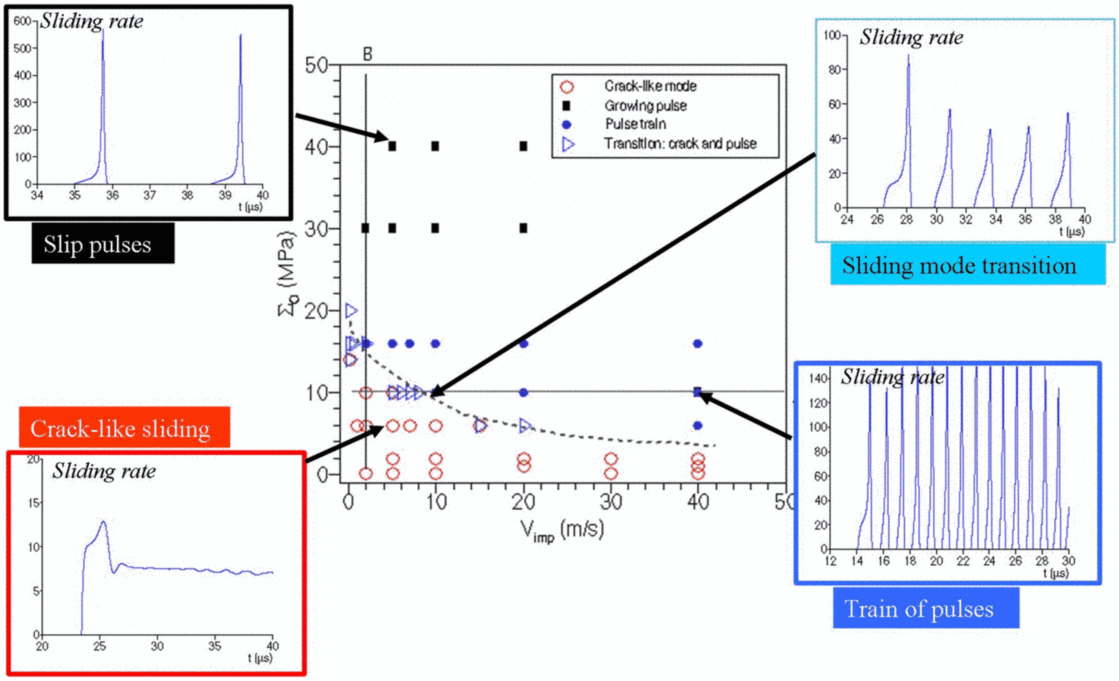


Isochromatic fringe patterns

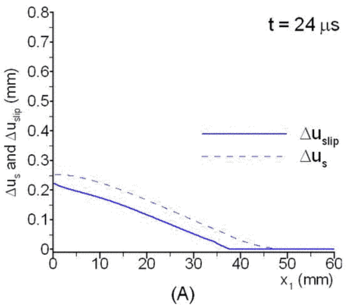


Sliding rate and shear traction

The frictional sliding mode depends on the compressive stress and the impact velocity

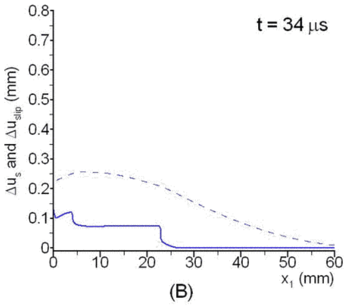


Total frictional sliding and total displacement jump across the interface



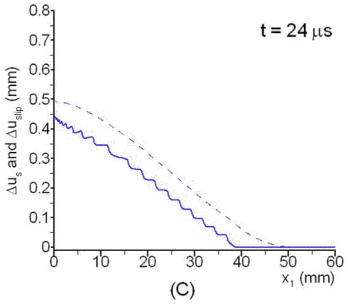
(A)

Case I:
Expanding crack-like frictional sliding



(B)

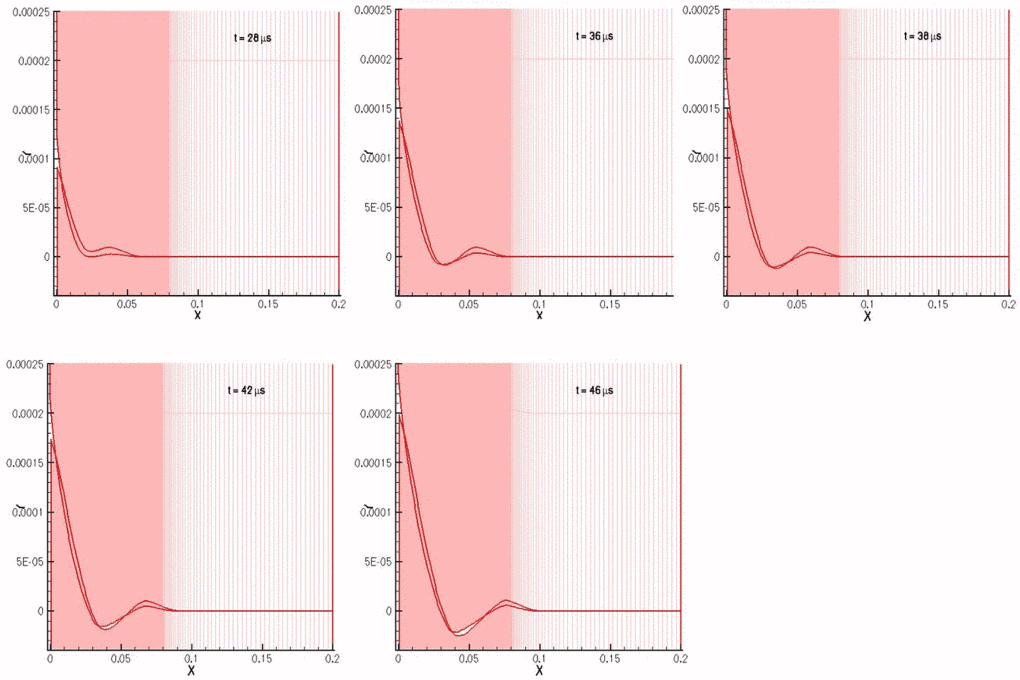
Case II:
Self healing slip-pulse



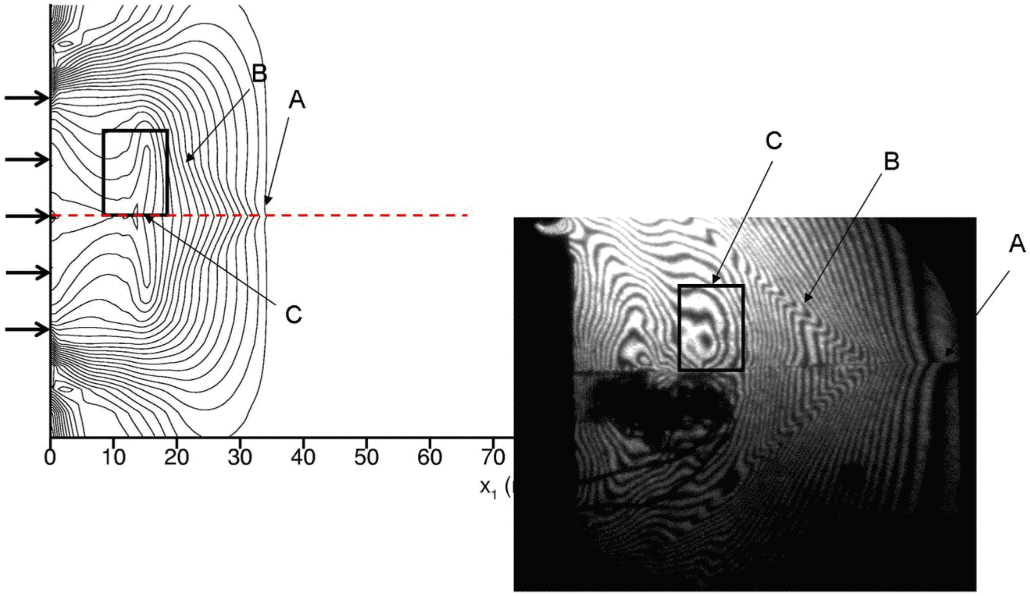
(C)

Case III:
Quasi-periodic slip-pulses

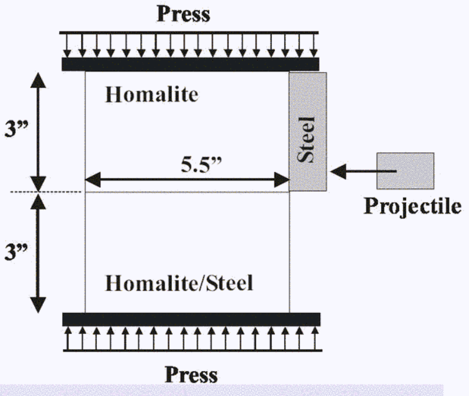
Opening region behind the rupture tip

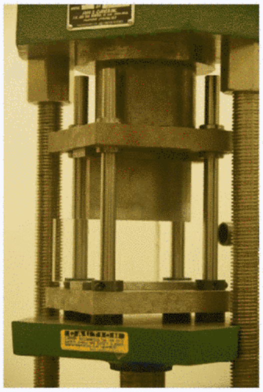


Symmetric loading with no frictional sliding
Experiments and simulations



SPECIMEN CONFIGURATION

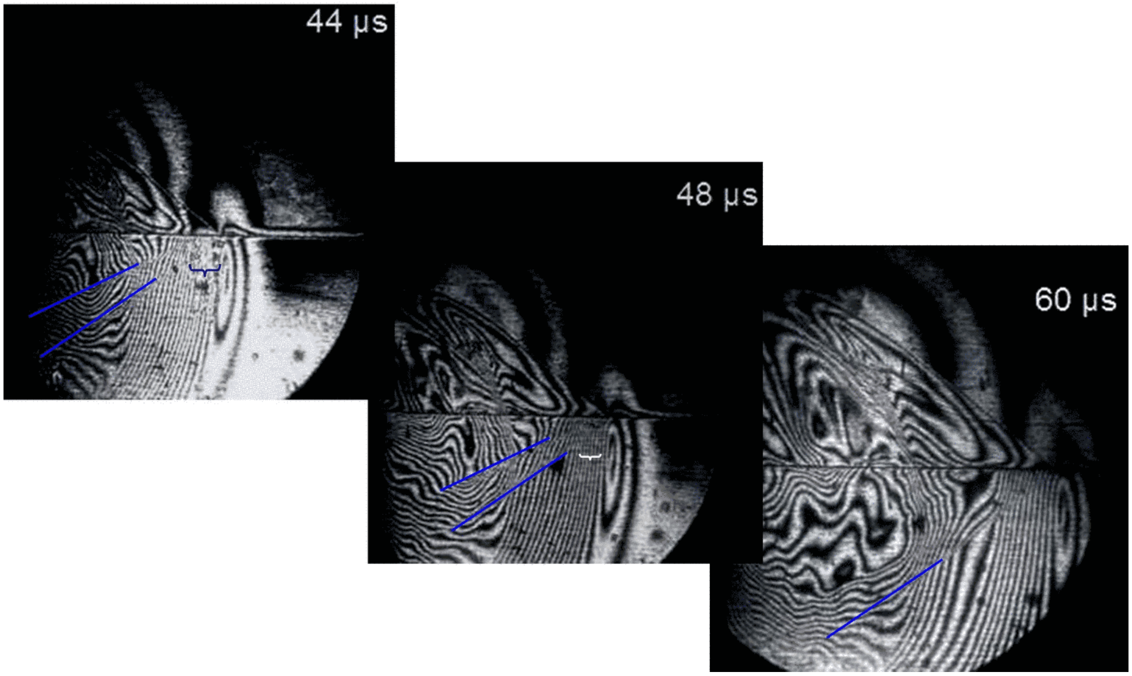




Homalite-100 Characteristic Speeds
P-wave (Plain Strain): 2583 m/sec
P-wave (Plain Stress): 2187 m/sec
Shear wave: 1249 m/sec
Rayleigh wave 1150 m/sec
Steel Characteristic Speeds
P-wave (Plain Strain): 5838 m/sec
P-wave (Plain Stress): 5378 m/sec
Shear wave: 3227 m/sec

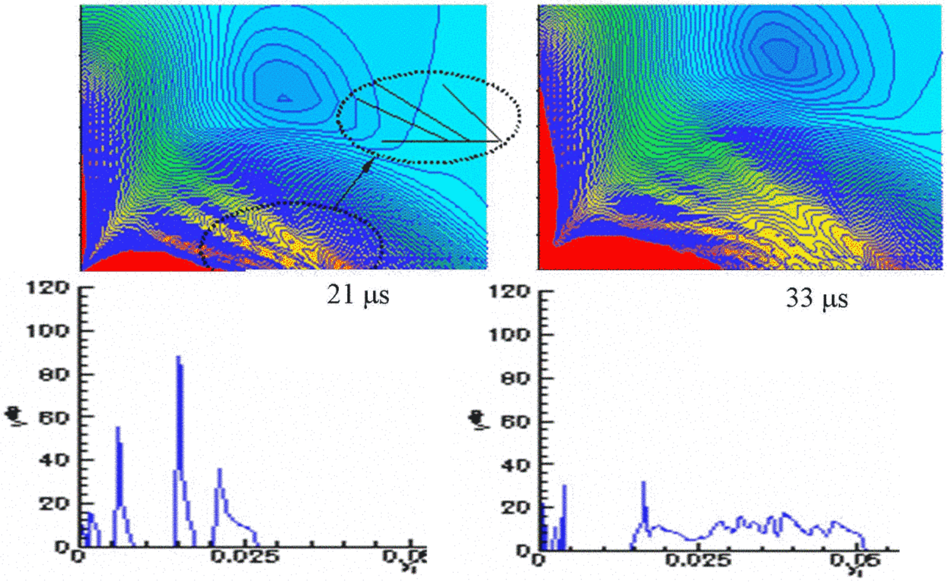
Homalite plate: 3 in x 5.5 in x 3/8 in
Surface roughness: Ra = 405 nm
Steel buffer plate: 3 in x 1 in
Projectile: 1 in diameter, 2 in long
Impact speeds: 10 m/s – 74 m/s
Pressure: 0 MPa – 20 MPa

Transient slip pulses observed in experiments :
Propagation speeds $\sqrt{2}\,c_s < v < c_l$ with associated shear Mach waves



Evolution of frictional sliding from multiple pulses to crack-like sliding region

Σ_o =0.9 MPa   V=10 m/s

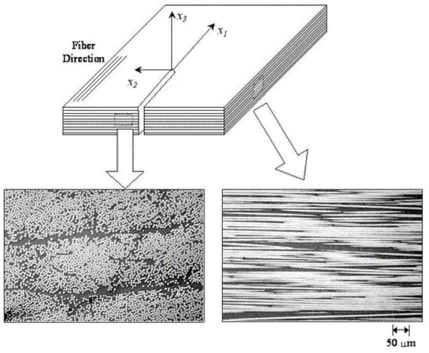


Some remarks regarding frictional sliding

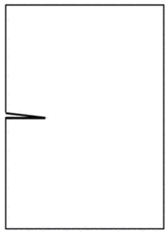
1) Different modes of frictional sliding are observed numerically: crack-like (full sliding), self healing slip pulse (partial sliding), quasi-periodic train of slip pulses, and mixed mode.
2) The sliding modes are found to be dependent on the applied compressive stress and the driving speed.
3) Rate and state friction models are able to capture the spatio-temporal complexity in sliding behavior.
4) The range of sliding modes obtained appear to be generic, arising in a wide variety of configurations and applications, and at a wide variety of size scales.
5) The energy dissipated and heat generated can depend on the mode of sliding in multiple pulses vs crack like sliding. Although these two deformation mechanisms show similar gross displacement behavior, the energy dissipation may be different.
6) Mode of surface deformation is expected to play an important role in the failure initiation. This will be important at small scale devices where critical failure at small scales is due to surface failure and not bulk failure.

Shear-dominated dynamic fracture in heterogeneous materials with a weak plane: Unidirectional Graphite fiber reinforced epoxy composite laminate

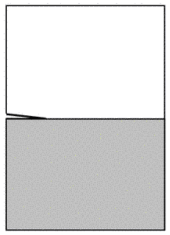
Heterogeneous Composite Material



Homogenized Elastic Properties		Characteristic Wave Speeds	
E_1	80 GPa	$c_l^{//}$	7500 m/s
E_2	8.9 GPa	$c_l^{\perp}$	2700 m/s
ν_{12}	0.25	c_s	1560 m/s
μ_{12}	3.6 GPa	c_R	1548 m/s

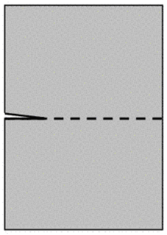


Homogeneous orthotropic material

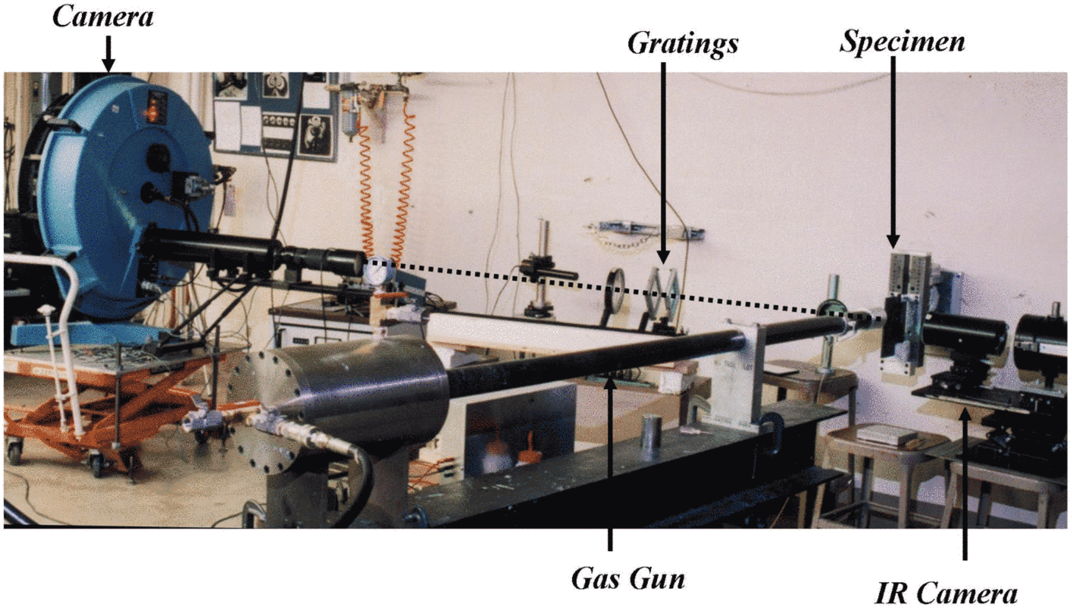


Bi-material

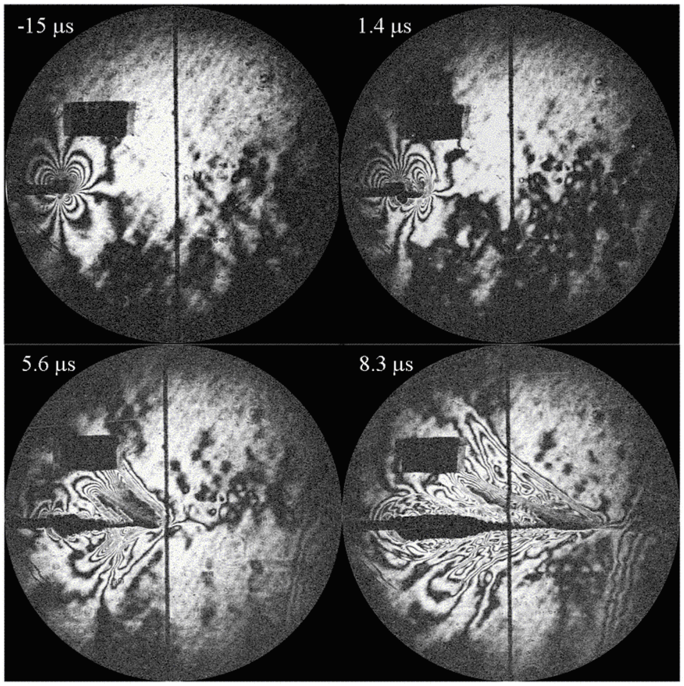
Homogeneous orthotropic material with a **weak plane**

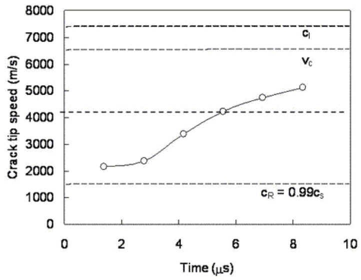


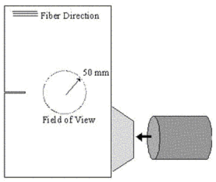
Experimental set-up for dynamic fracture



Sequence of CGS interferograms of shear dominated intersonic crack growth in unidirectional composites

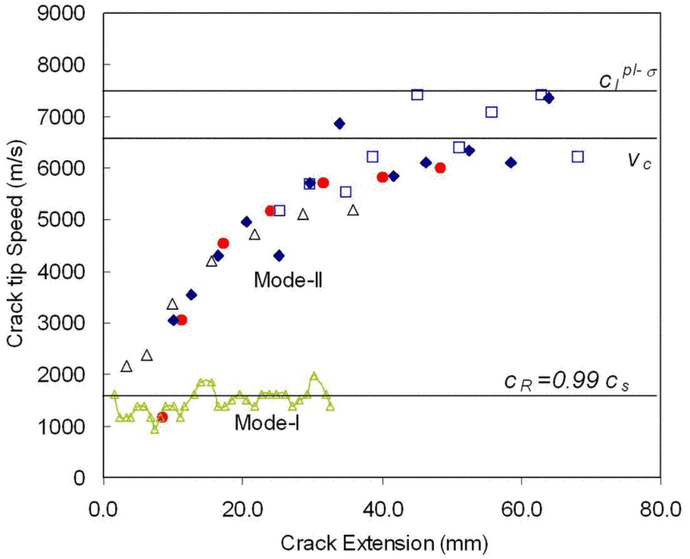






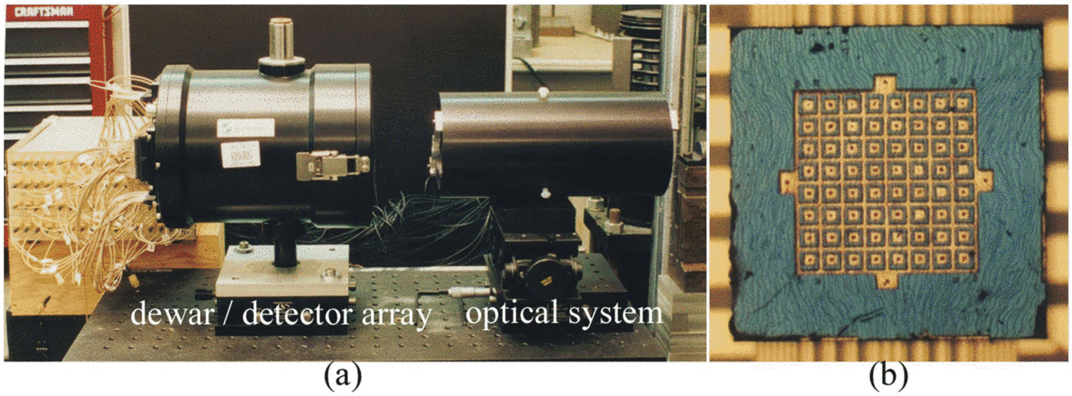
Coker and Rosakis (2001)

Crack-tip speeds for mode-I and mode-II: dynamic crack propagation in unidirectional composites



High-speed full-field IR microprobe camera

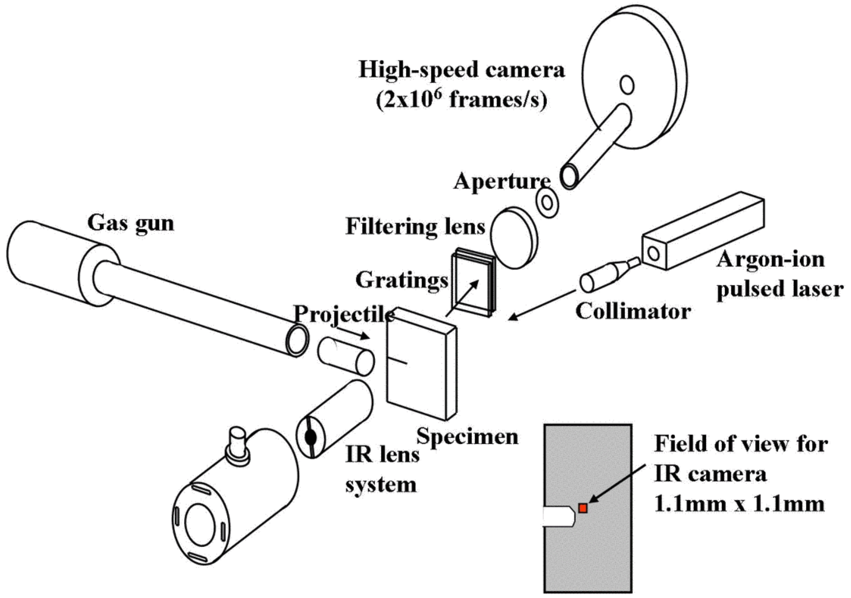
Zehnder, A.T., Guduru, P.R., Rosakis, A.J. and Ravichandran, G., *Review of Scientific Instruments*, 2000



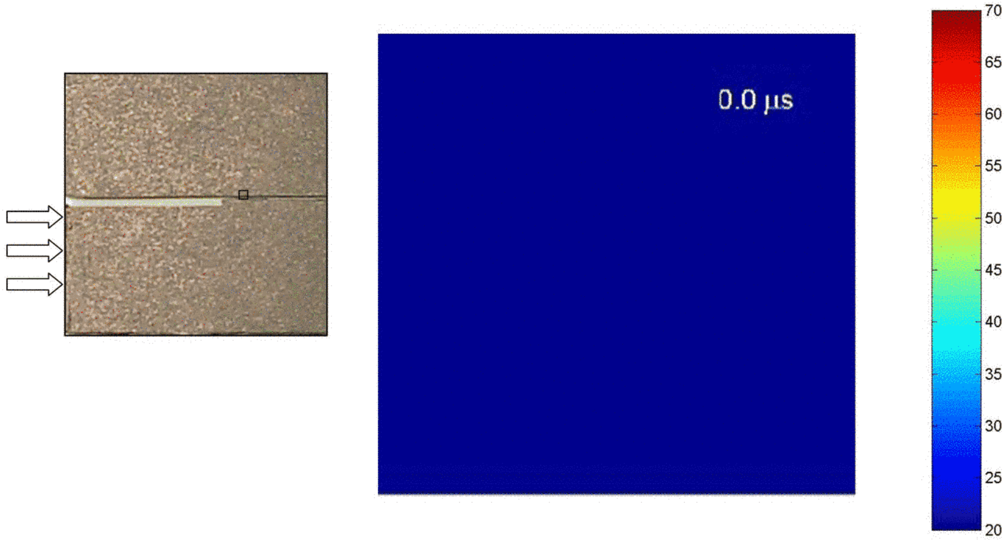
(a) (b)

- **HgCdTe detectors sensitive: to 2-10μm**
- **Field of view: 300 μm^2 - 1mm^2**
- **Detector size: 100 μm^2**
- **Response time: 20ns**

Full field imaging of transient temperature fields behind a growing shear crack in composites

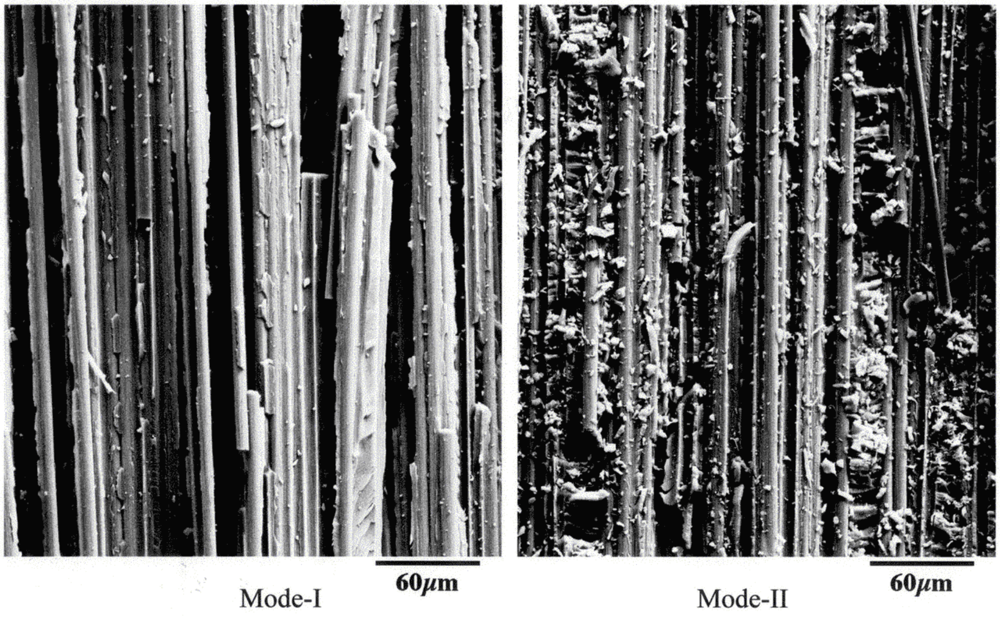


High-speed infrared images of hot spot formation behind an intersonically moving shear crack



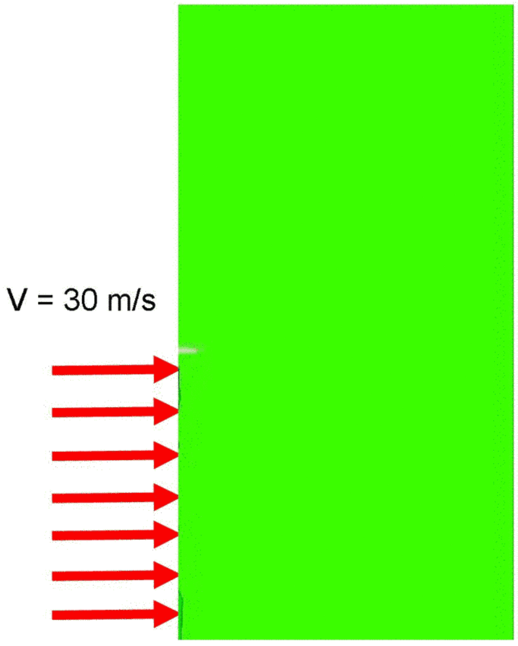
SEM June 1-4, 2003 at Charlotte NC /
Coker,Needleman,Rosakis

Fracture surface morphologies for mode-I and mode-II dynamically growing cracks

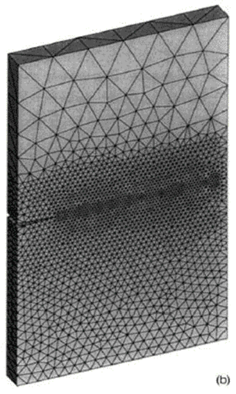


Finite Element Simulations with an irreversible cohesive law

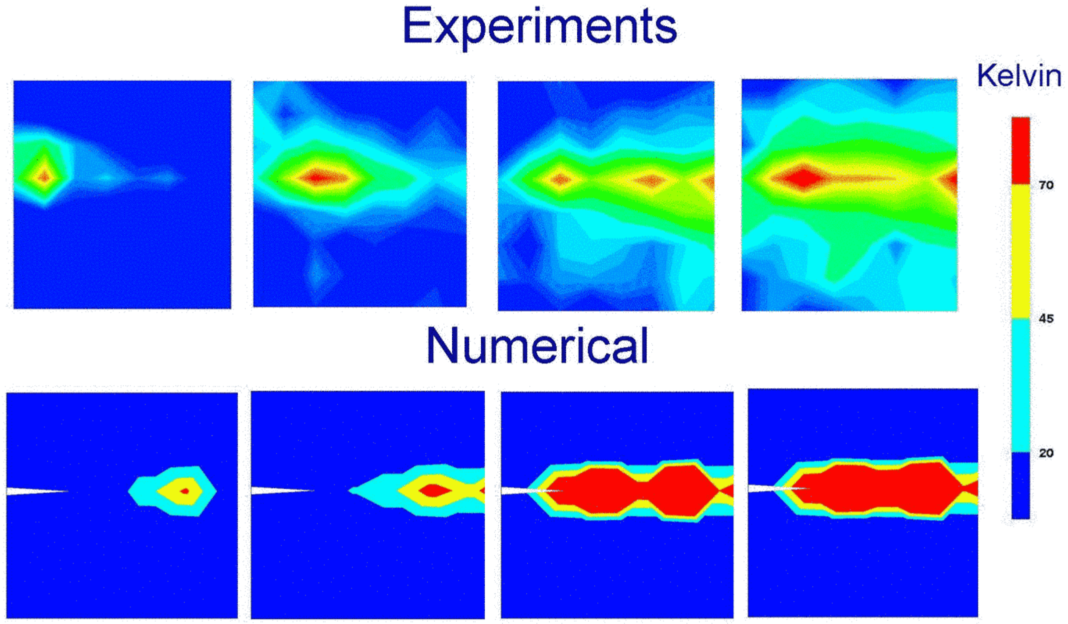
(Yu, Pandolfi, Coker, Ortiz and Rosakis, IJSS, 2002)



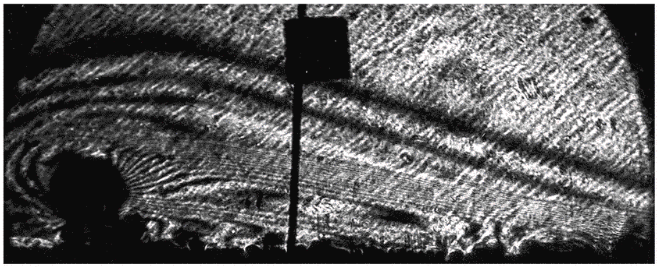
- Used orthotropic cohesive law
- Impact velocity: V = 30 m/s
- 3-D automatic remeshing
- Coulomb friction law when contact occurs after separation

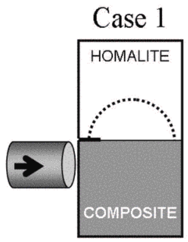


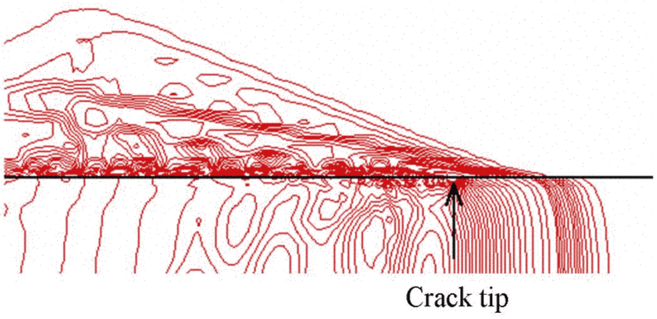
TEMPERATURE INCREASE (HOT SPOTS) AT 40, 50, 60, AND 70 MICROSECONDS

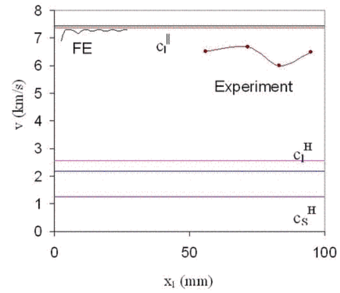


Supersonic rupture of composite/homalite interface (impact on composite)

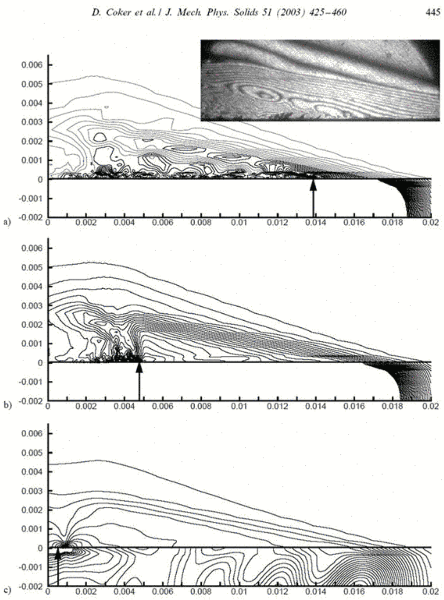


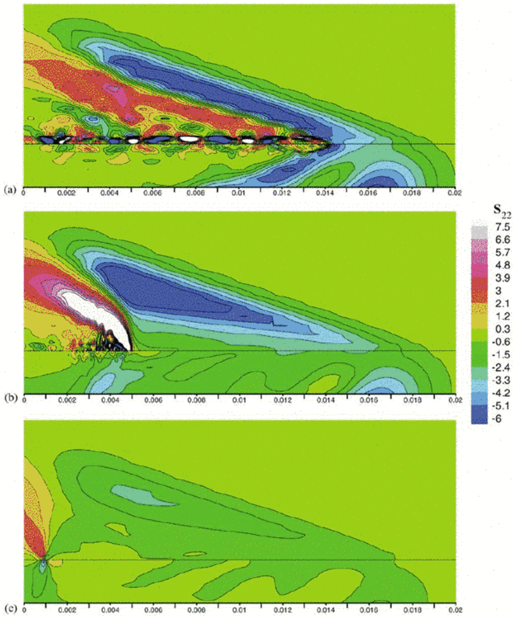



Crack tip

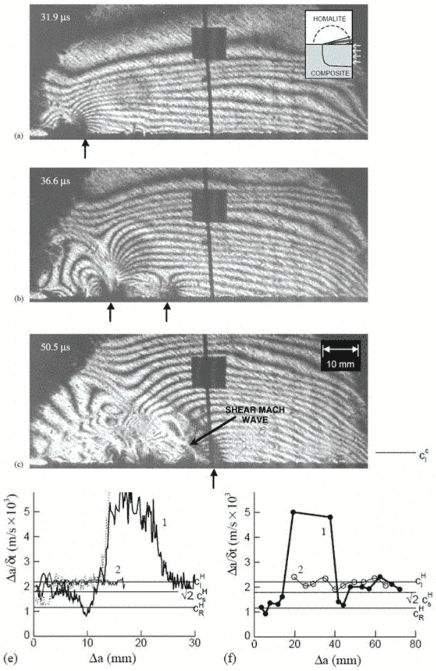


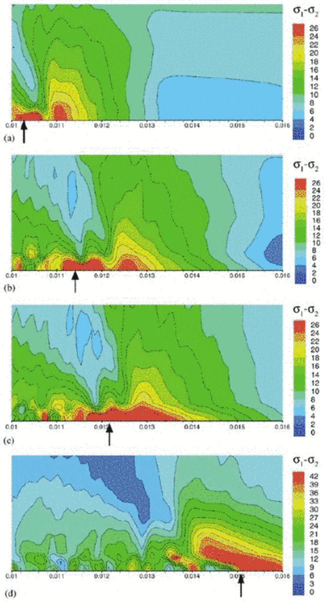
Supersonic shear crack propagation



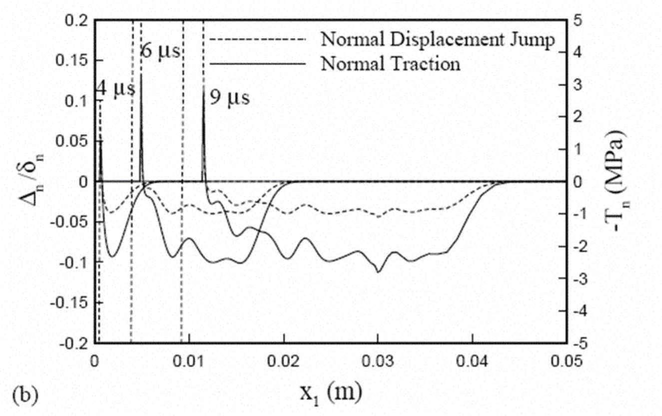


Transition from sub-Rayleigh to Super-shear rupture





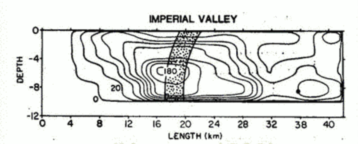
Opening pulse in a bimaterial



Coker, Needleman, Rosakis, 2003

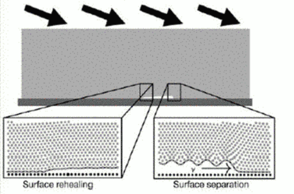
Frictional pulses at different length scales

earthquakes → sliding polymers → fiber pull-out → molecular dynamics

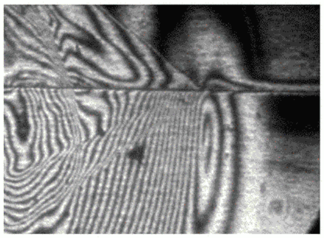


(Heaton, 1990)

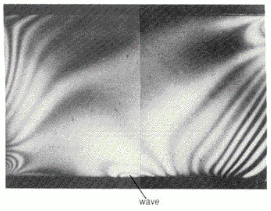
(Tsai & Kim, 1996)



(Gerde and Marder, 2001)



(Coker, Lykotrafitis, Needleman, Rosakis, 2004)



(Mouwakeh, Villechaise, Godet, 1991)

Universal features of Rupture (size independent)

For weak-straight-smooth-interfaces between two deformable bodies (due to low roughness or low cohesion) we show:

- Relative sliding is complex, composed of at least three sliding modes. (What are the microscopic mechanisms?)
- Supershear rupture propagation is common with shear Mach waves emanating from points of stress concentration,
- Localized deformation regions/hot spots,
- Transition mechanism from sub-Rayleigh to super shear,
- Opening pulse behind the rupture tip is possible even at high compressive loads.

Possible at all continuum length scales…

For further details

- Coker, D., Lykotrafitis, G., Needleman, A., and Rosakis, A. J., 2005. **Frictional sliding modes along an interface between identical elastic plates subject to shear impact loading.** Journal of the Mechanics and Physics of Solids, 53, pp. 884-922.
- Coker, D., and Rosakis, A. J., and Needleman, A., 2003. **Dynamic crack growth along a polymer composite-Homalite interface.** Journal of the Mechanics and Physics of Solids, 51, pp. 425-460.
- Coker, D. and Rosakis, A. J., 2001. **Experimental observations of intersonic crack growth in asymmetrically loaded unidirectional composite plates.** Philosophical Magazine A, Vol. 81, No. 3, pp. 571-595.
- Rosakis, A. J., Coker, D., Yu, C. and Ortiz, M., 2000. **Subsonic and intersonic failure of composites: High-speed optical and thermographic measurements and numerical simulations.** Dynamic Failure in Composite Materials and Structures, AMD-Vol. 243, Eds. Rajapakse, Y. D. S. and Sun, C. T., pp.49-65.
- Yu, C., Pandolfi, A., Ortiz, M., Coker, D., and Rosakis, A. J., 2002. **Three-dimensional modeling of intersonic crack growth in asymmetrically loaded unidirectional composite plates.** International Journal of Solids and Structures, Vol. 39, pp. 6135-6157.
- Rosakis, A. J., Samudrala, O. and Coker, D., 1999. **Cracks faster than the shear wave speed.** Science, 284, pp. 1337-1340.
- Rosakis, A. J., Samudrala, O. and Coker, D., 2000. **Intersonic shear crack growth along weak interfaces.** Materials Research Innovations, 3, pp. 236-243.