Dynamic Shear Failure of Weak Planes in Materials

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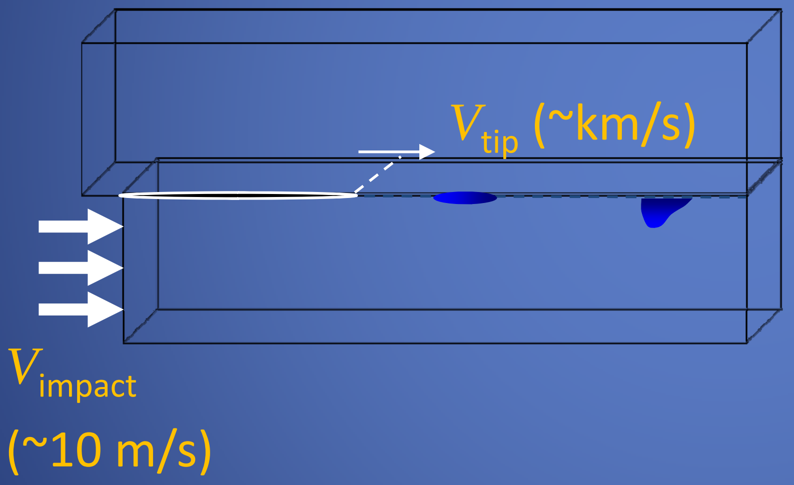
Outline

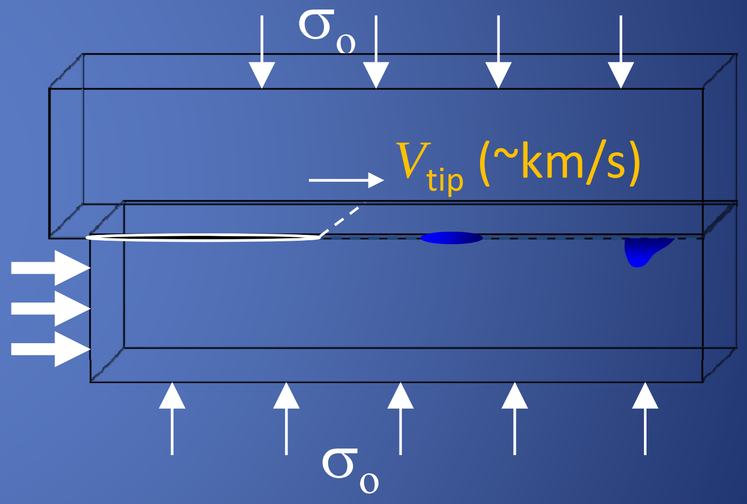
1. Examples of dynamic failure along weak planes
2. Fracture: Shear failure of coherent interfaces
    1. Dynamic fracture experiments
    2. How fast can cracks propagate in materials with weak planes?
3. Friction: Shear failure of incoherent interfaces
    1. Rate-State friction laws and the finite element model
    2. What are the frictional sliding modes?
4. Summary

Dynamic fracture and friction:
Shear failure along weak planes or interfaces

Coherent interface:
Fracture



Incoherent interface:
Friction



V_{tip} (~km/s) - - - propagation velocity of discontinuity tip

V_{impact} - - - - - - Driving speed (e.g. projectile impact)

Aircraft Hardening (FAA/Boeing)

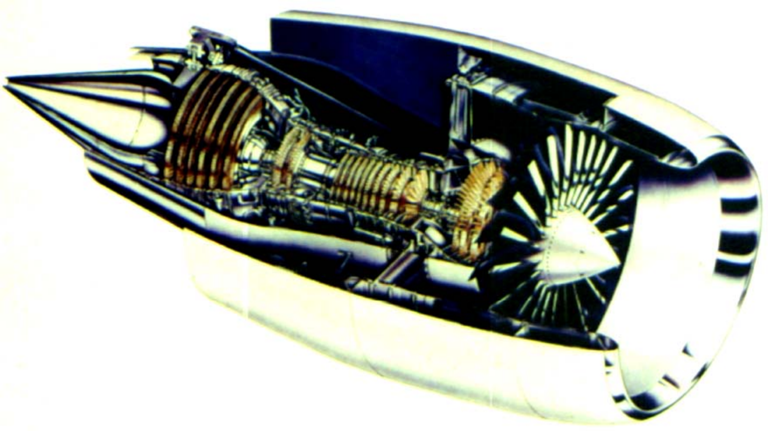
Damage sustained by aircraft fuselage during explosive loading experiment.

- Dynamic crack initiation and growth criteria in ductile metals.
- Formulation of local/global methodology to predict dynamic crack initiation and growth from pre-existing fatigue cracks thereby quantify the susceptibility of fuselage structures to global dynamic loading
- Evaluation of existing and future structural design concepts for their resistance to internal explosive loading (aircraft hardening).

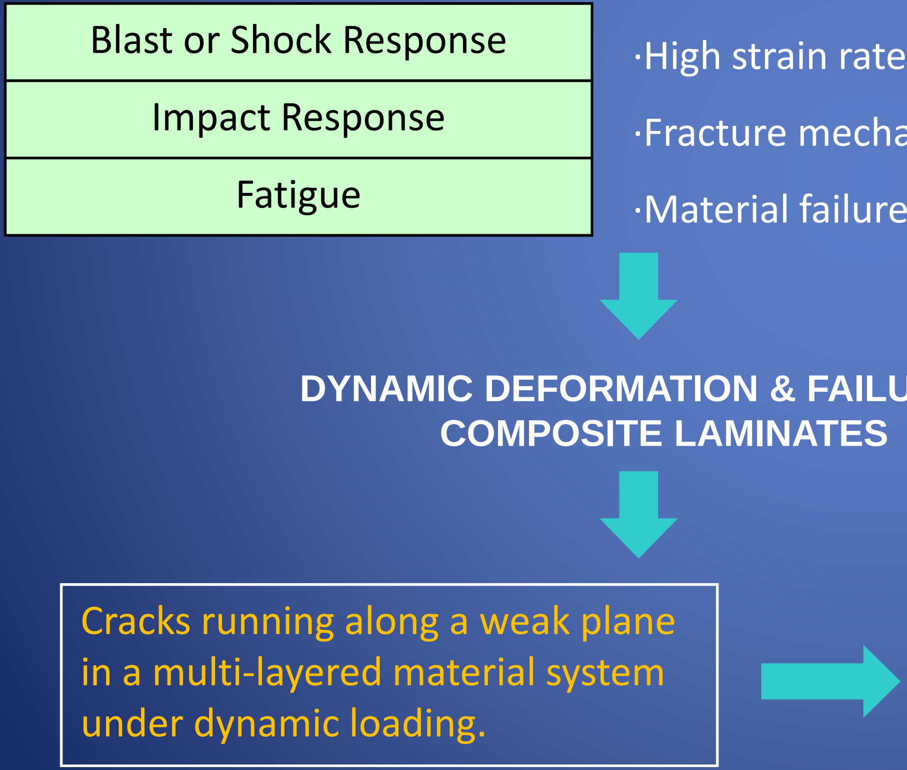
Composite Fan Blades (LANL/GE/Boeing)

Five foot long composite fan blades
of the GE-90 engine used in Boeing 777.

- Incorporation of dynamic fracture criteria and dynamic crack growth toughness values into elaborate 3-D numerical codes
- Codes utilized to model composite fan blade bird impact test for FAA certification.



Navy composite hull structures



Blast or Shock Response

Impact Response

Fatigue

- High strain rate effects and properties of thermoset composites
- Fracture mechanics (joints, strain energy release rates,…)
- Material failure models/Complex stress states

DYNAMIC DEFORMATION & FAILURE OF COMPOSITE LAMINATES

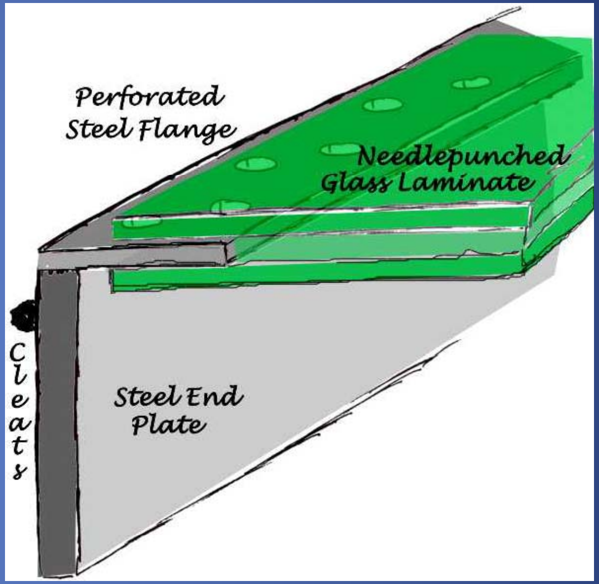
Model System

Cracks running along a weak plane in a multi-layered material system under dynamic loading.

Unidirectional Graphite/Epoxy composite laminates

Interface Failure in Engineering

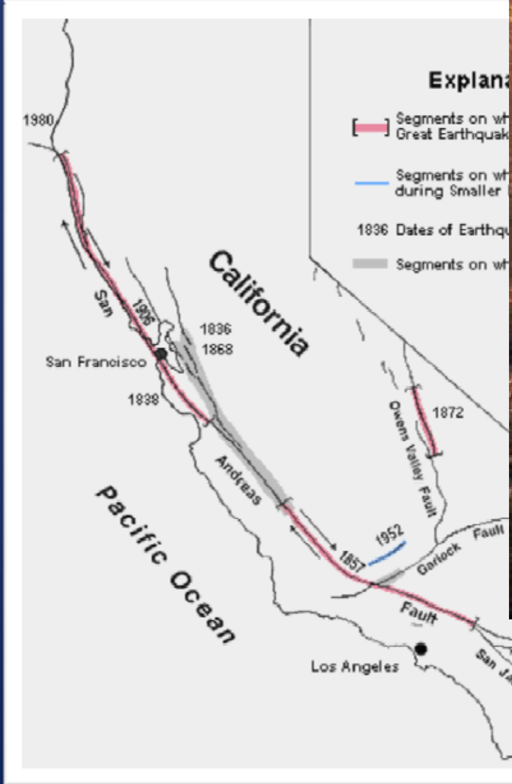
Lightweight Tomahawk Missile Capsule
Steel/S-Glass Composite Joint

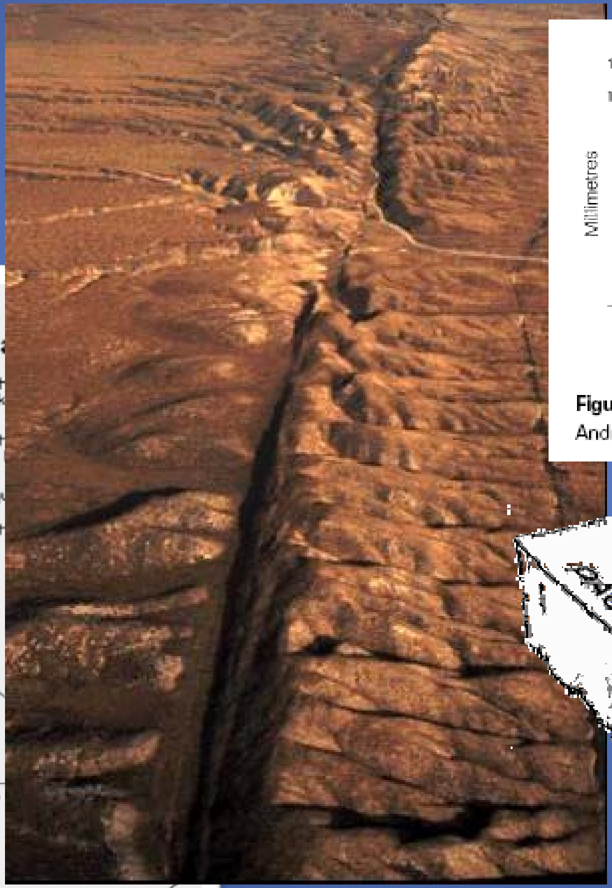


Co-molded Hybrid FRP - Steel Joint

The integrity of structures are often limited by failure at interfaces.

San Andreas fault as an example of crack growth along a weak plane





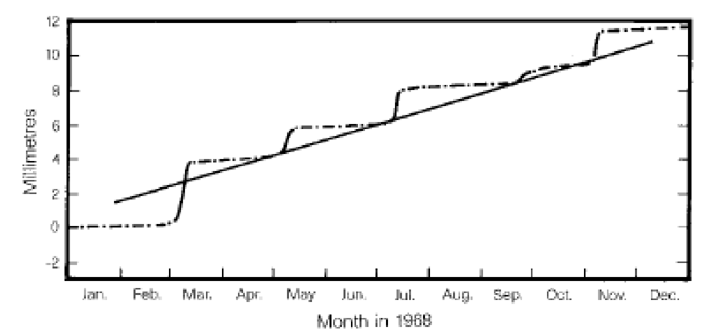
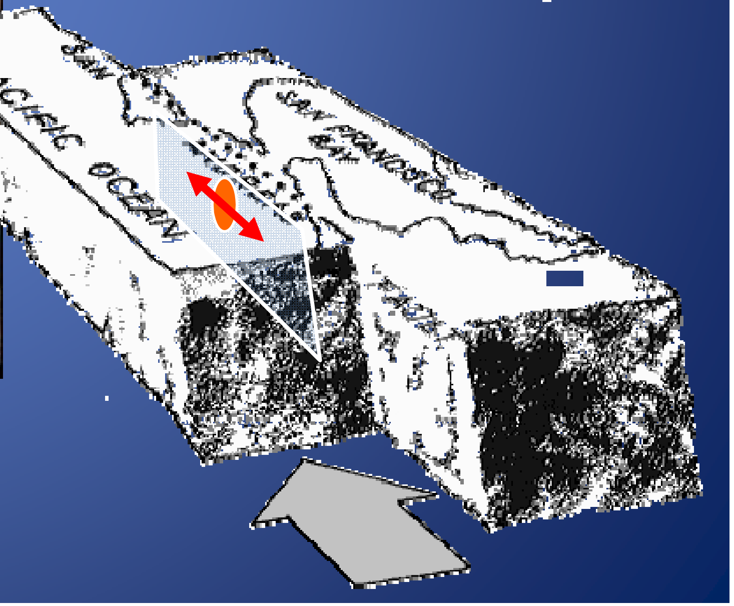
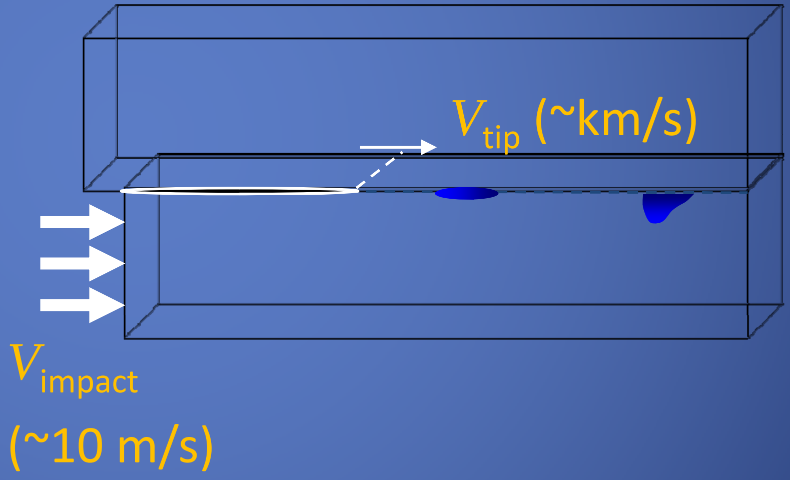


Figure 3 Oscillatory motion (creep episodes) of the creeping section of the San Andreas fault in central California (from ref. 10). The straight line is for reference.



Part I. Fracture
Crack Growth



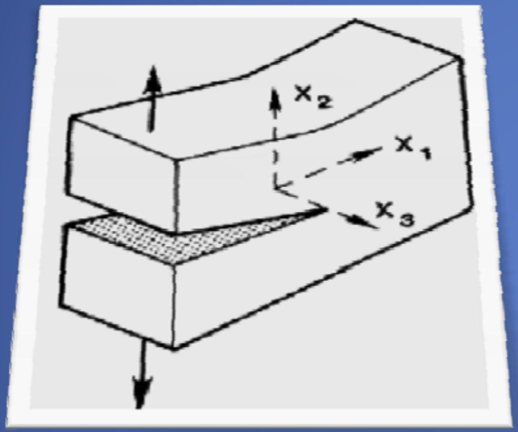
V_{tip} (~km/s)

V_{impact}

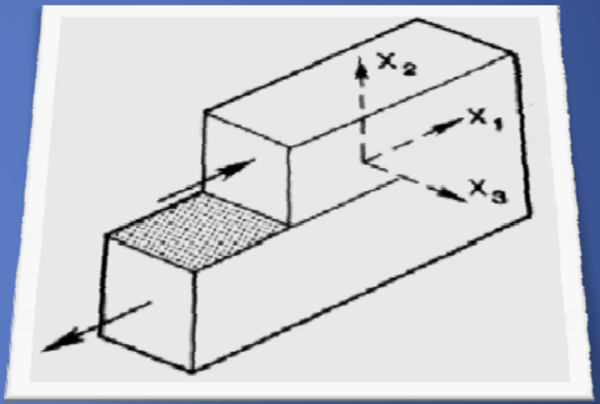
(~10 m/s)

Modes of crack growth

Mode-I (Opening)

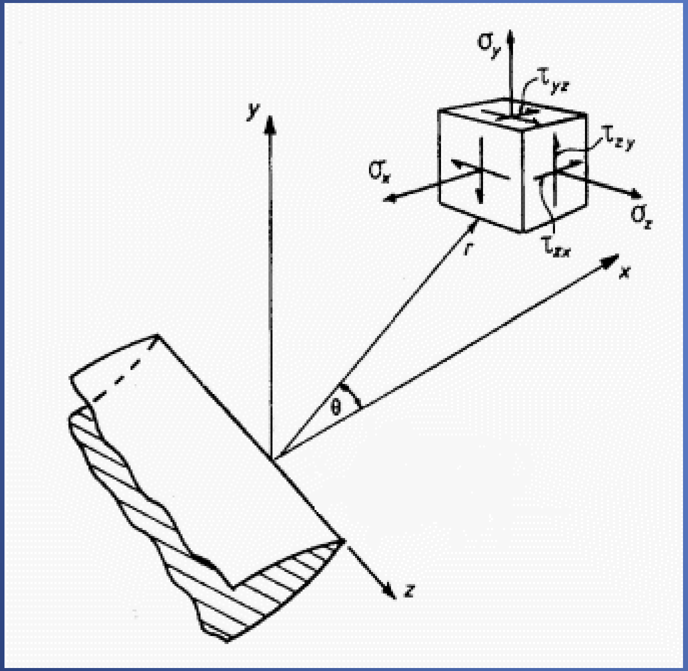


Mode-II (Shear)



- Crack growth in homogeneous materials can only occur by Mode-I
- In homogeneous materials, Mode-II cracks will change direction such that crack tip locally becomes mode-I.
- To grow Mode-II cracks, we need a weak plane that will trap it and force it to grow – an interface.

Stresses near a crack-tip



$$\sigma_{rr} = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 + \sin^2\frac{\theta}{2}\right)$$

$$\sigma_{\theta\theta} = \frac{K_I}{\sqrt{2\pi r}} \cos^3\frac{\theta}{2}$$

$$\sigma_{r\theta} = \frac{K_I}{\sqrt{2\pi r}} \cos^2\frac{\theta}{2} \sin\frac{\theta}{2}$$

LINEAR-ELASTIC FRACTURE MECHANICS
Stationary and Growing cracks

Stationary Crack:

Stress field: $$\sigma_{ij} = \frac{K_{I,II}}{\sqrt{2\pi r}} f^{I,II}{}_{ij}(\theta)$$ **$K_{I,II}$: Stress Intensity Factor**

Failure Criterion:

$$\boxed{\text{Elasticity} \longrightarrow K_I(Q,a) = K_{Ic}(Material) \longleftarrow \text{Experiments}}$$

Energy release rate: $$G_I = \frac{K_I^2}{E}$$

Growing Cracks:

Equations for slow crack growth is the same except a velocity dependence is added.

Dynamic crack growth criterion

$$\boxed{K_I^d(t)=K_I^d\big(Q(t),a,v\big)=K_D(v)\quad \text{for}\quad t>t_f}$$

$K_D(v)$ …. Dynamic Crack Growth Toughness

(Crack tip driving force)

- Depends on local strain rate through crack tip velocity only.

Steady-state singular stress field for a subsonically growing crack in orthotropic materials:

(Liu, Rosakis, Stout and Ellis (1996))

$$\sigma_{11}(x_1,x_2,v,t)=\frac{K_I^d(t)}{2\sqrt{2\pi}}\left(\frac{A_1(b_{ij},v)}{r_1^{1/2}}\cos(\theta_1/2)-\frac{B_1(b_{ij},v)}{r_2^{1/2}}\cos(\theta_2/2)\right)$$

$$\sigma_{22}(x_1,x_2,v,t)=\frac{K_I^d(t)}{2\sqrt{2\pi}}\left(\frac{A_2(b_{ij},v)}{r_1^{1/2}}\cos(\theta_1/2)-\frac{B_2(b_{ij},v)}{r_2^{1/2}}\cos(\theta_2/2)\right)$$

Scaled Coordinates

$$r_\alpha=\sqrt{x_1^2+\mu_\alpha^2 x_2^2}$$

$$\theta_\alpha=\tan^{-1}\left(\frac{\mu_\alpha x_2}{x_1}\right)$$

$$\mu_\alpha=\mu_\alpha(b_{ij},v)$$

Question

- Can a crack travel faster than any of the characteristic waves in the material?
- Initial Answer: NO!

Mach wave for a disturbance traveling faster than the characteristic speed

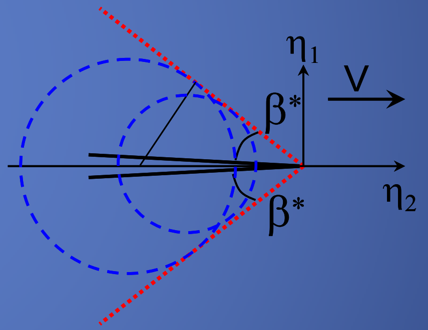
FLUIDS

Subsonic

Supersonic

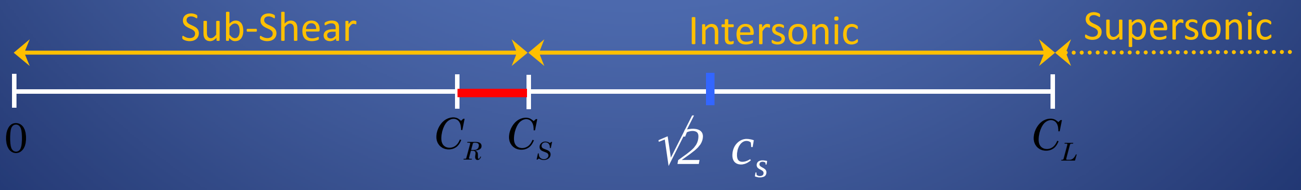
0

C_L



$$V = \frac{C_S}{Sin\beta^*}$$

SOLIDS



Sub-Shear

Intersonic

Supersonic

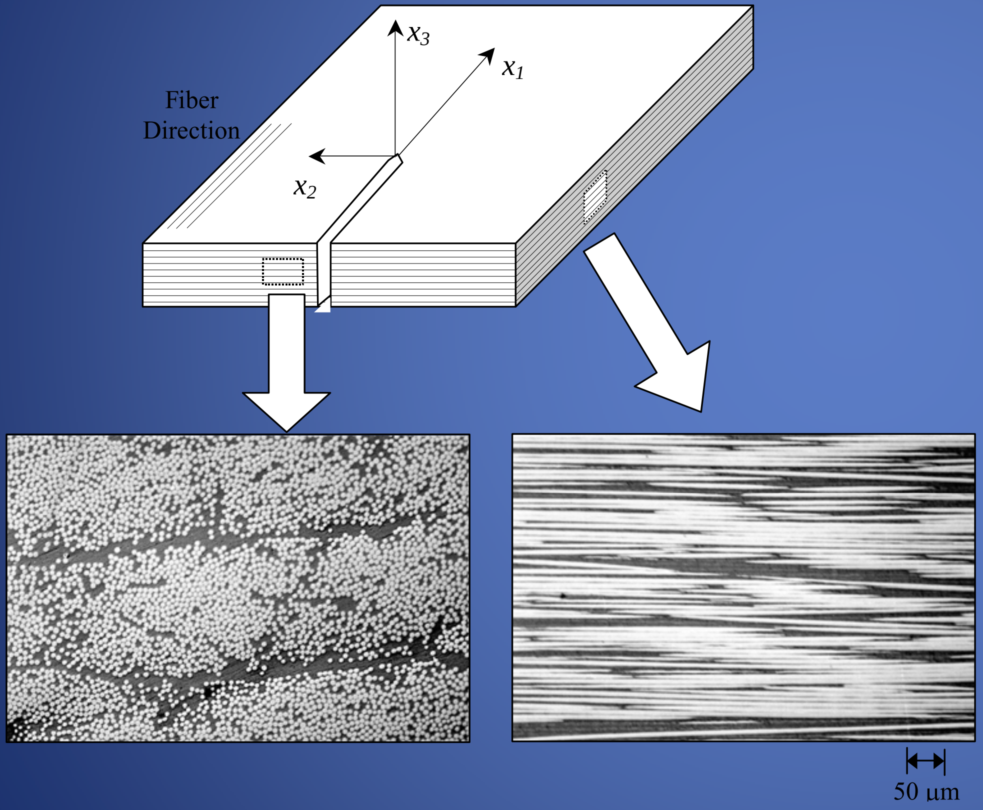
0

C_R C_S

$\sqrt{2}\ c_s$

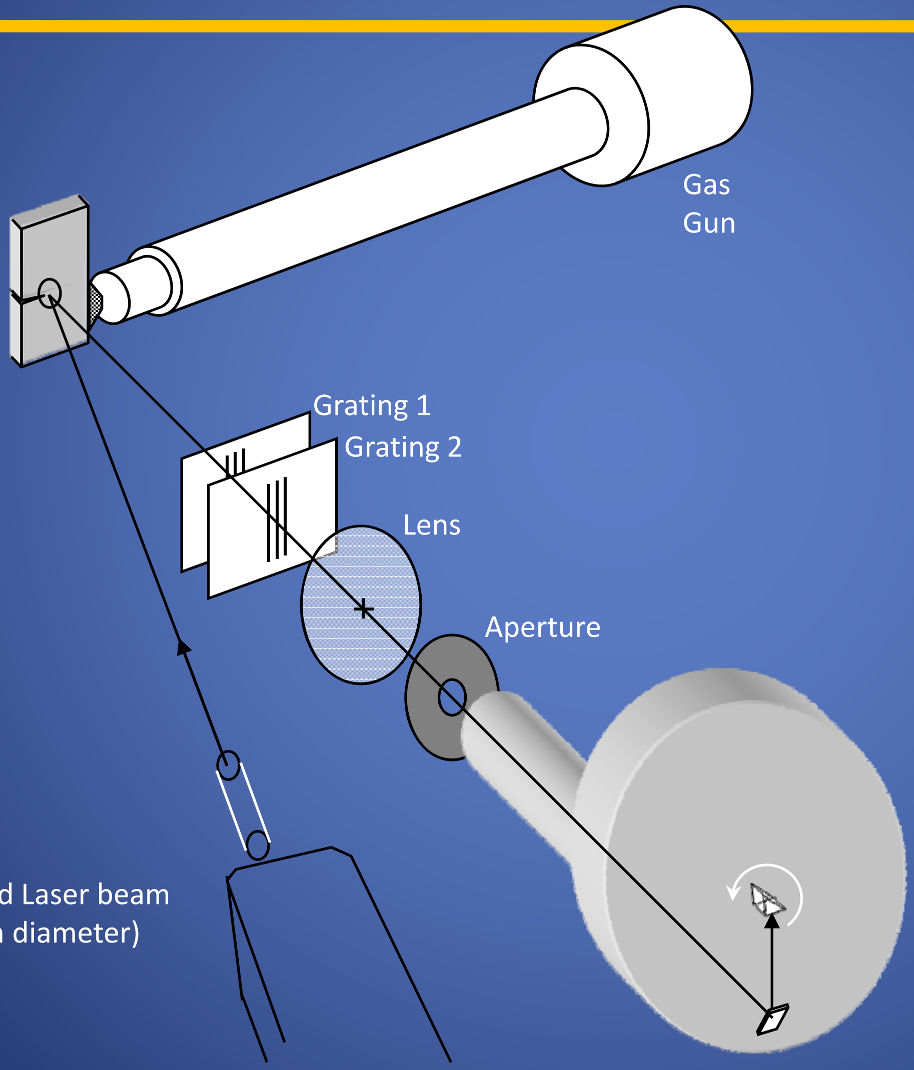
C_L

Fiber reinforced unidirectional graphite/epoxy composite laminate



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

Experimental set-up for dynamic fracture testing using coherent gradient sensing (CGS) optical technique



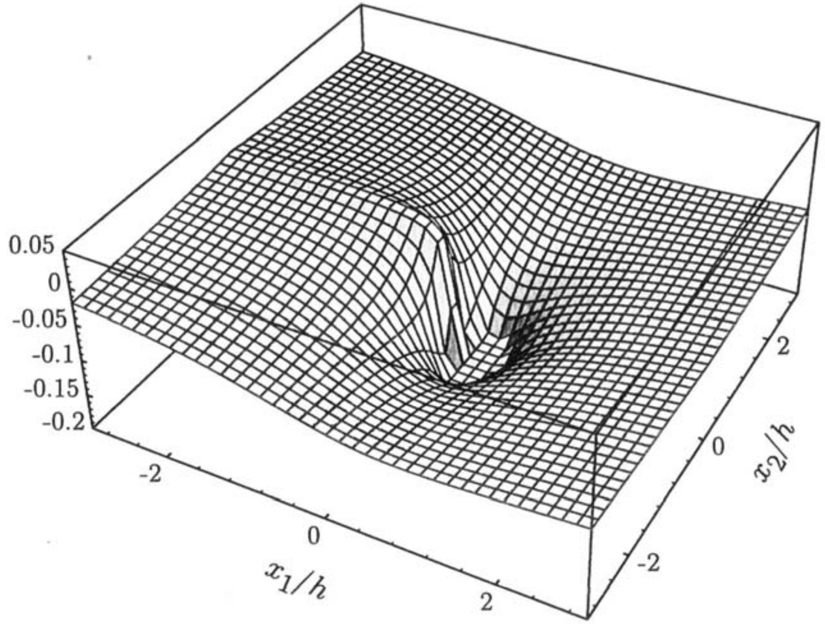
Rotating Mirror type high-speed camera
$2\mathrm{x}10^6$ frames/sec

Collimated Laser beam
(50 mm diameter)

Mode-I Opening Crack

- CGS fringe pattern

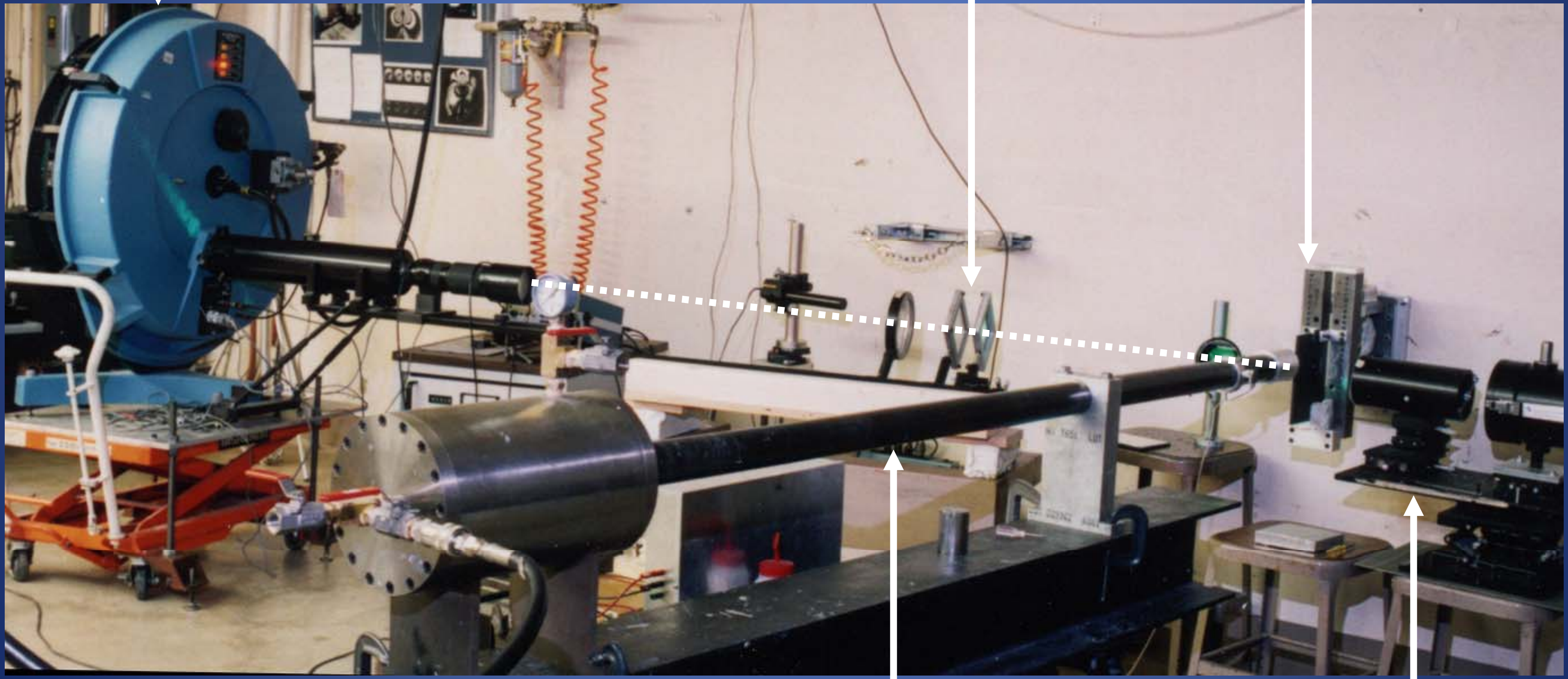
Surface Deformation



$$\frac{\partial u_3(x_1,x_2)}{\partial x_1} = \frac{mp}{2\Delta}$$

$$u_3 = \frac{h}{2}\left(b_{31}\sigma_{11} + b_{32}\sigma_{22}\right)$$

EXPERIMENTAL SET-UP FOR DYNAMIC FRACTURE TEST USING OPTICAL TECHNIQUE OF CGS



Camera

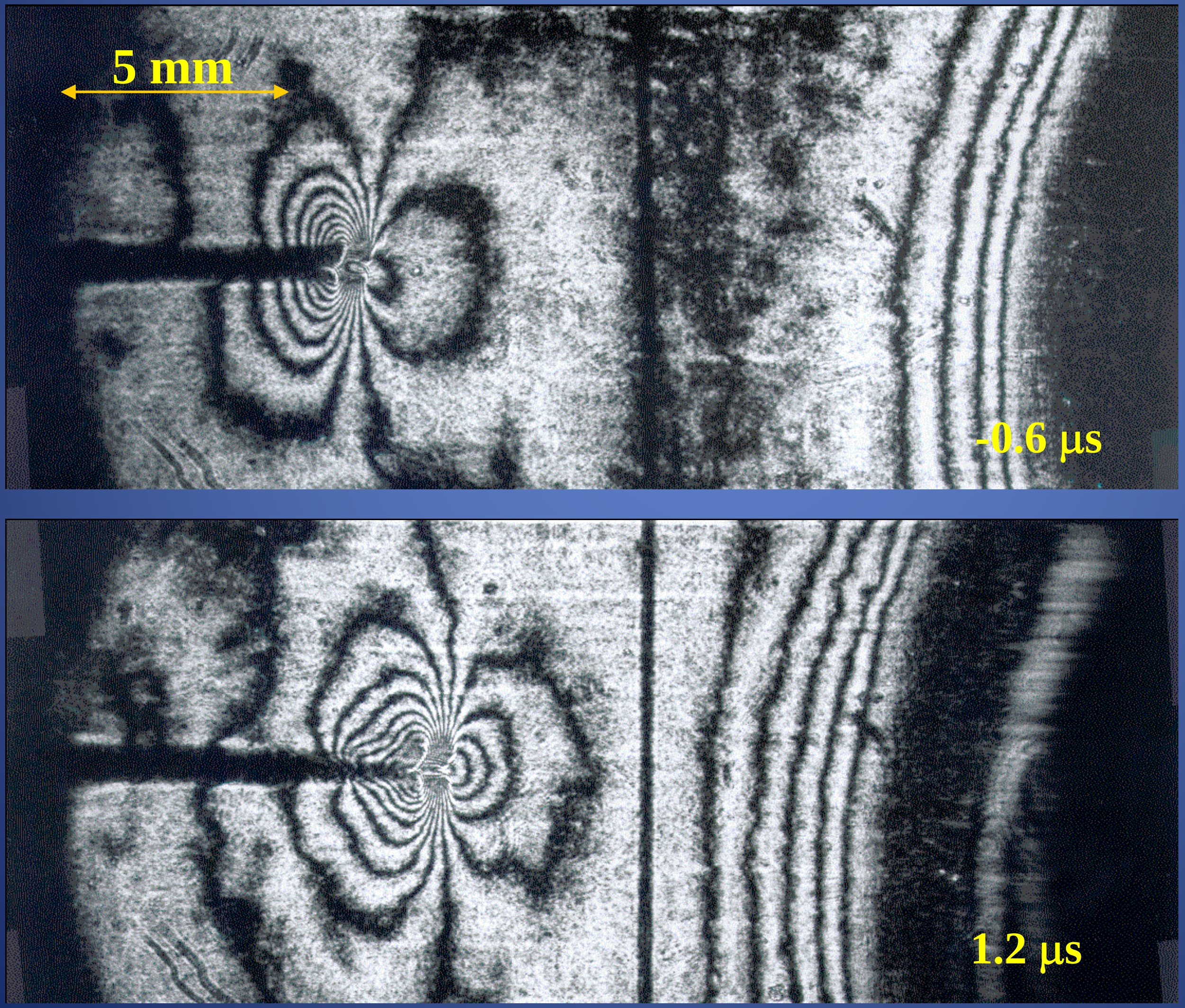
Gratings

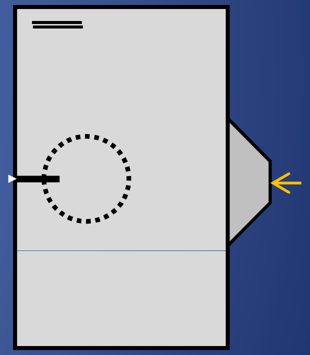
Specimen

Gas Gun

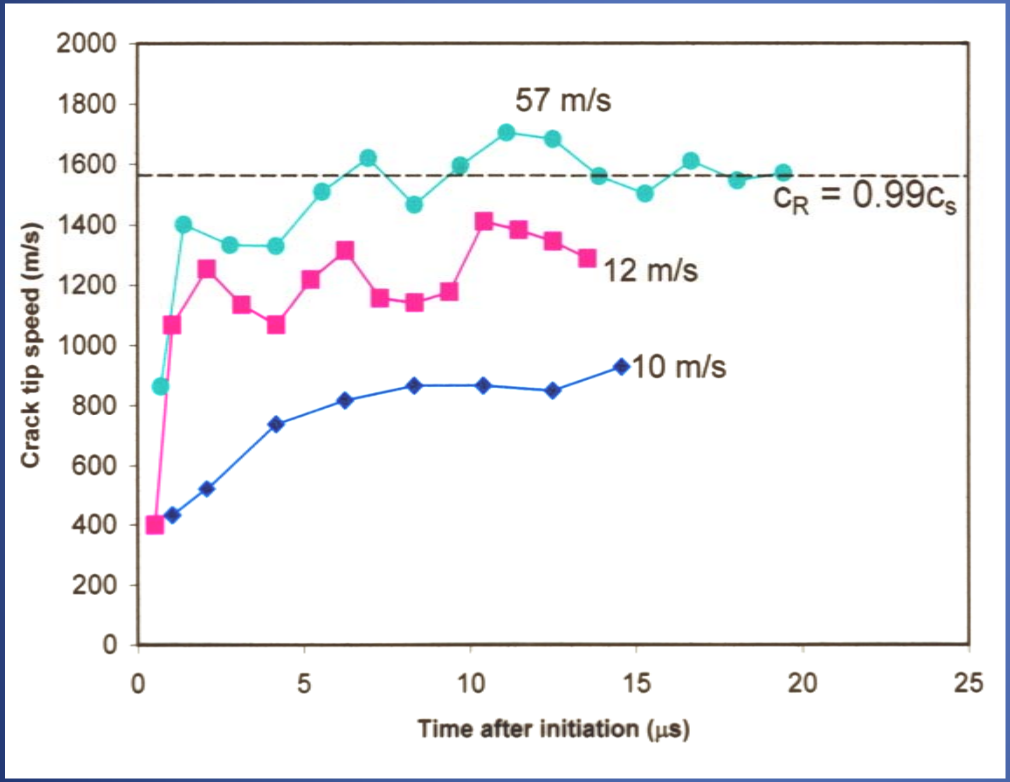
IR Camera

Mode-I (Opening) crack propagation



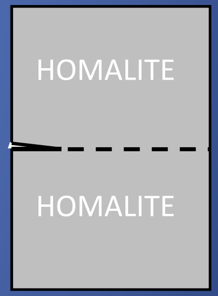


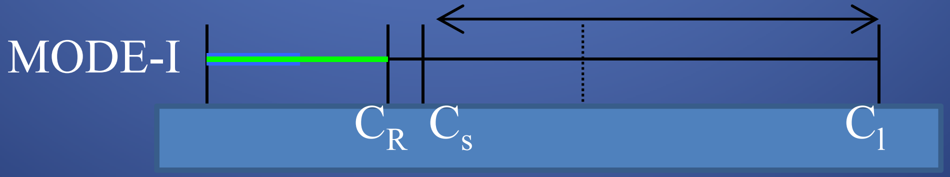
Crack-tip speeds for dynamic mode-I crack propagation in Gr/Ep unidirectional composites



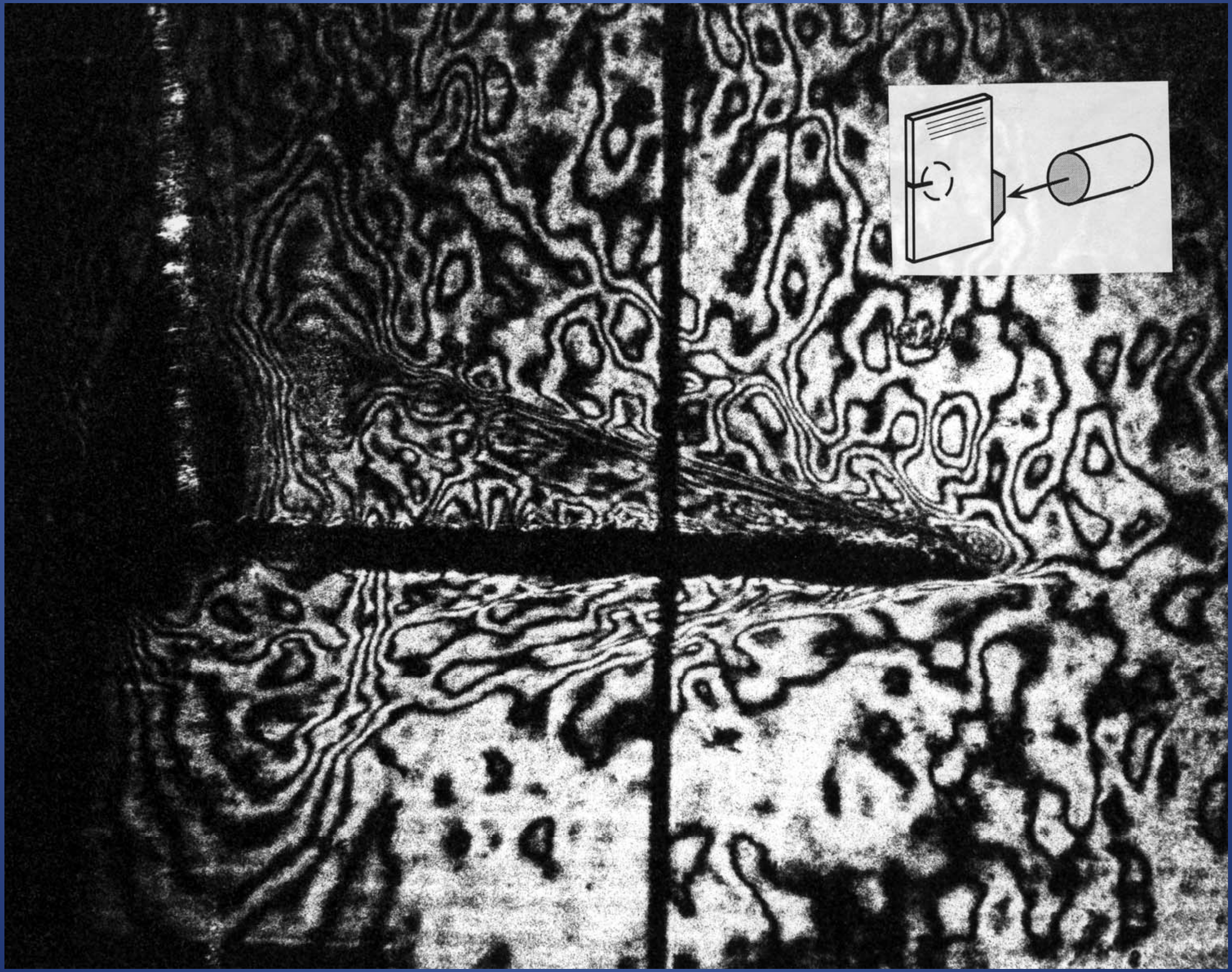
Homogeneous material with a weak plane

(Washabaugh & Knauss, 1994)

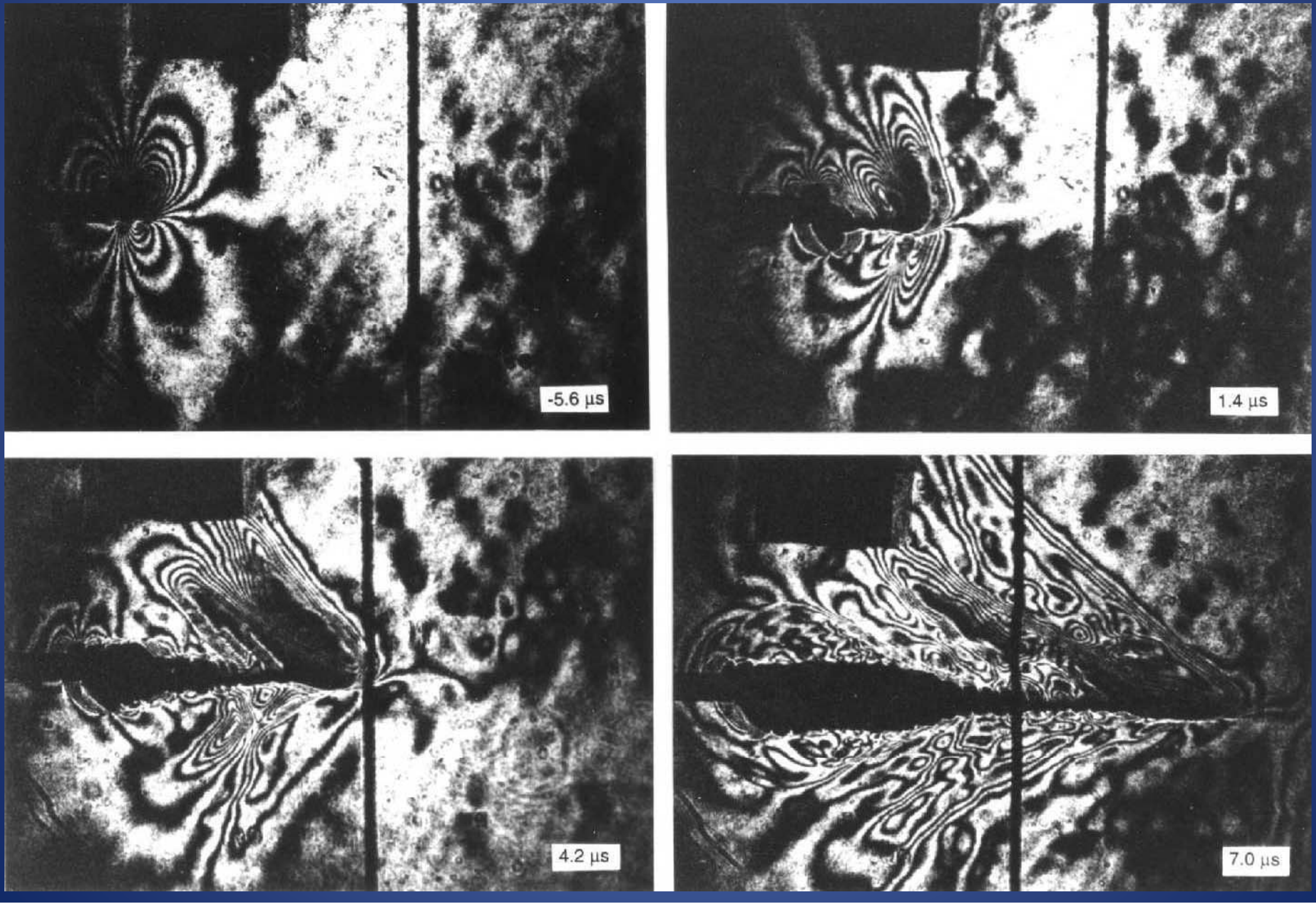




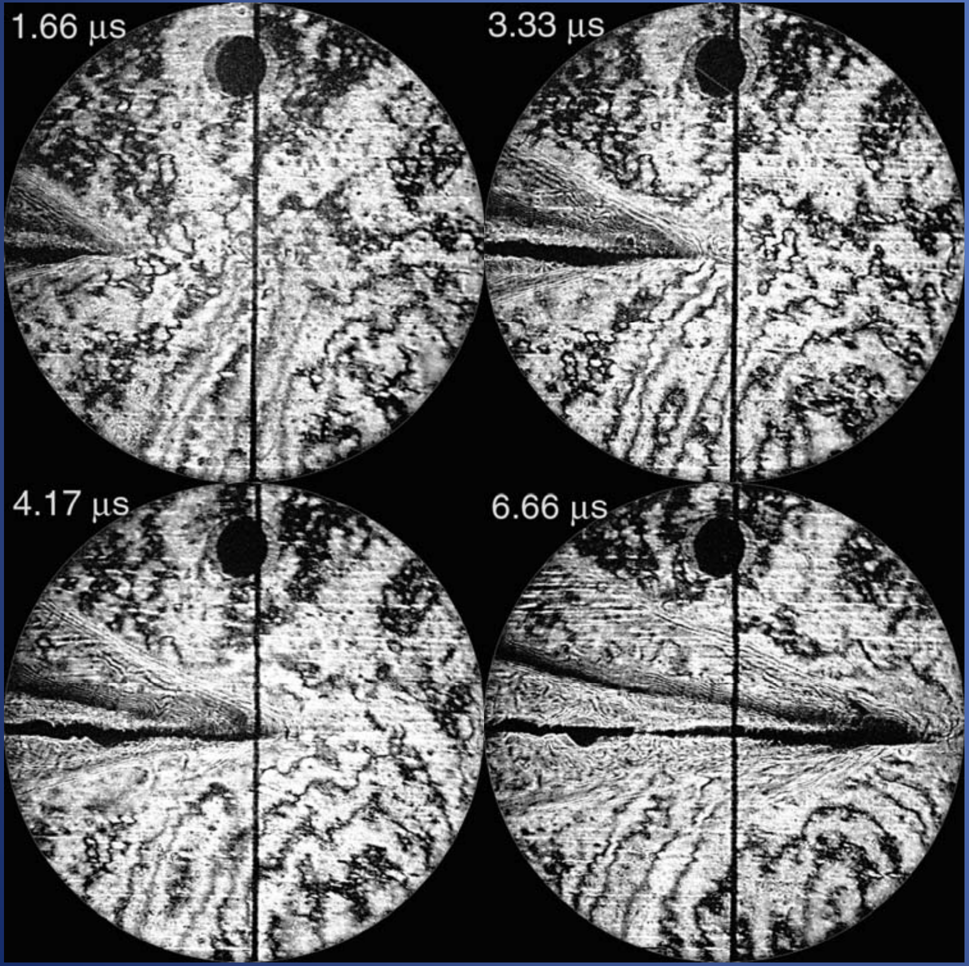
Experimental CGS Interferogram of a fast moving shear crack

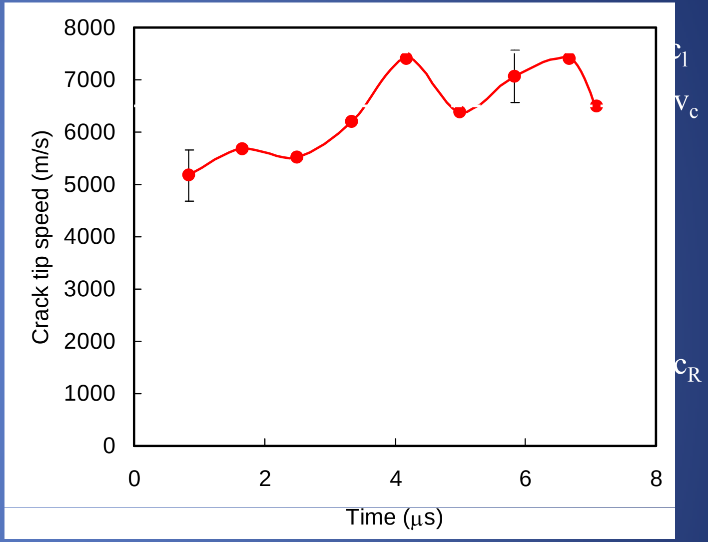


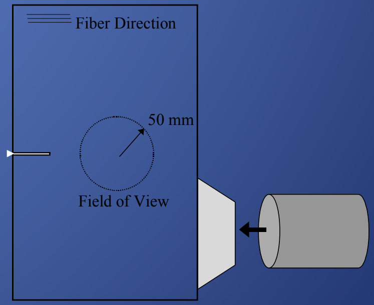
Shear dominated intersonic crack growth in a unidirectional graphite-epoxy composite laminate



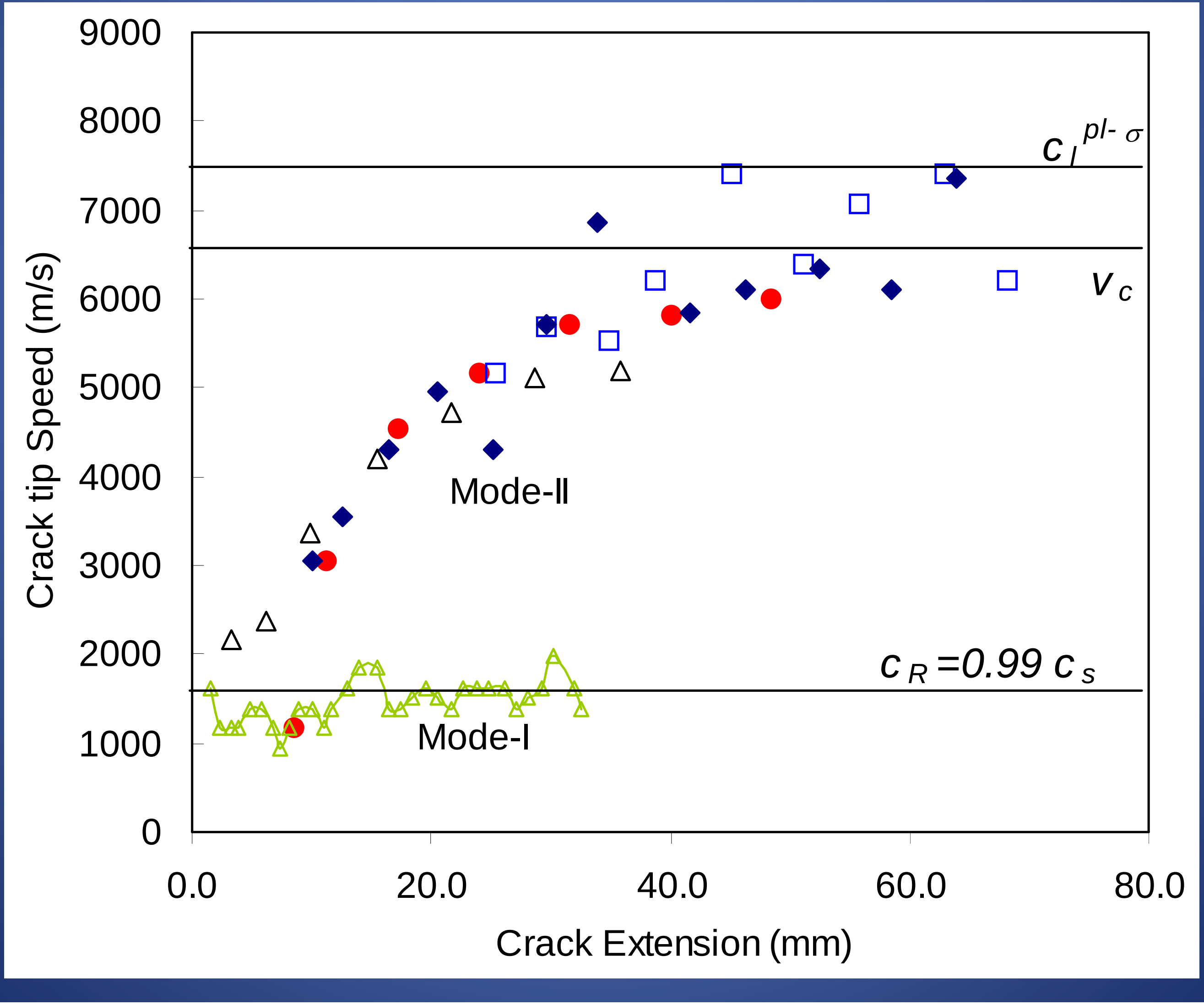
Intersonic shear crack propagation in unidirectional composites





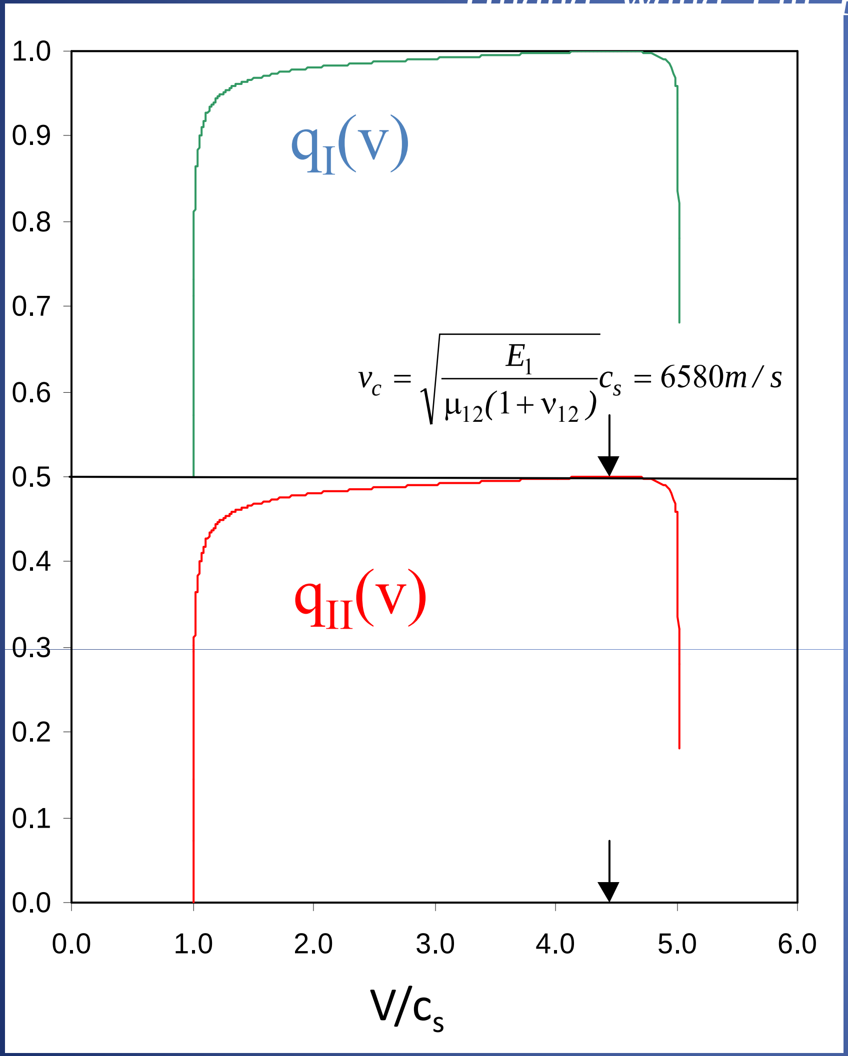


Crack-tip speeds for mode-I and mode-II dynamic crack propagation in unidirectional composites



Crack tip stress singularities for intersonically growing cracks in orthotropic materials

Huang, Wang, Liu, Rosakis; 1998



Mode-I

$$\sigma_{\alpha\beta} = \frac{A_I}{r^{q_I(v)}} f_{\alpha\beta}(\theta, v/c_s, c_{ij})$$

- Energy needed for Mode-I fracture:

$G_I = -\infty$ for $c_s < v < c_l$

Mode-II

$$\sigma_{\alpha\beta} = \frac{A_{II}}{r^{q_{II}(v)}} f_{\alpha\beta}(\theta, v/c_s, c_{ij})$$

- Energy needed for Mode-II fracture:

$G_{II} = 0$ for $c_s < v < c_l$

$G_{II} =$ finite for $v = v_c$ only

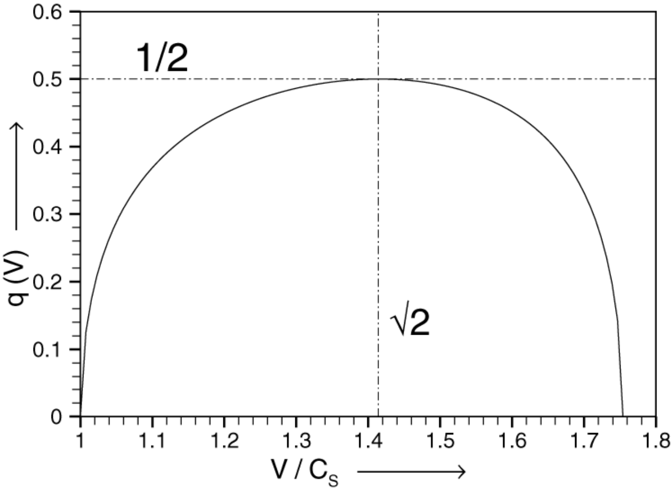
•Stable and unstable intersonic crack growth is possible under shear (mode-II) conditions only.

•Stable intersonic growth is possibly at $v=v_c$.

Steady state crack tip speed for intersonic shear crack growth

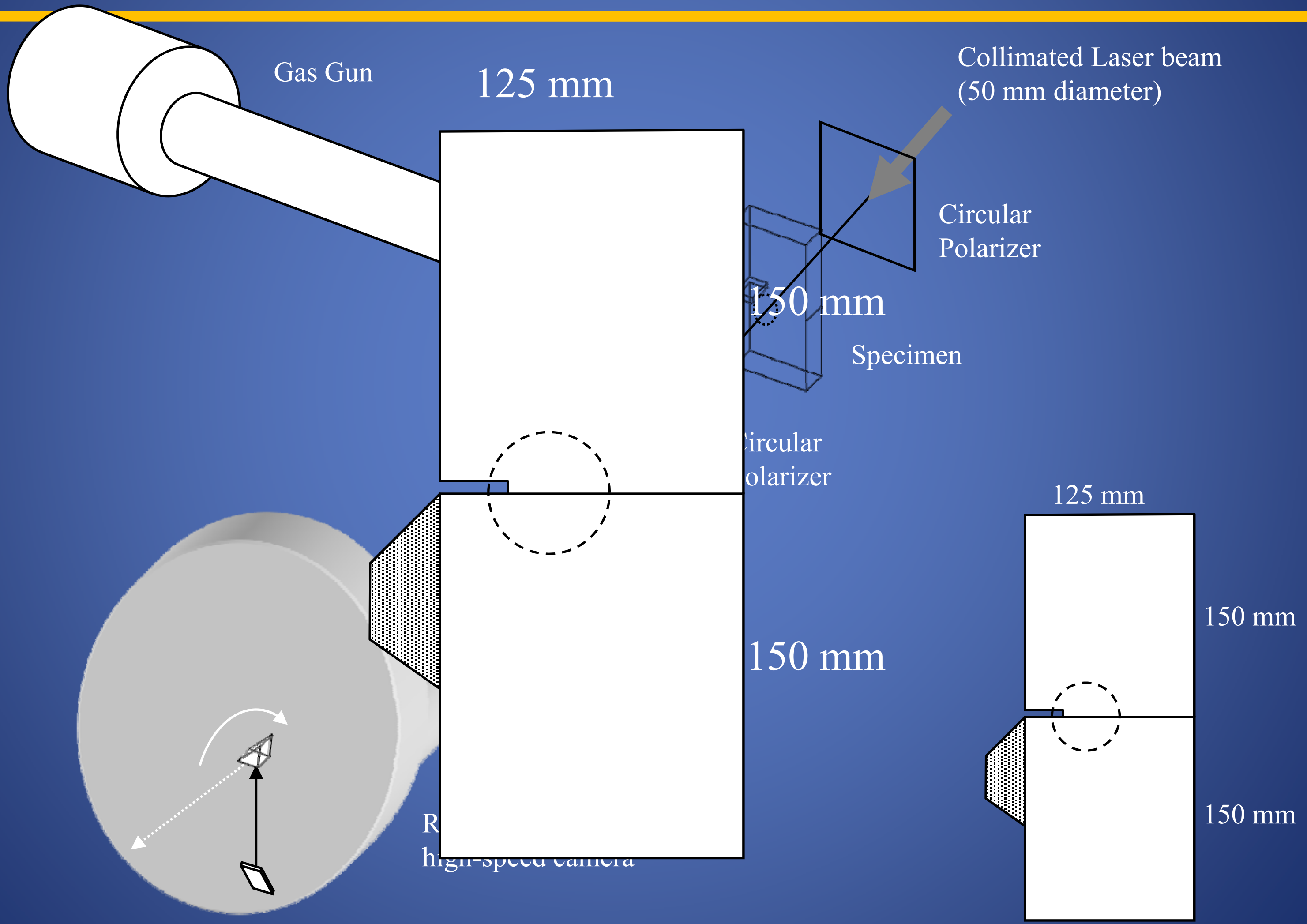
Orthotropic Materials: $v_c = \sqrt{\dfrac{c_{11}c_{22} - c_{12}^2}{\rho(c_{12} + c_{22})}} = \sqrt{\dfrac{E_1}{\rho(1+\nu_{12})}}$ = 6600 m/s

Isotropic Materials (*Freund, 1979*):



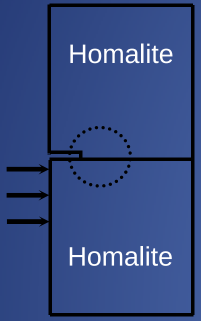
$$v_c = \sqrt{\frac{E}{\rho(1+\nu)}} = \sqrt{\frac{2\mu}{\rho}} = \sqrt{2}C_S$$

Fracture along a weak plane: experiments

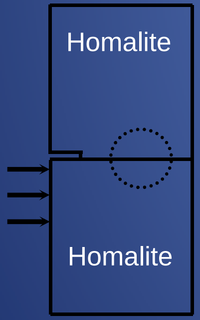


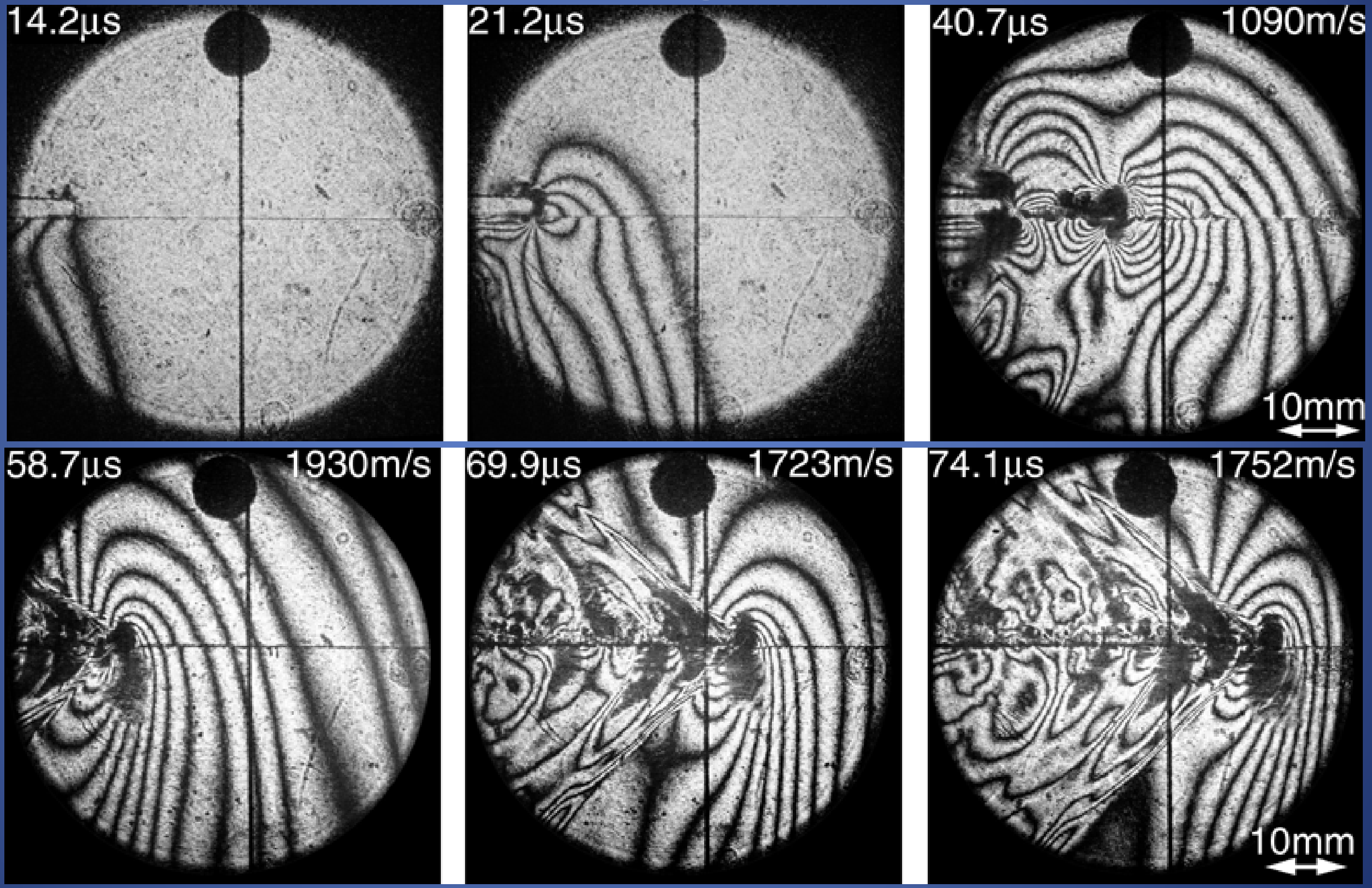
Intersonic shear crack growth
in a homogeneous materials with a weak plane

Isochromatic Fringe Patterns



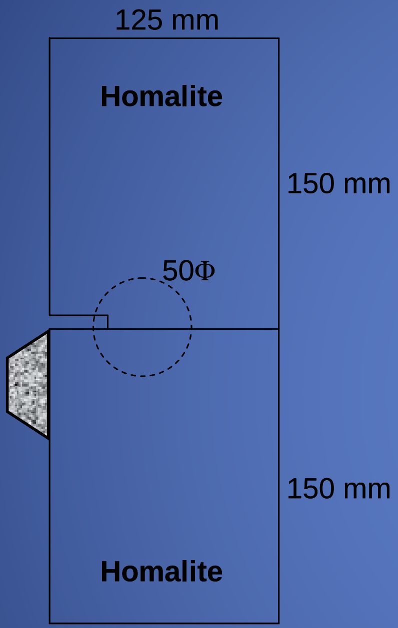
28 m/s

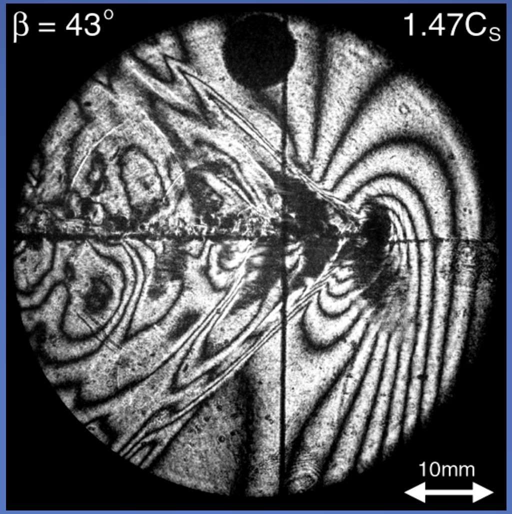




Rosakis, Samudrala, Coker; SCIENCE, 1999

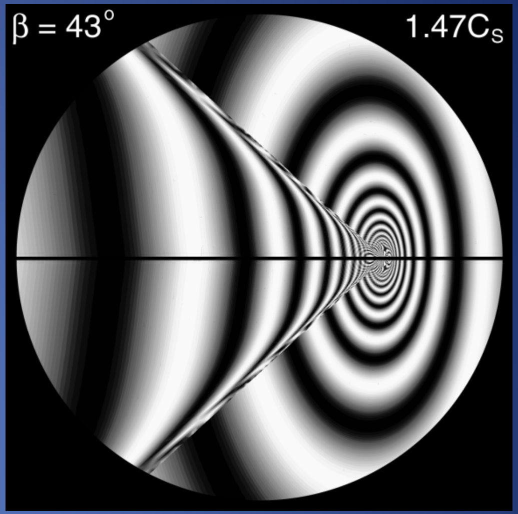
Intersonic Mode-II Crack Propagation





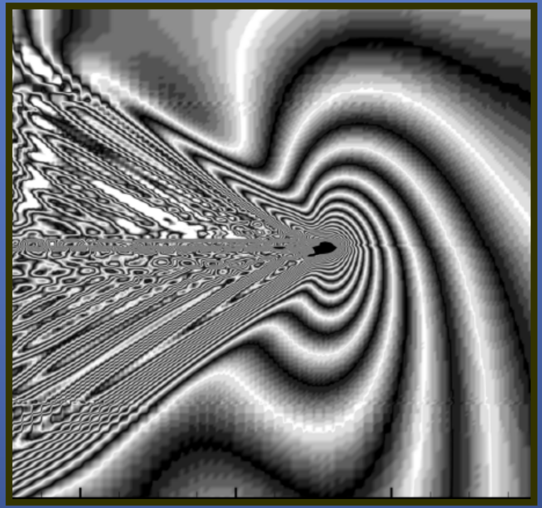
Experiment

Rosakis, Samudrala & Coker '99



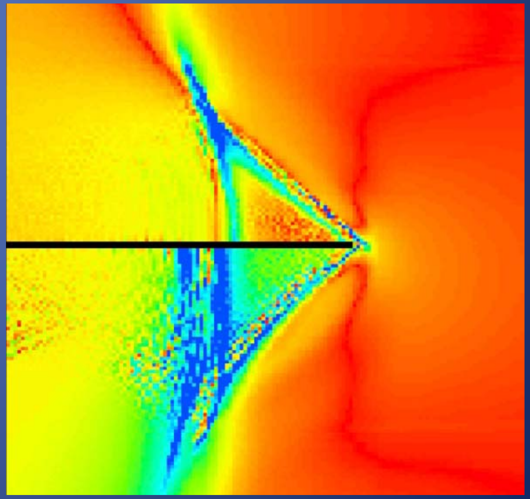
Theory

Freund '79



GIMP

Daphalapurkar, Lu, Coker, Komanduri '07

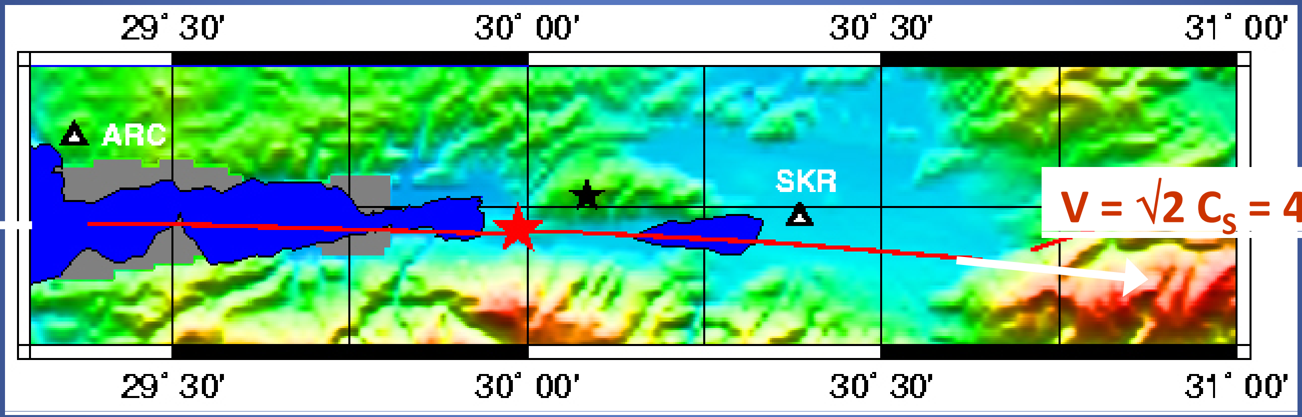


MD Simulations

Abraham '04

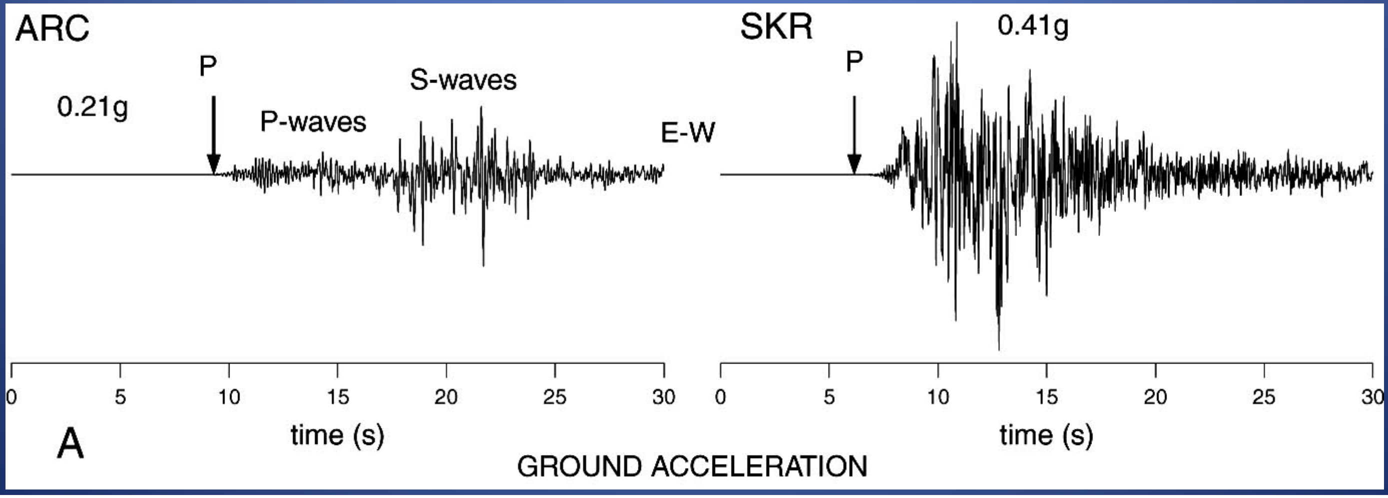
Field evidence of intersonic rupture during the 1999 Izmit and Duzce earthquakes in Turkey

M. Bouchon, M. Bouin, H. Karabulet, M. Toksöz, M. Dietrich and A. Rosakis,
Geophysical Research Letters, 2001



$V = C_R$

$V = \sqrt{2}\, C_S = 4.9$ km/s



Question

- Can a crack travel faster than any of the characteristic waves in the material?
- Initial Answer: Depends!
- For Mode-I cracks: NO
- For Mode-II cracks: YES.

Part II. Friction

"God made solids but surfaces were the work of the devil"

- Wolfgang Pauli

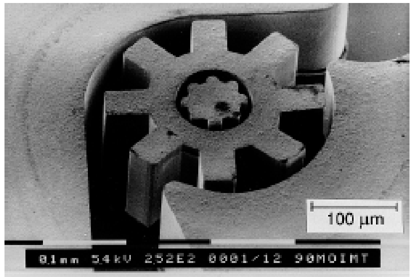


Fig. 1. SEM-micrograph of a LIGA-microturbine made of nickel in the unused state

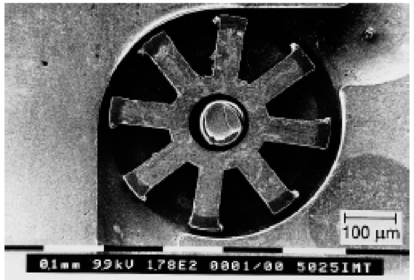
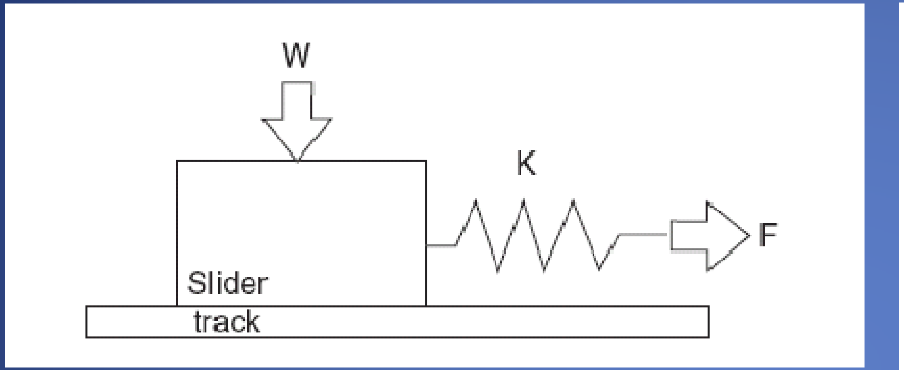
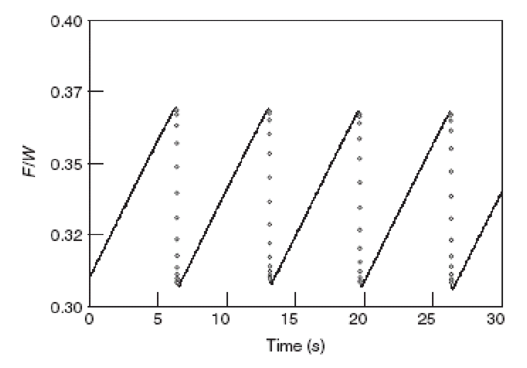


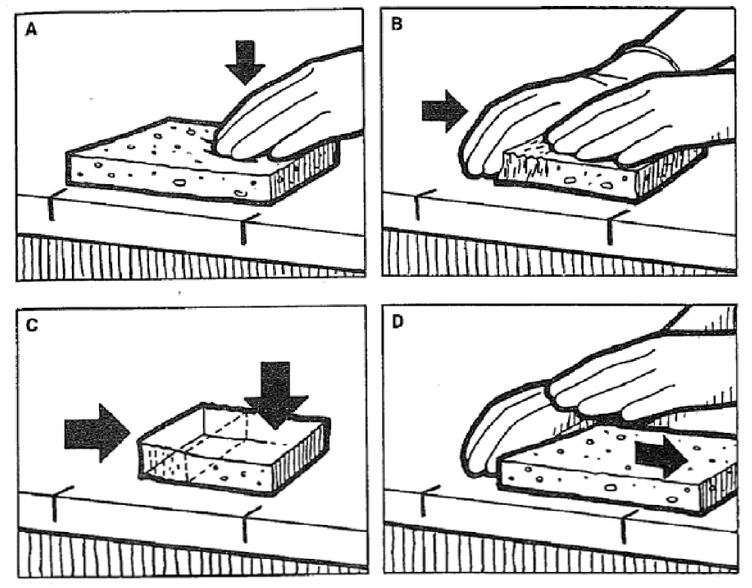
Fig. 2. SEM-micrograph of a LIGA-microturbine made of nickel after several thousands of revolutions

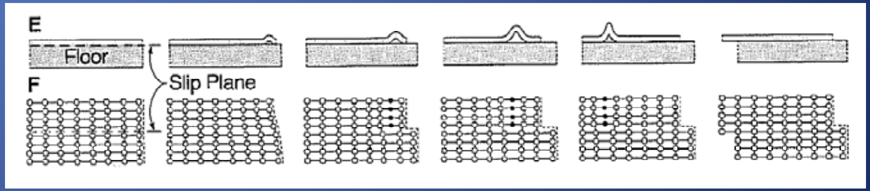
Tribological investigations of
LIGA microstructures
T. Bieger, U. Wallrabe

Frictional sliding:
Homogeneous and Heterogeneous Slip





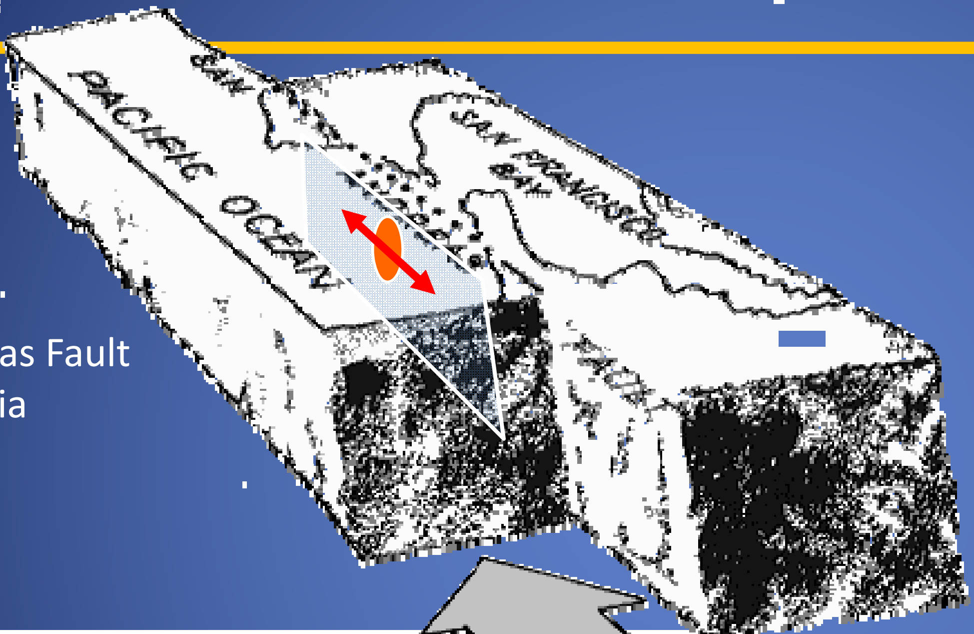




Davis and Reynolds, Structural Geology of Rocks and Regions

Earthquakes

San Andreas Fault in California



Earthquakes can be viewed as frictional sliding of tectonic plates at two time scales: Stick-slip at 100-1000 year time-scale and dynamic frictional sliding at 100 seconds time-scale.

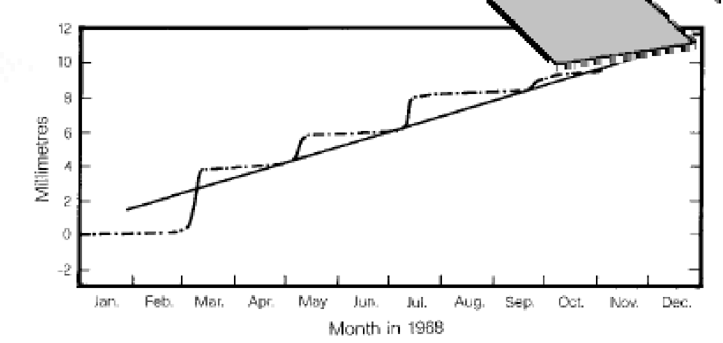
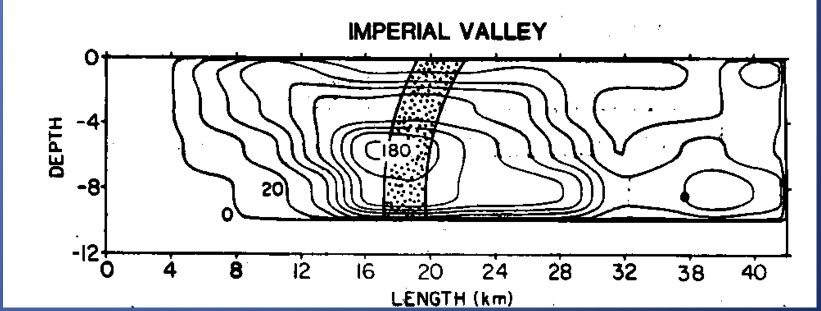


Figure 3 Oscillatory motion (creep episodes) of the creeping section of the San Andreas fault in central California (from ref. 10). The straight line is for reference.

Years

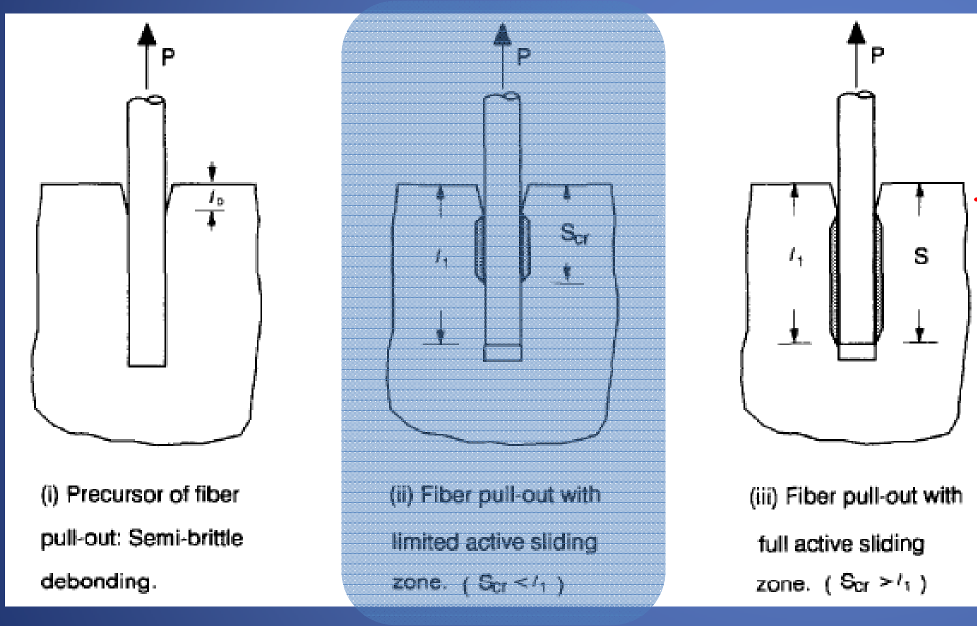
(Heaton, 1990)



Seconds

Frictional sliding in composite materials

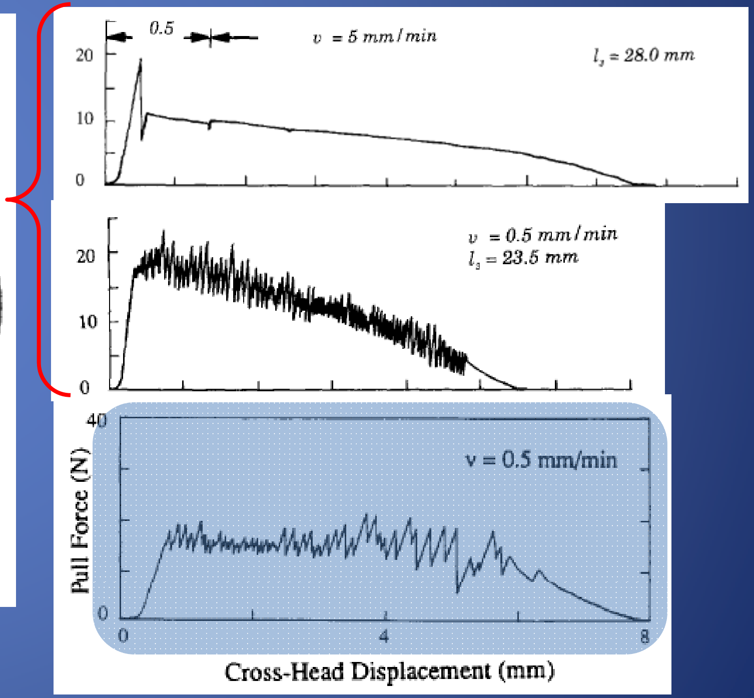
Frictional sliding is an important toughening mechanism during fiber pull-out in composite materials



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

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

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

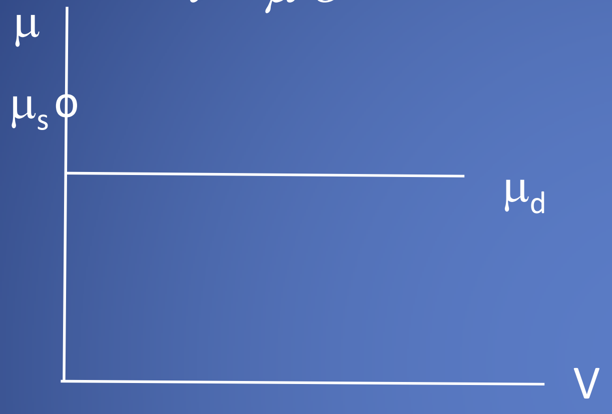


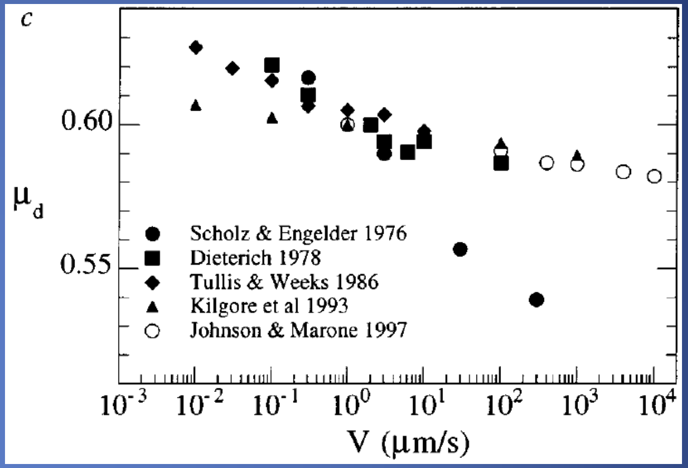
(Tsai & Kim, 1996)

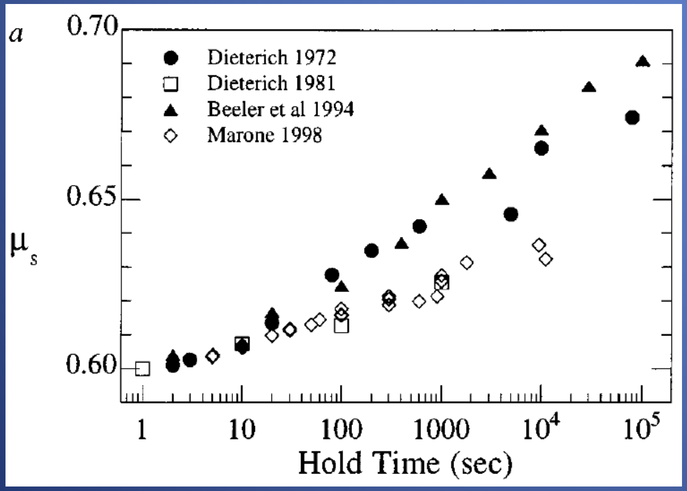
Effect of history and sliding speed on friction

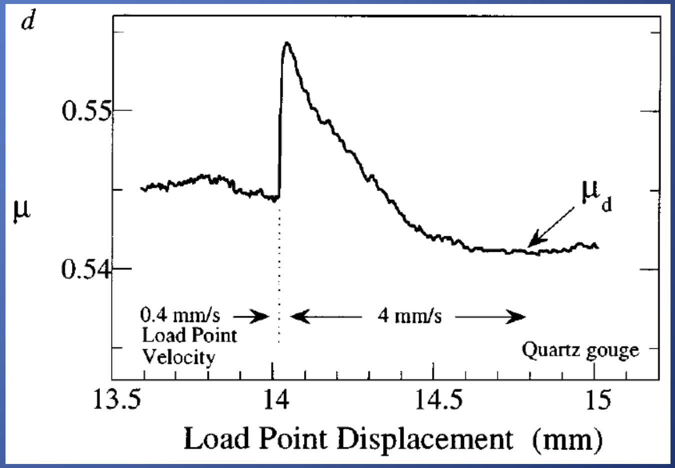
Amontons-Coulomb Law

$\tau = \mu\, \sigma$





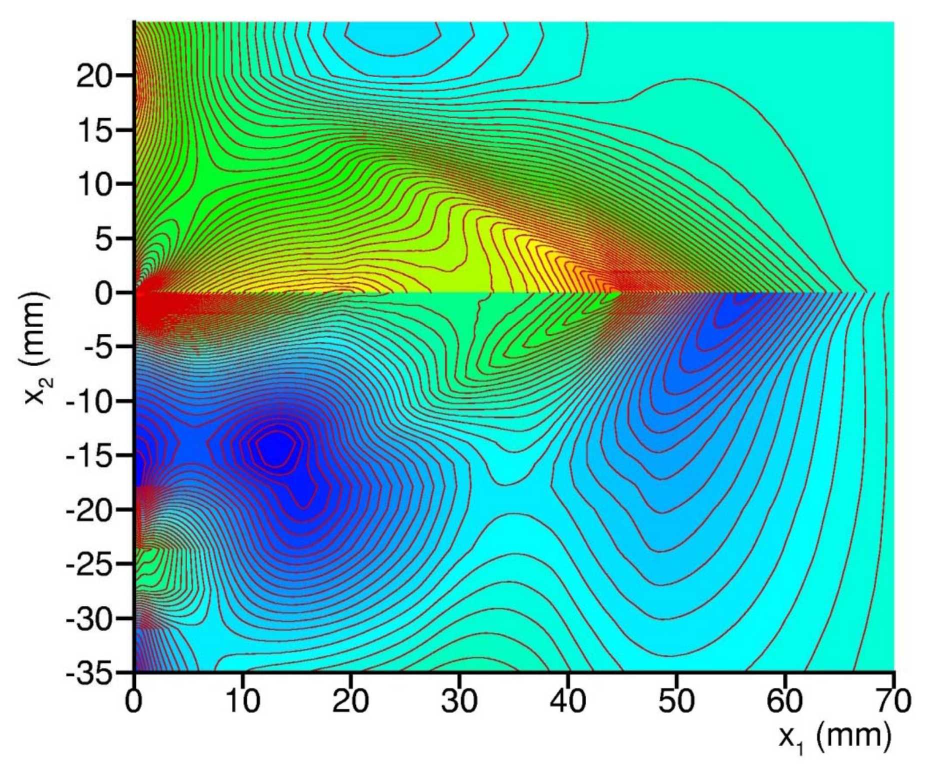


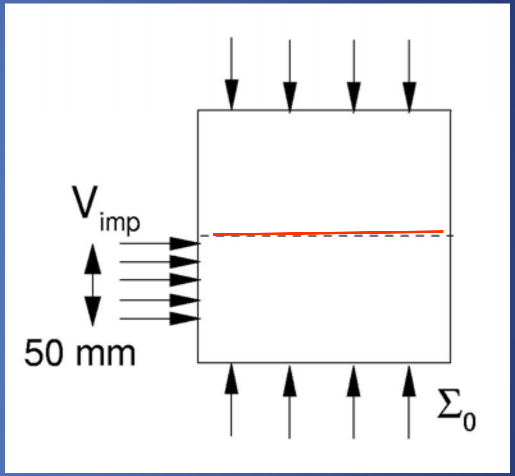


Modeling

- Continuum mechanics
- Elastic material properties
- Existence of an interface or weak plane
  - Mathematically straight interface
- Cohesive zone models used for the interface/weak plane
  - Cohesive law for fracture simulations
  - Rate- and state-dependent friction law for friction simulations
- No contact model is used

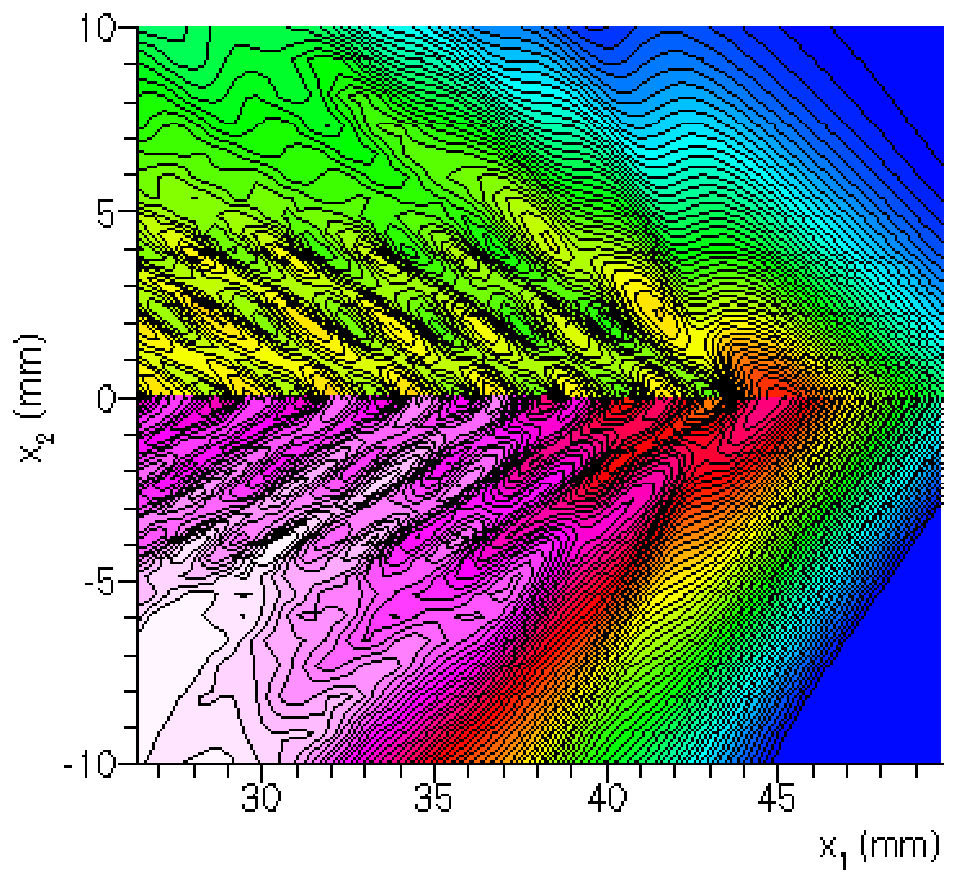
Isochromatic Fringe Patterns during Frictional Sliding showing shear Mach Waves

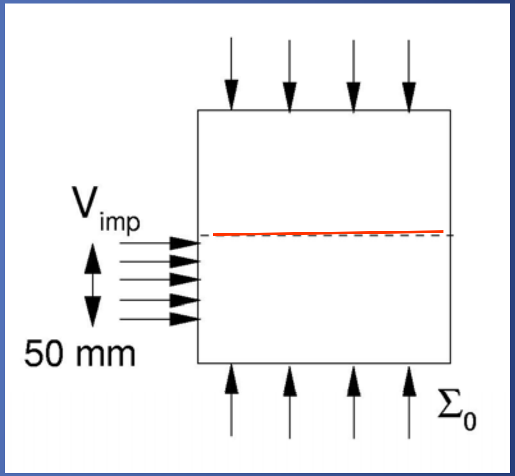




Σ_o =6 MPa, V_{imp}=2 m/s

Isochromatic Fringe Patterns during Frictional Sliding showing shear Mach Waves Periodic Slip Pulses

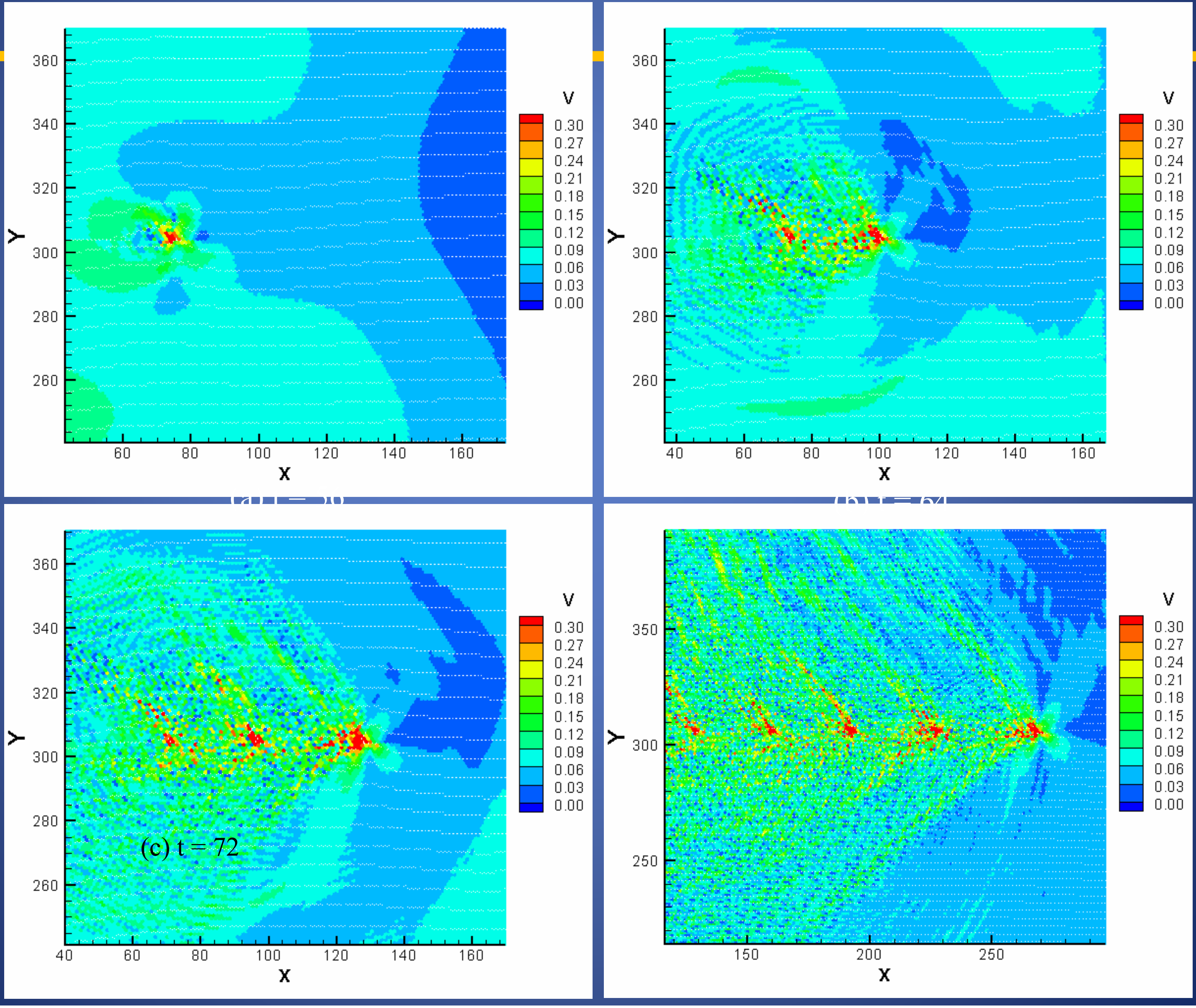




Σ_o =10 MPa, V_{imp}=20 m/s

Molecular Dynamic Simulations of Sliding

J. Ma, H. Lu, B. Wang, R. Hornung, A. Wissink, and R. Komanduri, 2006



Summary

- Sliding and Fracture of Interfaces show similar characteristics
  - Discontinuity tip travels at speeds faster than the shear wave speed
  - Shear Mach Waves are observed through optical techniques
- Frictional sliding in the form of multiple self-healing pulses traveling at intersonic speeds are observed
- These characteristics are observed at different length scales from the atomic to tectonic.