

Introduction to fracture mechanics (mostly LEFM)

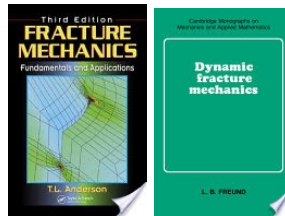
G. Anciaux

Civil Engineering, Materials Science, EPFL

EPFL

Outline

- Historical perspective
- Atomistic view of fracture and defects
- Griffith's theory
- Irwin, stress intensity factor
- Mode mixity
- Plastic-zone size estimates
- Cohesive zone model
- Dynamic fracture



T. Anderson. *Fracture Mechanics: Fundamentals and Applications, Fourth Edition.* (CRC Press, 2017).

L. Freund. *Dynamic Fracture Mechanics.* (Cambridge University Press, 1990).

F. Barras. *When Dynamic Cracks Meet Disorder: A Journey along the Fracture Process Zone.* EPFL (Lausanne), 2018.

Some rare structural failure events



Hawaii, April
24, 1988, plane loses 1/3 of its roof
due to stress fracture, at 6,000 meters
altitude...



Mineapolis,
August 1, 2007, collapse of I-35W
bridge

Accidents used to be not so rare...

Historical perspective

- Hammurabi code (1750 BC): Darwinian design
- May 1453, siege of Constantinople: huge cast iron cannon explodes after firing three shots, killing 40 people
- Industrial revolution, modern era: accident skyrocket due to poor design (no stress analysis) and lack of materials understanding
 - 1919, explosion of molasse tank in Boston (40 dead, <https://www.britannica.com/topic/Great-Molasses-Flood>)
 - 1920's: 200 dead/year in the US due to rupture of axis of wheels in trains
- Consequence: engineers sometimes use security coefficients of 10 in structures
- 1st significant progress: Griffith's theory 1920 (but still "academic" = intellectual curiosity)
- Founding element : liberty ships story (Fracture Mechanics born after World War II)
 - German submarines sink cargo ships at 3X construction rate
 - Need drastic new design; call Henri Kaiser (construction engineer, built Hoover dam); Kaiser invents revolutionnary procedure: «all-welded hull», i.e. no rivets; success!!
 - Until 1943: one vessel broke in 2 while sailing between Siberia and Alaska
 - 2700 boats built in WWII, of which 400 sustained fracture under «low stress»
 - **10 broke in 2**

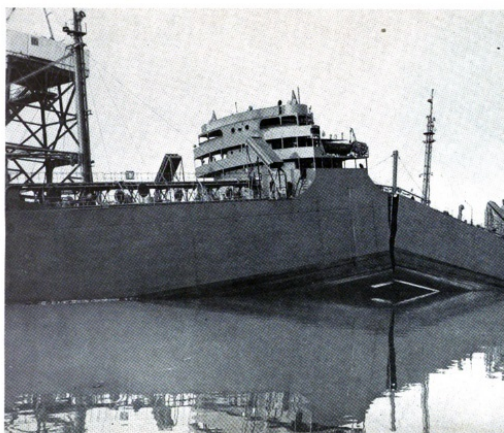
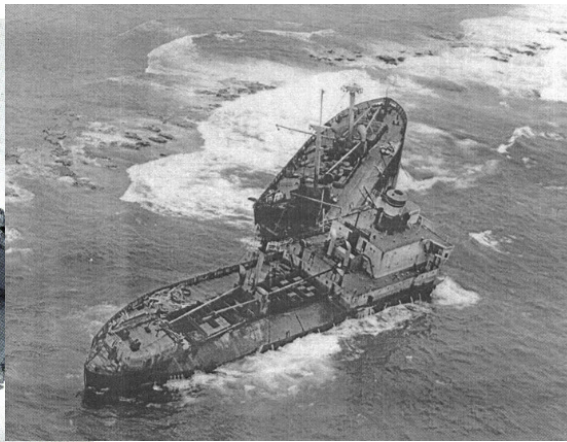


FIGURE 11.—View of S. S. Schenectady after splitting in two at her outfitting dock.



Reasons:

- Defects in weld (inexperienced welder)
- Fracture initiated at deck (where there is a stress concentration)
- Low toughness steel (especially at low temperature)
- And no rivets to block propagating crack

\$\Large \rightarrow\$ Irwin is called to start a lab at Naval Research Laboratory to study fracture mechanics

Birth of modern fracture mechanics:

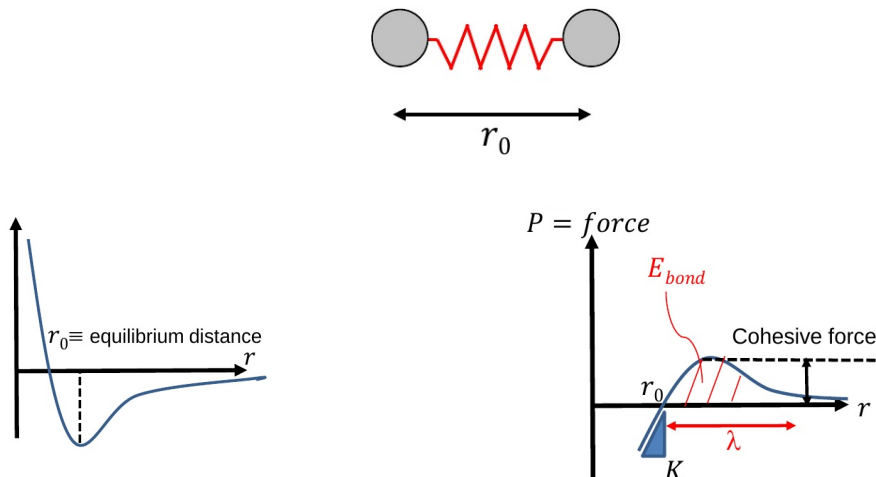
- Defects and cracks are present in each structure.
- Can be detected with *Non-destructive Examination* (NDE)
- Engineer balances cost of reparation with risk of failure
- Concept of damage tolerance and fracture mechanics analysis (today backed up with numerical modeling)

Historical references

S. Antolovich, A. Saxena, W. Gerberich. *Fracture Mechanics - An Interpretive Technical History*. Mechanics Research Communications. 91,46-86. (2018)

Atomic view of fracture

Fracture \equiv breaking of bonds

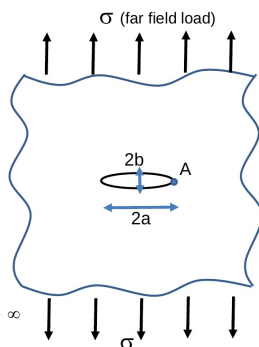


$$E_{\text{bond}} = \int_{r_0}^{\infty} P \, dr$$

- Approximation: $P(r) = P_c \sin\left(\frac{\pi r}{\lambda}\right)$
- Small displacements: $P(r) = P_c \frac{\pi r}{\lambda}$
- Bond rigidity: $K = P_c \cdot \left(\frac{\pi}{\lambda}\right)$
- $\sigma_c = P_c/A$ and $K = EA/\lambda$
- $\sigma_c = \frac{E}{\pi}$

$$\gamma_s = \frac{1}{2} \int_0^{\lambda} \sigma_c \sin\left(\frac{\pi r}{\lambda}\right) dr = \sigma_c \frac{\lambda}{\pi} \equiv \text{surface energy} \equiv [J \cdot m^{-2}]$$

Defects: create stress concentrations



Charles Inglis, 1913

Elliptical hole in plate: curvature
 $\rho = b^2/a$

$$\sigma_A = \sigma \left(1 + \frac{2a}{\rho}\right)$$

$$\lim_{\rho \rightarrow 0} \sigma_A = \sigma \left(1 + 2\sqrt{\frac{a}{\rho}}\right)$$

Limit $a \gg b$

$$\sigma_A = 2\sigma \sqrt{\frac{a}{\rho}}$$

Problem, when $\rho \rightarrow 0$, $\sigma_A \rightarrow \infty$

i.e. in thin crack limit, all materials would break (leads to Griffith's theory)

But cracks cannot be infinitely thin, they plastify;

Atomically sharp crack: $\rho = \lambda$

$$\sigma_A = 2\sigma \sqrt{\frac{a}{\lambda}}$$

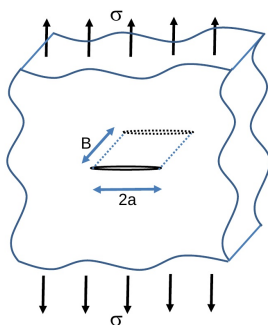
Fracture occurs if $\sigma_A = \sigma_c$

$$\sigma_{\text{failure}} = \sqrt{\frac{E \gamma_s}{4a}}$$

Rq: atomistically sharp crack cannot exist due to plasticity

Griffith's energy criteria (1920): Simple and powerful model

Plate under far field load:



Alan Arnold Griffith

Definitions

- $A = 2aB$: cracked surface
- dA : surface growth of crack
- dE_{pot} : potential energy variation (external and internal forces)
- dW_s : work necessary to create new surfaces

Critical point for propagation of a crack:

$\frac{dE}{dA} = \frac{dE_{\text{pot}}}{dA} + \frac{dW_s}{dA} \leq 0$ it $\text{Released potential energy must be greater than energy necessary to create cracks}$

At critical point:

$$-\frac{dE_{\text{pot}}}{dA} = \frac{dW_s}{dA}$$

It can be shown (Ingles) that

$$E_{\text{pot}} = E_{\text{pot}}^0 - \pi$$

$$\frac{\sigma^2 a^2 B}{E} = E_{\text{pot}}^0 - \frac{\pi \sigma^2 A^2}{4EB}$$

so that:

$$-\frac{dE_{\text{pot}}}{dA} = \frac{2\pi}{\sigma^2 A^2}$$

Surface energy proportional to A

$$W_s = 2A \gamma_s$$

so that:

$$\frac{dW_s}{dA} = 2\gamma_s$$

\rightarrow Critical stress based on energetic criterion:

$$\sigma_f = \sqrt{\frac{2E\gamma_s}{\pi a}}$$

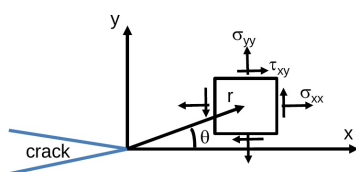
- Very close to Inglis ($\sqrt{\frac{E\gamma_s}{4a}}$)
- Works ok for brittle materials (not good for ductile materials)
- Does not require defining curvature ρ , unlike Inglis
- Profound model:

Small cracks heal, large cracks grow

$$\text{Griffith's length: } a_c = \frac{2E\gamma_s}{\pi\sigma^2}$$

From global to local analysis: stresses at crack tip

Rupture modes



\exists analytical solutions:

Westgaard 1939, Irwin 1957, Sneddon 1946, Williams 1957

H. Westergaard. *Bearing Pressures and Cracks: Bearing Pressures Through a Slightly Waved Surface or Through a Nearly Flat Part of a Cylinder, and Related Problems of Cracks.* Journal of Applied Mechanics. **6**,A49-A53. (1939)

I. Sneddon, N. Mott. *The Distribution of Stress in the Neighbourhood of a Crack in an Elastic Solid.* Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences. **187**(1009),229-260. (1946)

G. Irwin. *Analysis of Stresses and Strains Near the End of a Crack Traversing a Plate.* Journal of Applied Mechanics. **24**(3),361-364. (1957)

$$\sigma_{ij} = \left(\frac{K}{\sqrt{2\pi r}} \right) f_{ij}(\theta) + \sum_{m=0}^{\infty} A_m r^{\frac{m}{2}} g_{ij}^{(m)}(\theta)$$

Limit $r \rightarrow 0$, leading term is in $\frac{1}{\sqrt{r}}$

Stress singularity at crack tip !

- K : Stress intensity factor

M. Williams. *On the Stress Distribution at the Base of a Stationary Crack.* Journal of Applied Mechanics. **24**(1),109-114. (1956)

3 rupture modes

Mode I (opening)

Mode II (in-plane shear)

Mode III (out-of-plane shear)

$f_{ij}^I(\theta)$, $f_{ij}^{II}(\theta)$ and $f_{ij}^{III}(\theta)$ are known adimensional functions of θ , and are independent of the geometry

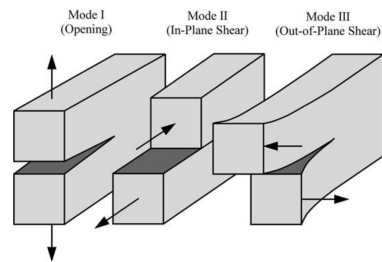
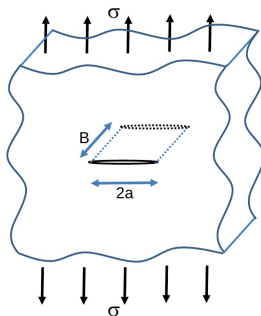


image from Anderson

Derivation of K : for through crack in an infinite plate under mode I opening



K depends on geometry and loading

- Known analytical derivation for through crack:

$$K_I = \sigma \sqrt{\pi a}$$

Other example, edge crack:

$$K_I = 1.12 \sigma \sqrt{\pi a}$$

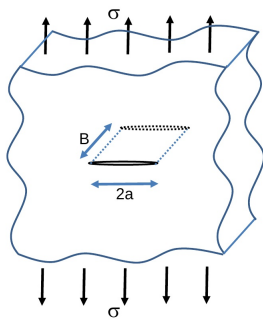
Analytical derivation difficult

- Alternative: numerical evaluation

More analytical cases found in:

T. Anderson. *Fracture Mechanics: Fundamentals and Applications, Fourth Edition.* (CRC Press, 2017).

Equivalence between G and K : through crack example



Energy release rate:

$$G = - \frac{dE_{\text{pot}}}{dA} = \frac{\pi \sigma^2 a}{E}$$

Stress intensity factor:

$$K_I = \sigma \sqrt{\pi a}$$

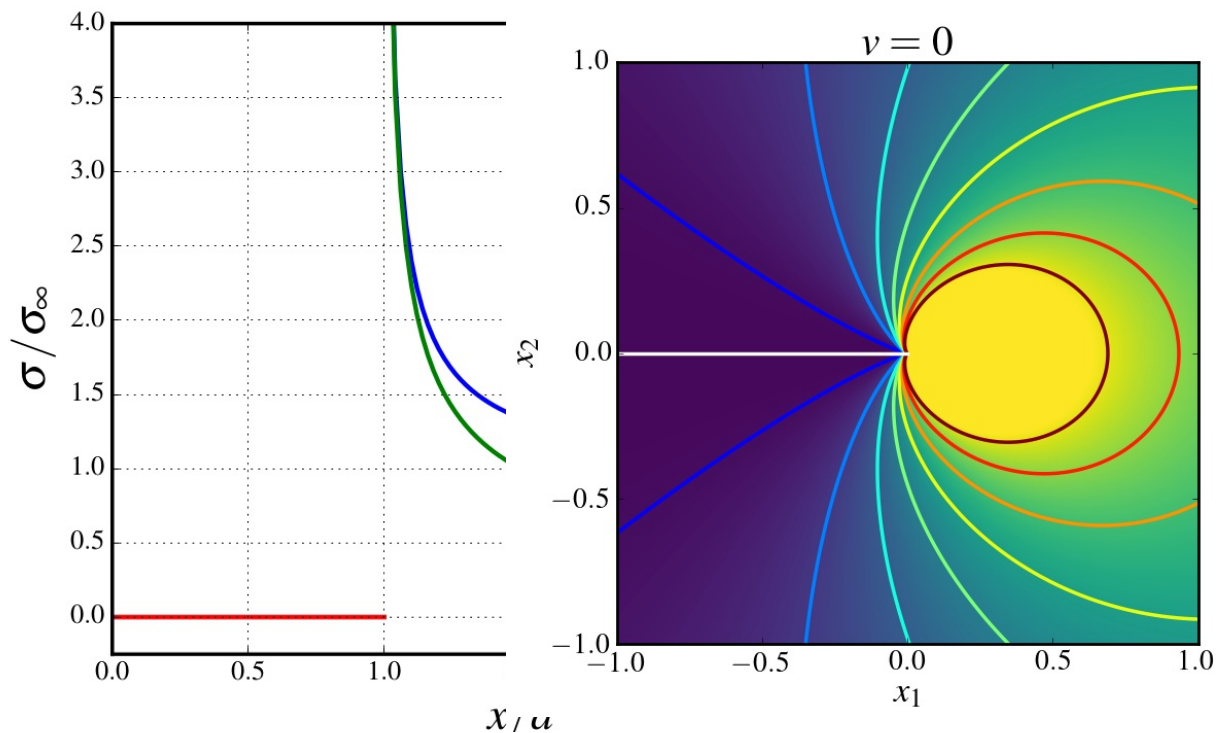
Gives:

$$G = \frac{K_I^2}{E}$$

Mixed-mode (with Poisson effects):

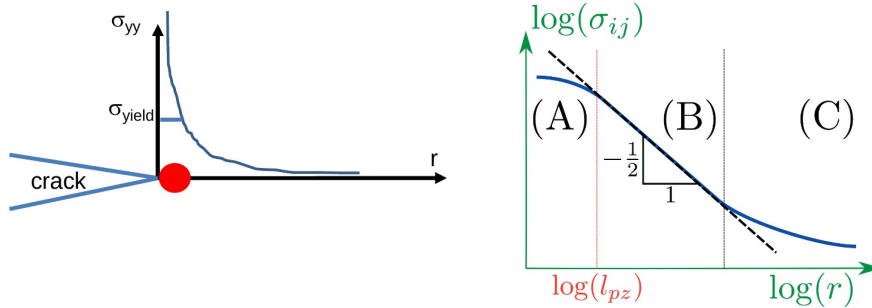
$$G = \frac{K_I^2}{E(1-\nu^2)} + \frac{K_{II}^2}{E(1-\nu^2)} + \frac{K_{III}^2}{2\mu}$$

Key points of LEFM: Griffith 1921, Westergaard 1939, Irwin 1957



- Stress intensity factor: $\sigma(r, \theta) \propto \frac{K}{\sqrt{2\pi r}} f(\theta)$
- Predict energy release by crack advance: $G = \frac{1-\nu^2}{E} (K_I^2 + K_{II}^2) + \frac{K_{III}^2}{2\mu}$
- Analyze the stability of crack in materials $G < G_c$

Crack tip plasticity: K dominated rupture



Stress singularity at crack tip, **but stresses cannot be infinite**

\Rightarrow A plastic zone must exist

Plastic/Process zone size can be estimated

- with the **Yield stress** σ_Y

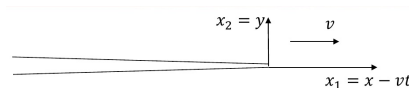
$$r = \frac{1}{\pi} \left(\frac{K}{\sigma_Y} \right)^2$$

Numerically:

- we will add a non-linear zone at crack tip to remove singularity
- cohesive zone model

Dynamic Fracture Mechanics: Freund 1990, Kostrov and Das 1988

Moving crack (mode-III) in the x direction at velocity v



Elastodynamic wave equation (mode-III)

$$u_{z,xx} + u_{z,yy} = \frac{1}{c_s^2} u_{z,tt}$$

Apply the Lorentz transform: System of coordinates at tip

$$x_1 = \frac{x - vt}{\sqrt{1 - v^2/c_s^2}}, \quad x_2 = y, \quad x_3 = z, \quad t' = \frac{1 - vx/c_s^2}{\sqrt{1 - v^2/c_s^2}}$$

For a semi-infinite crack (elliptic PDE if $v \ll c_s$, no shocks), equation shape is preserved

$$\left(1 - \frac{v^2}{c_s^2} \right) u_{3,11} + u_{3,22} = \frac{1}{c_s^2} u_{3,t't'}$$

For a steady state propagating crack $\partial/\partial t' = 0$

$$\left(1 - \frac{v^2}{c_s^2} \right) u_{3,11} + u_{3,22} = 0$$

Dynamic Stress Intensity Factor:

$$\sigma_{yy} \simeq \frac{K^d_I}{\sqrt{2\pi r}} \Sigma(v, \theta) = \frac{1}{\left(1 - v^2/c_s^2 \right)^{3/4}} \frac{K^s_I}{\sqrt{2\pi r}} \Sigma(v, \theta)$$

K^s : static stress intensity factor

K^d : dynamic stress intensity factor

Contraction of space when approaching wave speed (larger stresses)

L. Freund. *Dynamic Fracture Mechanics.* (Cambridge University Press, 1990).

F. Barras. *When Dynamic Cracks Meet Disorder: A Journey along the Fracture Process Zone.* EPFL (Lausanne), 2018.

Asymptotic fields for dynamics crack: Mode I, Freund 1990

$$\sigma_{ij} = \frac{K_I(t)}{\sqrt{2\pi r}} \Sigma_{ij}^I(\theta, v) + o_{ij}^{(1)} + o(1) \quad \text{as } r \rightarrow 0. \quad (4.3.10)$$

The functions $\Sigma_{ij}^I(\theta, v)$ that represent the angular variation of stress components for any value of instantaneous crack tip speed v are

$$\begin{aligned} \Sigma_{11}^I &= \frac{1}{D} \left\{ (1 + \alpha_s^2)(1 + 2\alpha_d^2 - \alpha_s^2) \frac{\cos \frac{1}{2}\theta_d}{\sqrt{\gamma_d}} - 4\alpha_s\alpha_d \frac{\cos \frac{1}{2}\theta_s}{\sqrt{\gamma_s}} \right\}, \\ \Sigma_{12}^I &= \frac{2\alpha_d(1 + \alpha_s^2)}{D} \left\{ \frac{\sin \frac{1}{2}\theta_d}{\sqrt{\gamma_d}} - \frac{\sin \frac{1}{2}\theta_s}{\sqrt{\gamma_s}} \right\}, \\ \Sigma_{22}^I &= -\frac{1}{D} \left\{ (1 + \alpha_s^2)^2 \frac{\cos \frac{1}{2}\theta_d}{\sqrt{\gamma_d}} - 4\alpha_d\alpha_s \frac{\cos \frac{1}{2}\theta_s}{\sqrt{\gamma_s}} \right\}, \end{aligned} \quad (4.3.11)$$

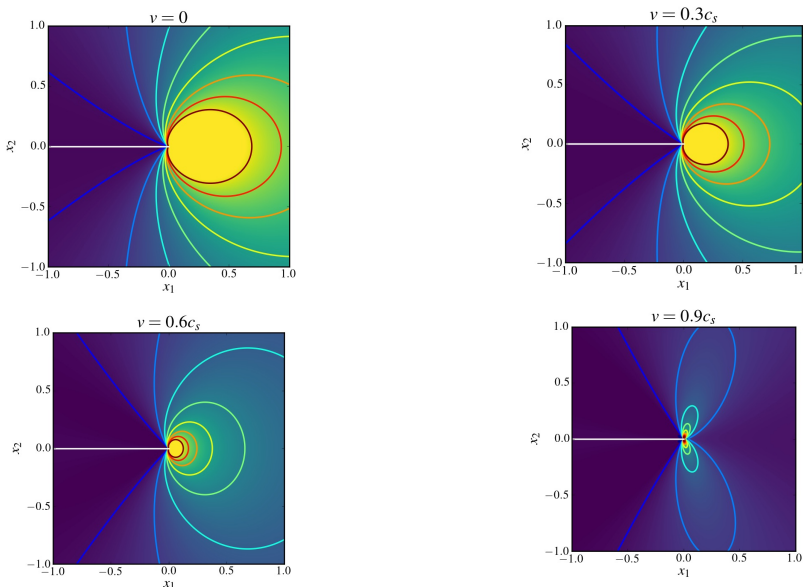
where

$$\begin{aligned} \gamma_d &= \sqrt{1 - (v \sin \theta / c_d)^2}, \quad \tan \theta_d = \alpha_d \tan \theta, \\ \gamma_s &= \sqrt{1 - (v \sin \theta / c_s)^2}, \quad \tan \theta_s = \alpha_s \tan \theta. \end{aligned} \quad (4.3.12)$$

L. Freund. *Dynamic Fracture Mechanics.* (Cambridge University Press, 1990).

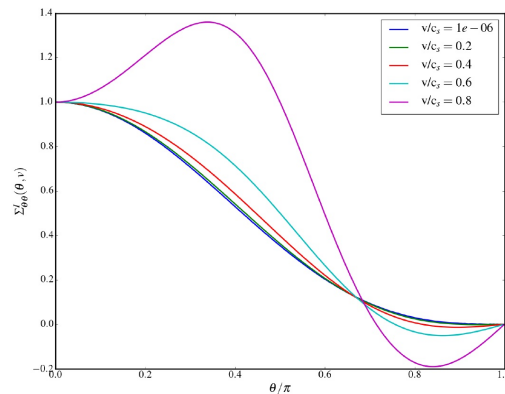
Asymptotic fields for dynamic crack: Mode I, Freund 1990, Kostrov and Das 1988

Hoop stress



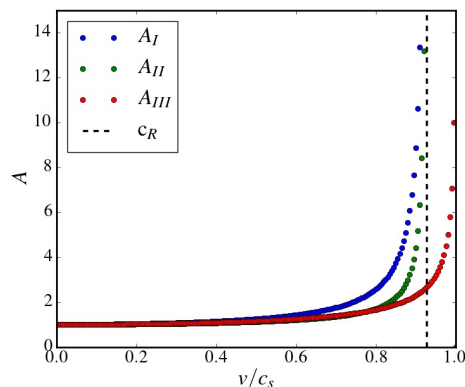
F. Barras. *When Dynamic Cracks Meet Disorder: A Journey along the Fracture Process Zone.* EPFL (Lausanne), 2018.

Asymptotic fields for dynamic crack: Maximum hoop stress



Dynamic energy release rate: Freund 1990, Kostrov and Das 1988

$$G(a, v) = \frac{1-\nu^2}{E} \left[A_I(v) K_I^2 + A_{II}(v) K_{II}^2 \right] + \frac{1}{2\mu} A_{III}(v) K_{III}^2$$



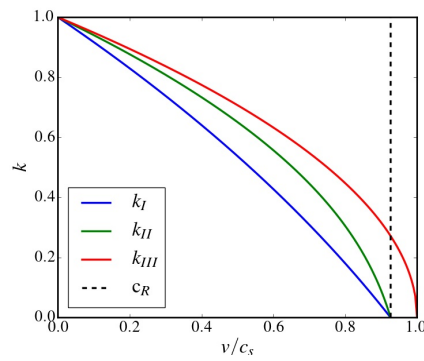
L. Freund. *Dynamic Fracture Mechanics*. (Cambridge University Press, 1990).

B. Kostrov, S. Das. *Principles of Earthquake Source Mechanics*. (Cambridge University Press, 1989).

K dependance on crack speed: Freund, 1990

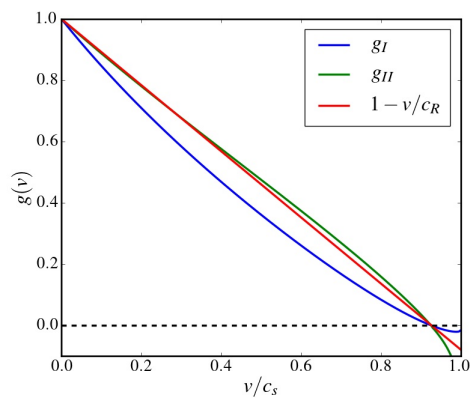
Freund's assumption: $\lim_{v \rightarrow c_R} K(a, v) = k(v) K(a, v = 0)$

$$\begin{aligned} k_I(v) &\simeq \frac{1-\nu/c_R}{\sqrt{1-v/c_s}} \\ k_{II}(v) &\simeq \frac{1-\nu/c_R}{\sqrt{1-v/c_s}} \\ k_{III}(v) &\simeq \sqrt{1-v/c_s} \end{aligned}$$



Dynamic energy release rate: Freund, 1990

$$G(a, v) = \frac{1-\nu^2}{E} A(v) k(v)^2 K_{II}^2(a, v=0) = G(a, v=0) g(v)$$



Crack tip equation of motion: Freund, 1999

- Infinite homogeneous plate
- Uniform crack speed
- $G_{I, II} > 0$ when $v < c_R$
 \rightarrow Admissible crack speed

$$G \simeq G^{\text{static}} \left(1 - \frac{v}{c_R}\right) \quad \text{for } v \leq c_R$$

$$G < 0, \quad c_R < v < c_S$$

$$G \leq 0, \quad v > c_S$$

$$G > 0, \quad v = \sqrt{2} c_S \text{ (mode II)}$$

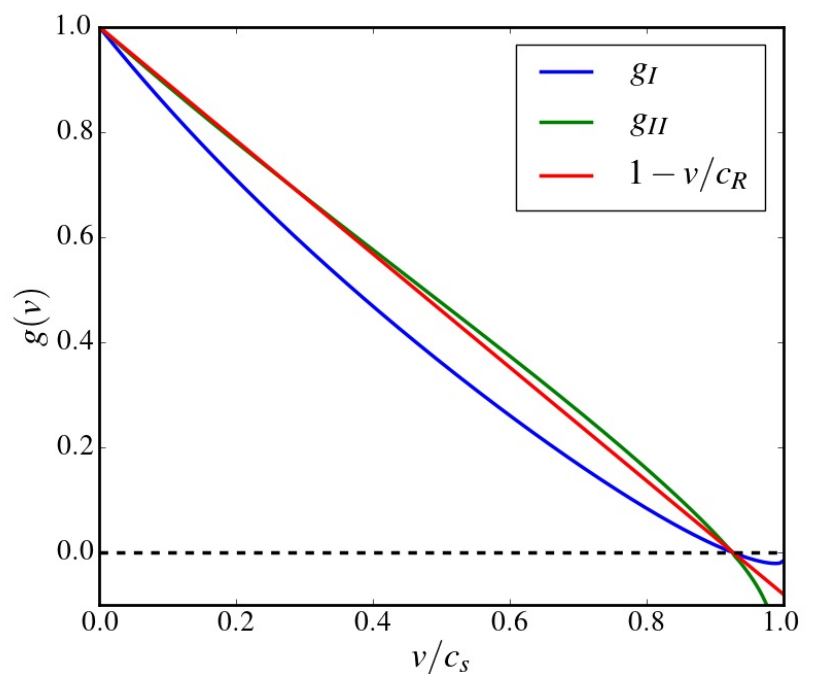


Table 2.1 – Summary of the admissible crack speeds predicted by LEFM.

	$0 < v_c < c_R$	$c_R \leq v_c < c_s$	$c_s < v_c < c_d$
Mode I	✓	✗	✗
Mode II	✓	✗	✓
Mode III	✓	✓	✗

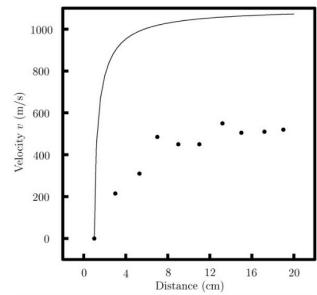
L. Freund. *Dynamic Fracture Mechanics*. (Cambridge University Press, 1990).

F. Barras. *When Dynamic Cracks Meet Disorder: A Journey along the Fracture Process Zone*. EPFL (Lausanne), 2018.

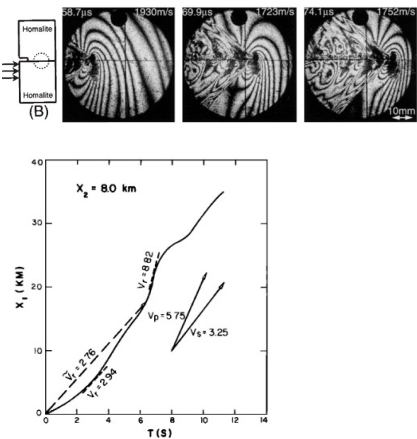
And is it working ?

Kobayashi et al, 1974

Mode-I: no!



Mode-II: no!



A. Kobayashi, B. Wade, W. Bradley, S. Chiu. *Crack Branching in Homalite-100 Sheets*. Engineering Fracture Mechanics. **6**(1),81-92. (1974)

R. Archuleta. *A Faulting Model for the 1979 Imperial Valley Earthquake*. Journal of Geophysical Research: Solid Earth. **89**(B6),4559-4585. (1984)

A. Rosakis, O. Samudrala, D. Coker. *Cracks Faster than the Shear Wave Speed*. Science. **284**(5418),1337-1340. (1999)

A. Rosakis. *Intersonic Shear Cracks and Fault Ruptures*. Advances in Physics. **51**(4),1189-1257. (2002)

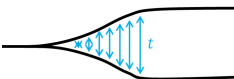
... but why ?

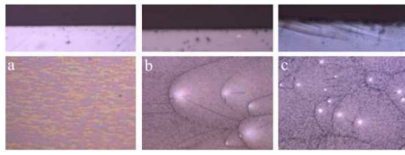
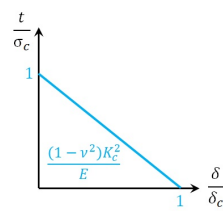
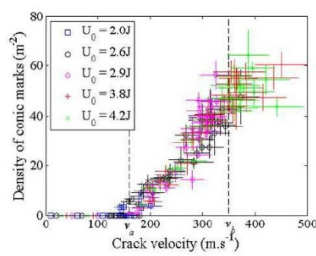
Scheibert et al. 2010

Mode-I: Interplay between crack and microstructure

Burridge 1973, Andrews 1976

Mode-II: non-singular fracture theory





R. Burridge. *Admissible Speeds for Plane-Strain Self-Similar Shear Cracks with Friction but Lacking Cohesion.* Geophysical Journal International. **35**(4),439-455. (1973)

D. Andrews. *Rupture Velocity of Plane Strain Shear Cracks.* Journal of Geophysical Research (1896-1977). **81**(32),5679-5687. (1976)

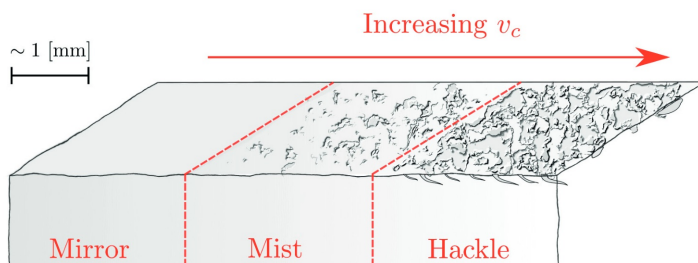
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Mitigated results

- slow crack propagation speeds: ok
- $v > c$ a few tenths of c : not ok
- underestimates the dissipated energy
- overestimates the crack propagation speed (already for $v > 0.65c$)

Three dynamic phases



Postmortem appearance of the fracture surfaces

- Mirror: smooth surfaces.
- Mist: surface roughen (interplay between a crack front and microstructure)
- Hackle: microbranching instability

Relativistic contraction brings microstructure heterogeneity at play !!

Large \rightarrow Rupture front distorsion

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- G. Irwin.** *Analysis of Stresses and Strains Near the End of a Crack Traversing a Plate.* Journal of Applied Mechanics. **24**(3),361-364. (1957) [10.1115/1.4011547](https://doi.org/10.1115/1.4011547)
- R. Burridge.** *Admissible Speeds for Plane-Strain Self-Similar Shear Cracks with Friction but Lacking Cohesion.* Geophysical Journal International. **35**(4),439-455. (1973) [10.1111/j.1365-246X.1973.tb00608.x](https://doi.org/10.1111/j.1365-246X.1973.tb00608.x)
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- D. Andrews.** *Rupture Velocity of Plane Strain Shear Cracks.* Journal of Geophysical Research (1896-1977). **81**(32),5679-5687. (1976) [10.1029/JB081i032p05679](https://doi.org/10.1029/JB081i032p05679)
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- B. Kostrov, S. Das.** *Principles of Earthquake Source Mechanics.* (Cambridge University Press, 1989).
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