Brittle fracture under mode I+III loading

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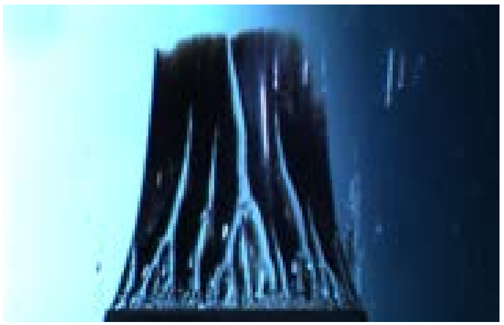
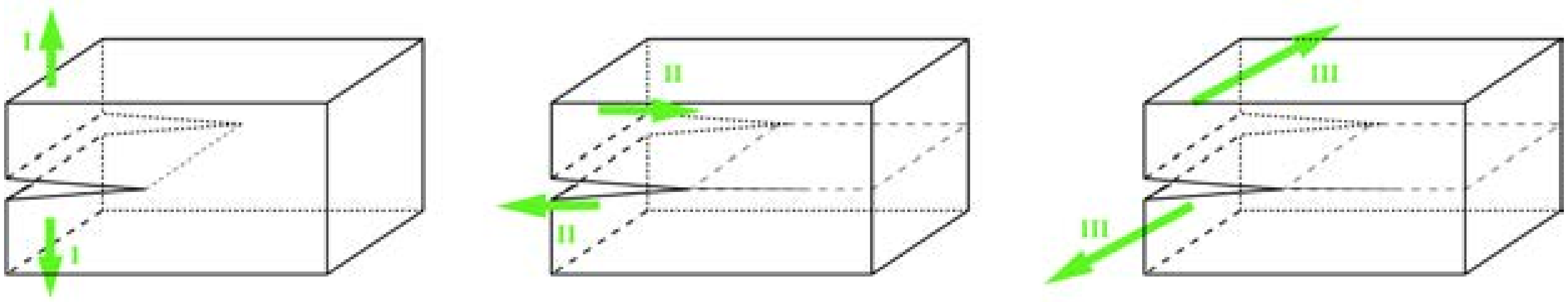
   

Lazarus, Buchholz, Fulland, Wiebesiek, IJF 2008

A glimpse on the complexity
of the propagation in presence of mode III...

Modes



- Mode I: opening
- Mode II: shearing
- **Mode III: tearing**

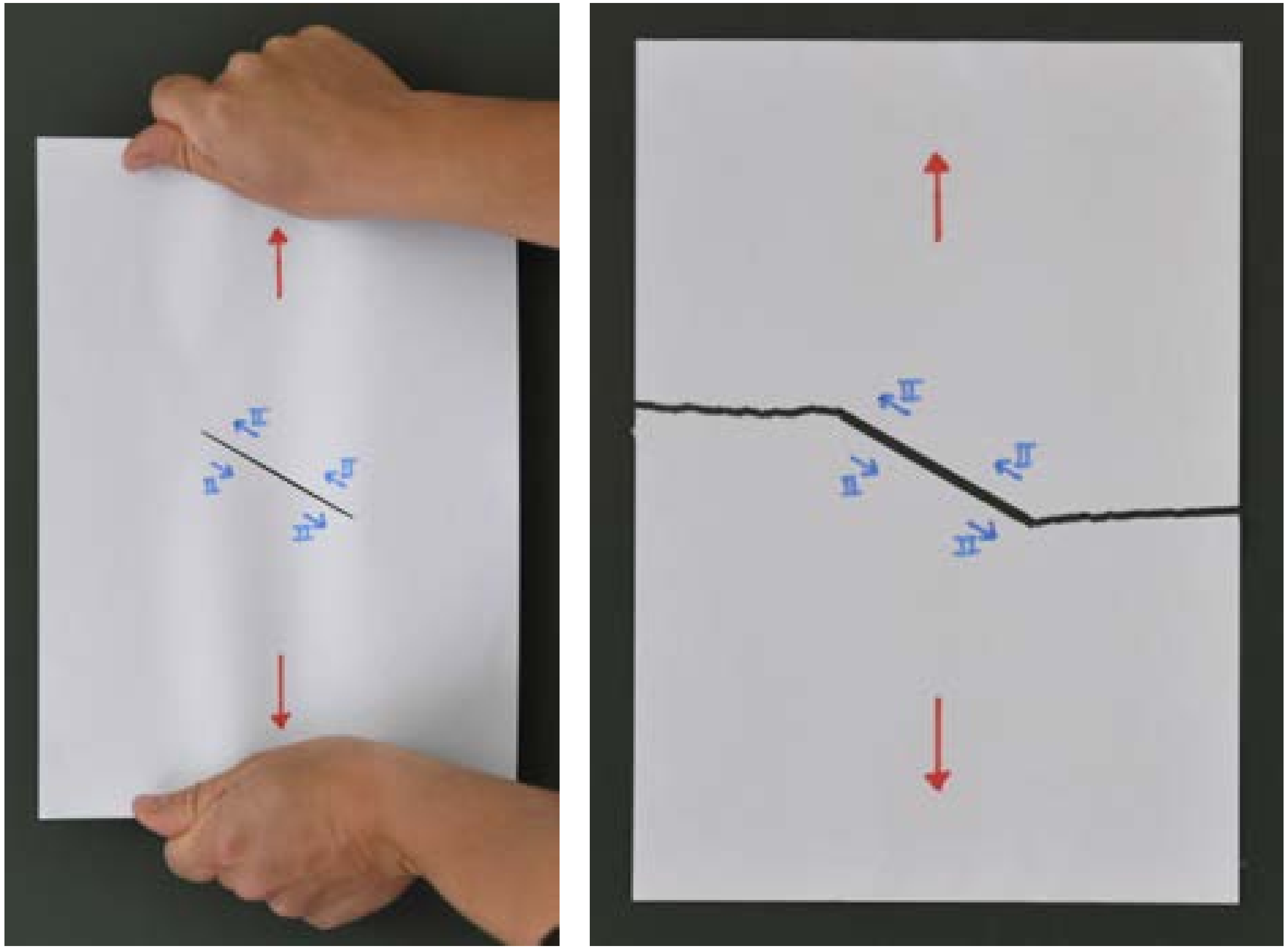
Outline

Experimental observations
- Mode I+II
- Mode I+III

Linear Elastic Fracture Mechanics (LEFM)

Is LEFM able to predict the experimental observations?
- Mode I+II
- Mode I+III

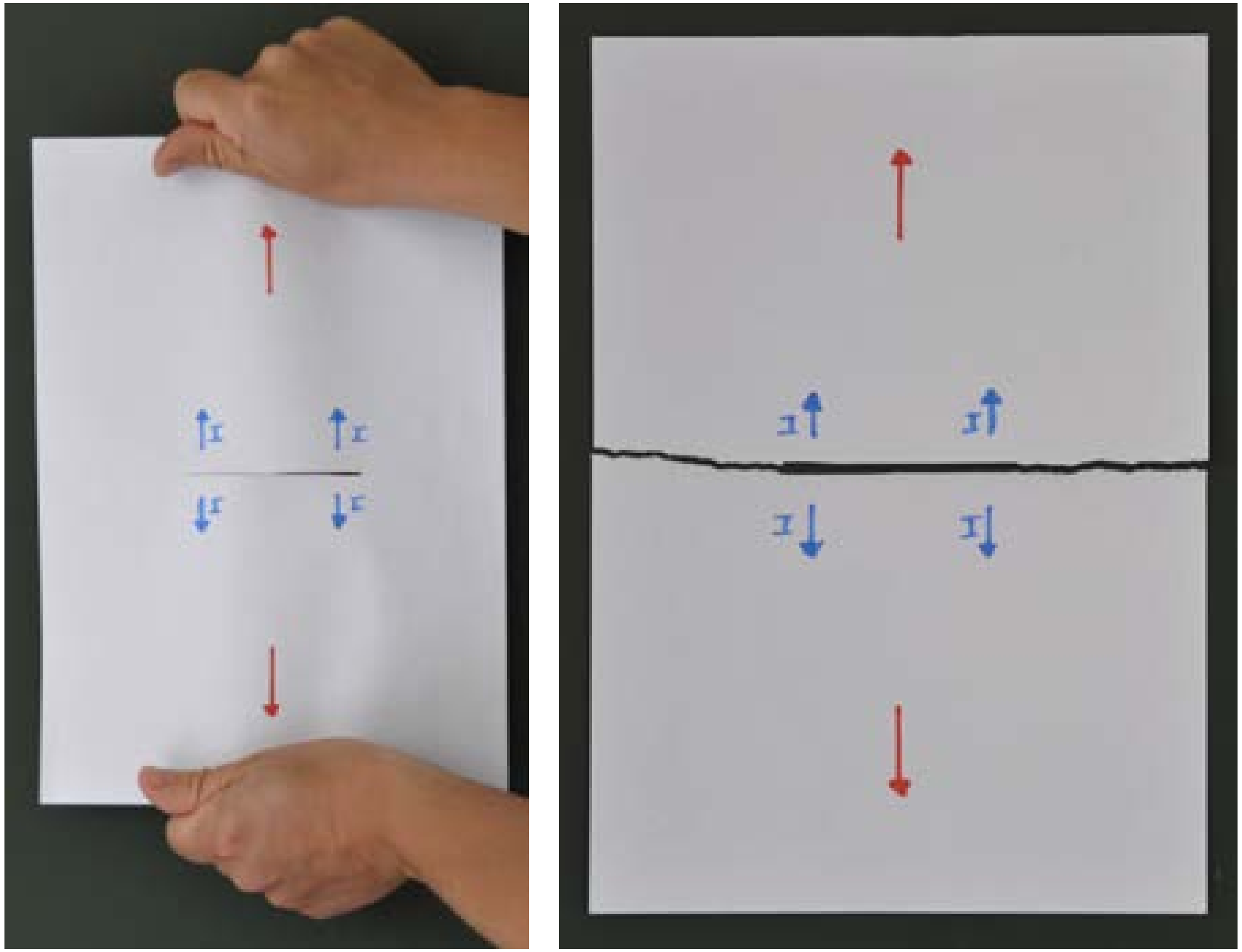
Mode I+II



The crack doesn't extend in its plane,

but kinks to reach a mode I orientation.

Mode I



Chap. 'Endommagement, rupture', Lazarus (La matière en désordre, EDP, 2014

The path is nearly straight.

Mode I: From straight to more complex paths

Yuse et Sano, 1993, 1997; Ronsin et al., 1995; Yang and Ravi-Chandar, 2001

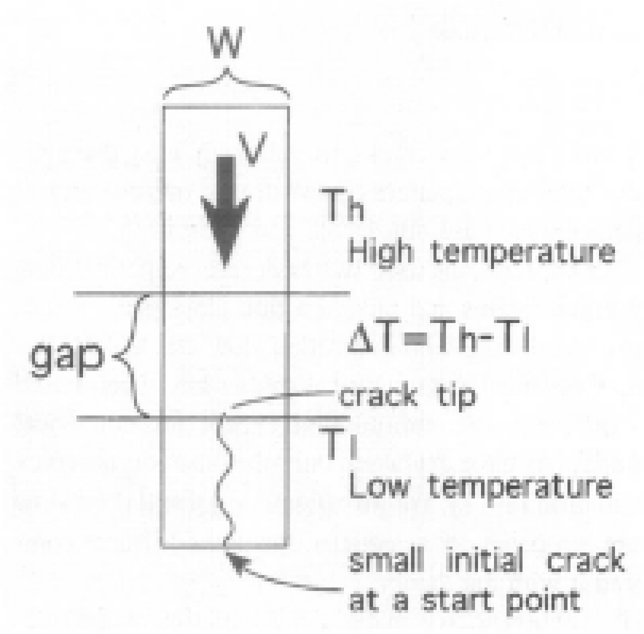
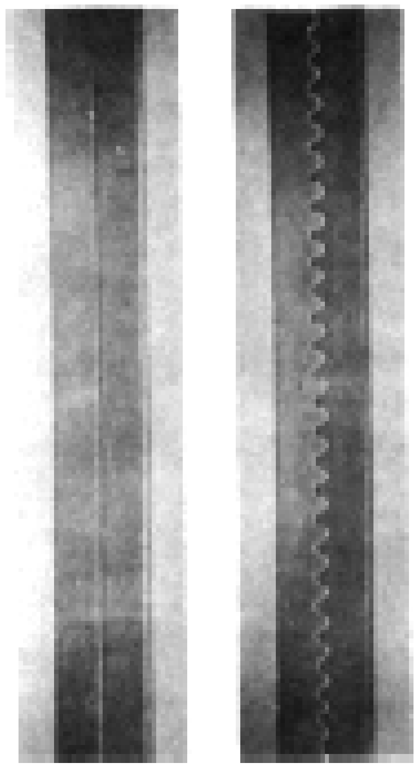
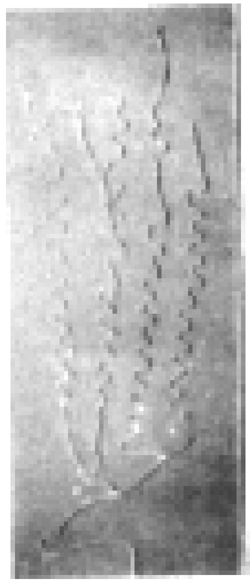


Fig. 1. Temperature configuration of the experiment. A thin sample plate moves slowly across the temperature gradient gap in the direction of the arrow with velocity V.



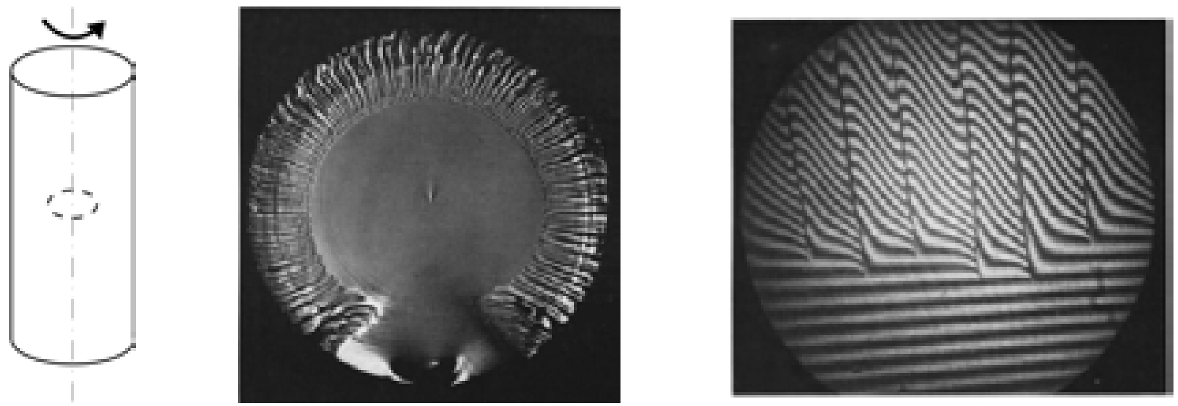


From Yuse et Sano, 1993, 1997

Though the crack is initially loaded in mode I, out of plane propagation may occur.

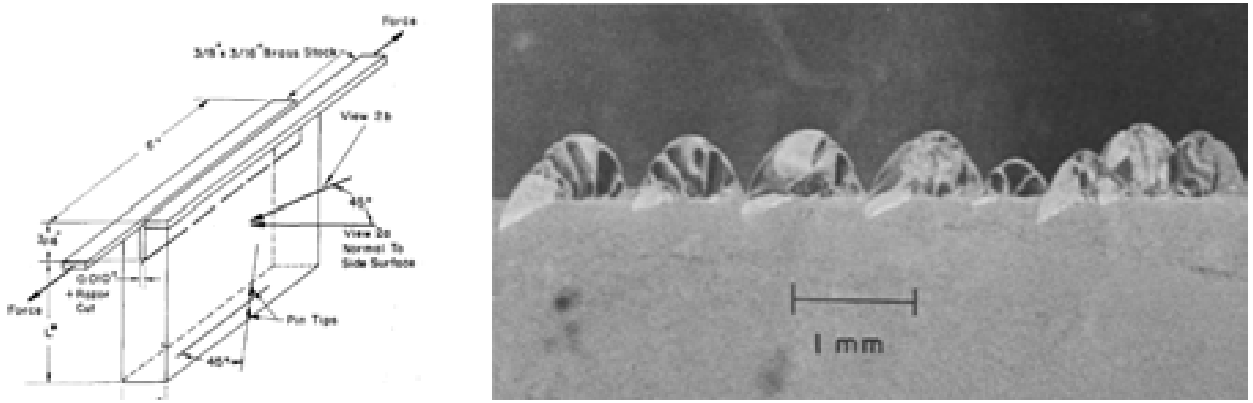
Mode I+III . Pioneer experiments.

- Segmentation and *progressive* rotation of the facets



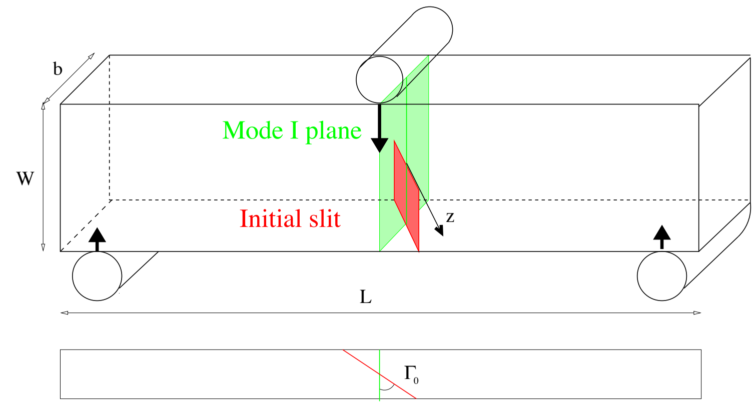
Sommer (1969)

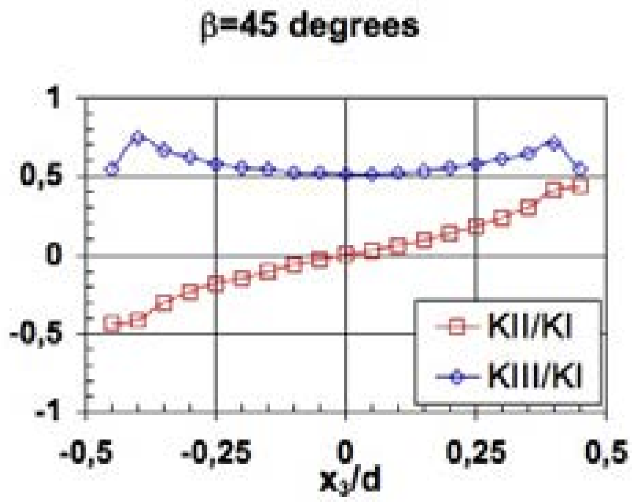
- Nucleation of *abrupt* rotated facets

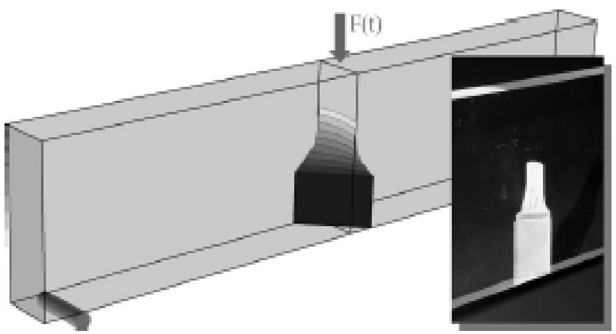


Knauss (1970)

Mode I+III. 3 point bending experiments (Macroscale)



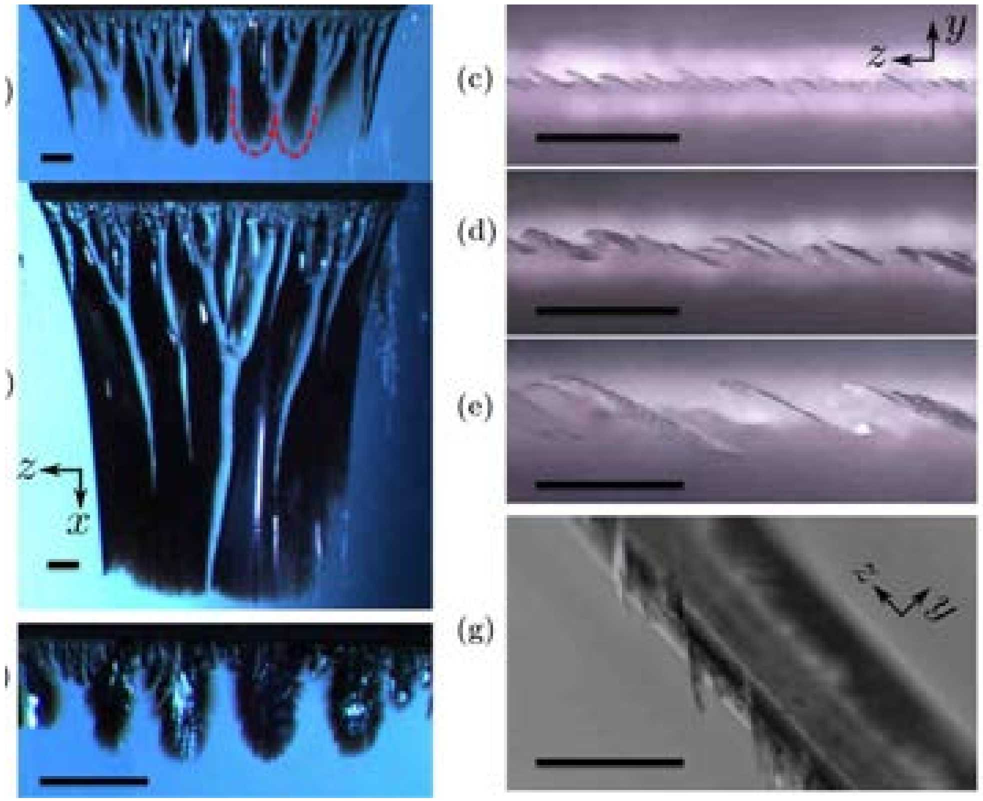




Buchholz et al. (2004); Lazarus et al. (2008)

At the macroscale, the front twists due to the presence of mode II...

Mode I+III. 3 point bending experiments (Microscale)

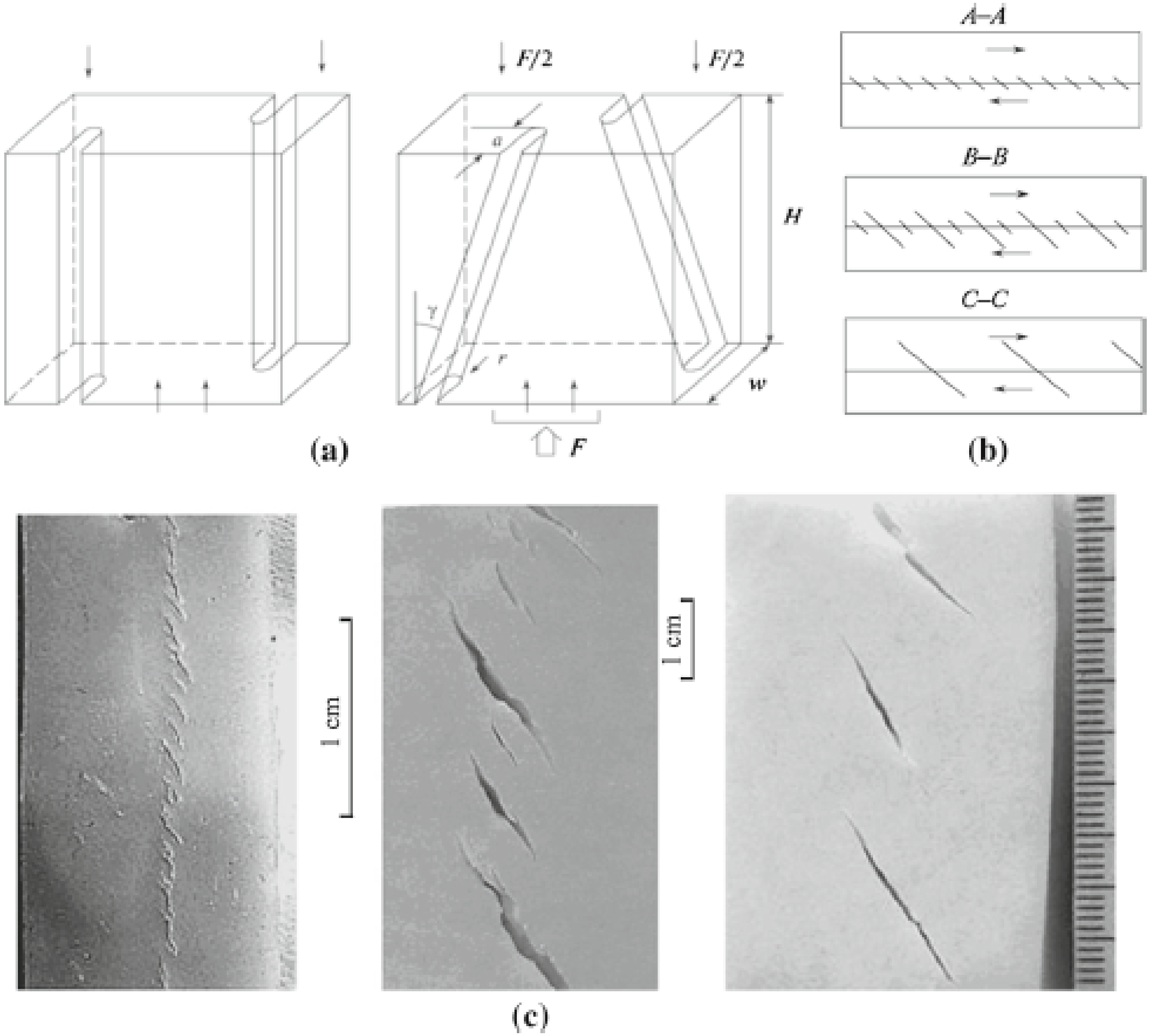


Chen et al. (2015)

1. Apparition of small tilted finger shaped facets
2. Progressive coalescence
3. Facets are rotated toward the shear-free direction

Similar observations in other materials, e.g. Lin et al. (2010), and setups...

Mode I+III. An experiment on cheese



Goldstein and Osipenko (2012)

Mode I+III. Transition smooth/facets

- Ronsin et al. (2014)

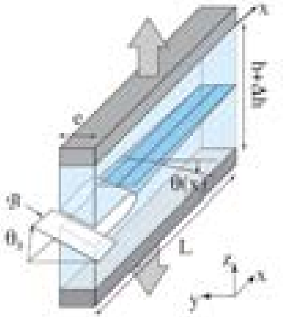
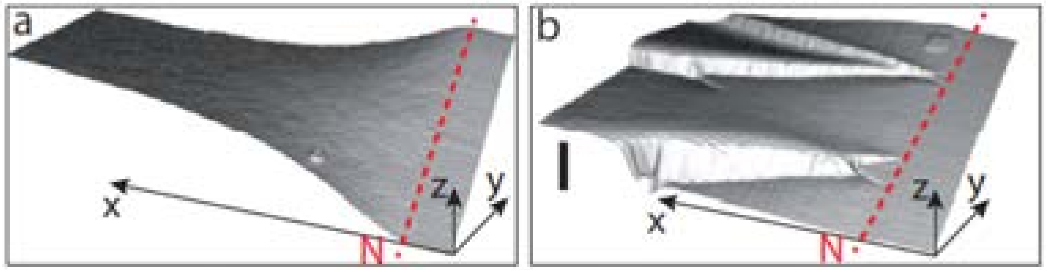
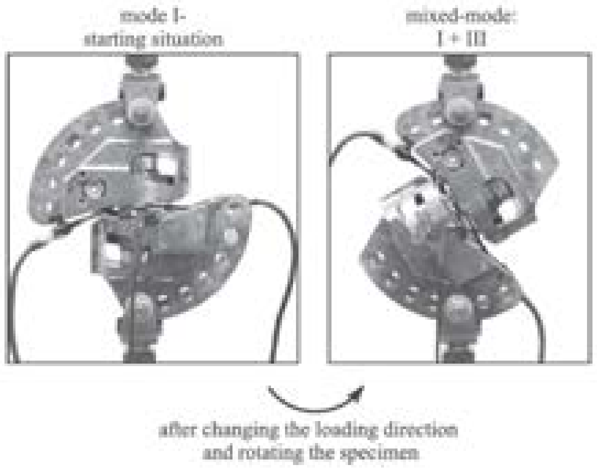


Fig. 1: (Colour on-line) Sketch of the experimental setup: the gel slab (unstrained dimensions $L \times h \times e$), once stretched by Δh, is notched at angle θ_0 by the blade B.



$\theta_0 < \theta_0^c$ and $\theta_0 > \theta_0^c$

- Eberlein et al. (2017)



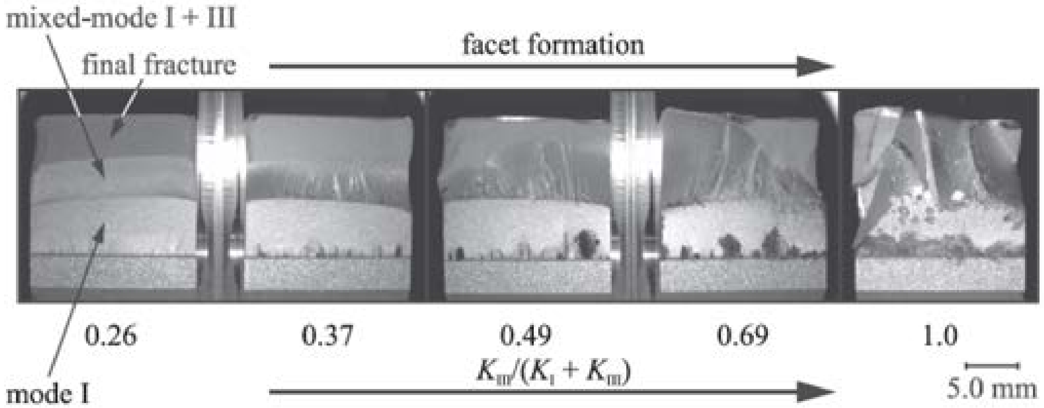
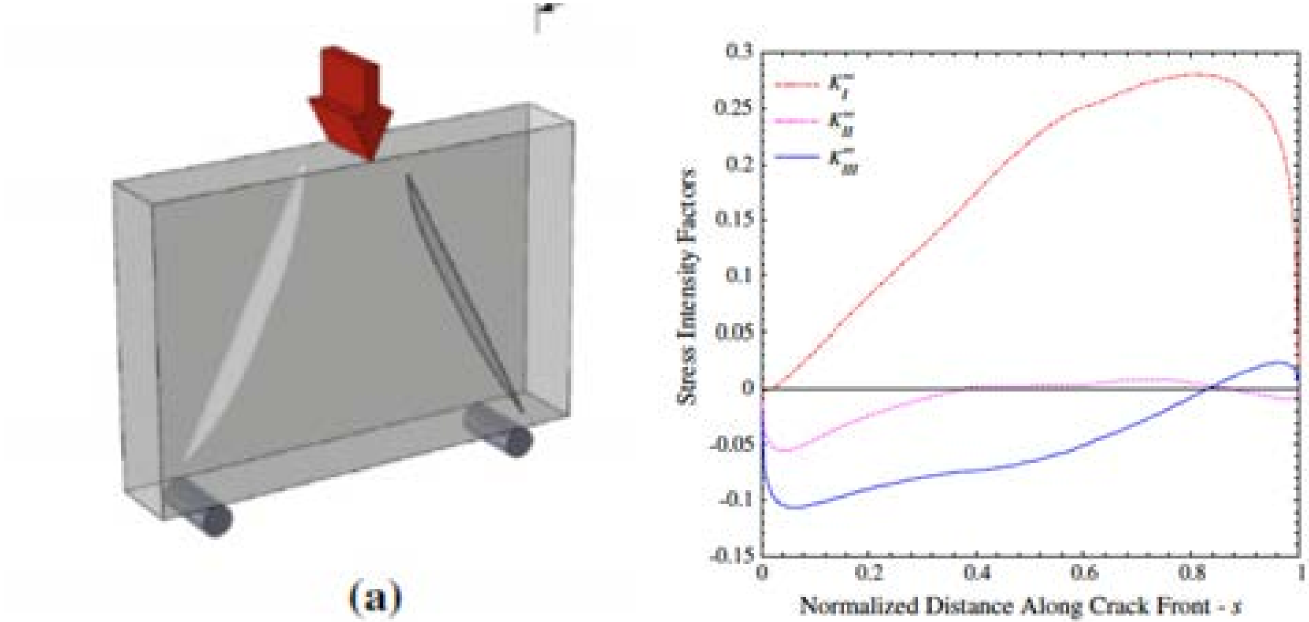


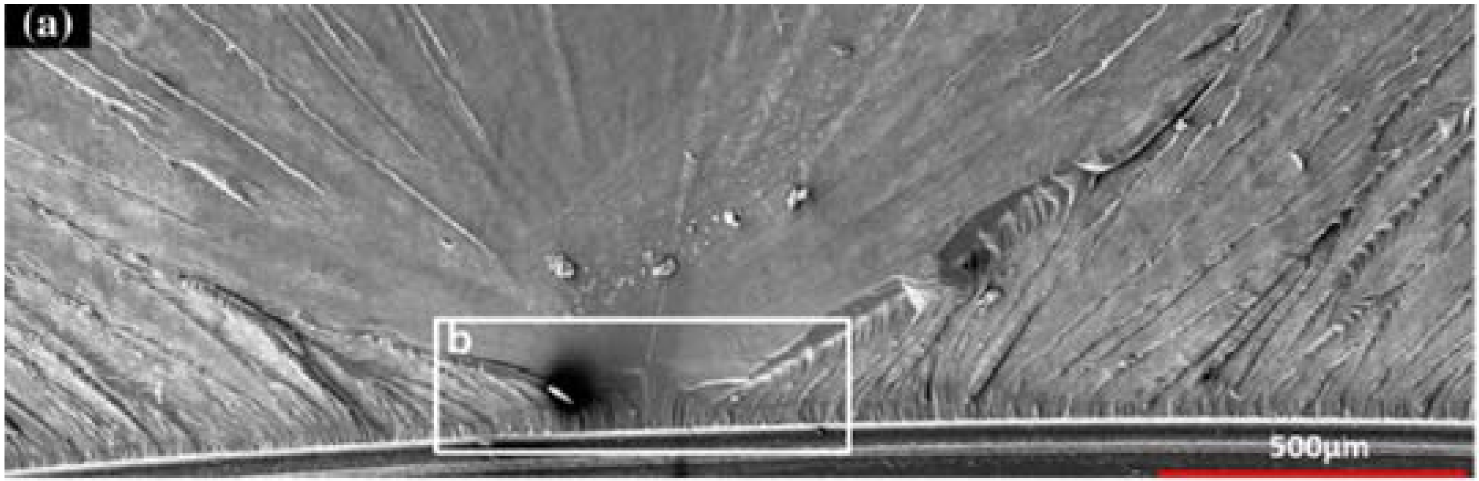
Fig. 6. Facet formation with increasing mode III-part.

In these experiments, the precrack is a 'real' *sharp* crack.

Mode I+III. Facets whatever the amount of mode III

Pham and Ravi-Chandar (2014)

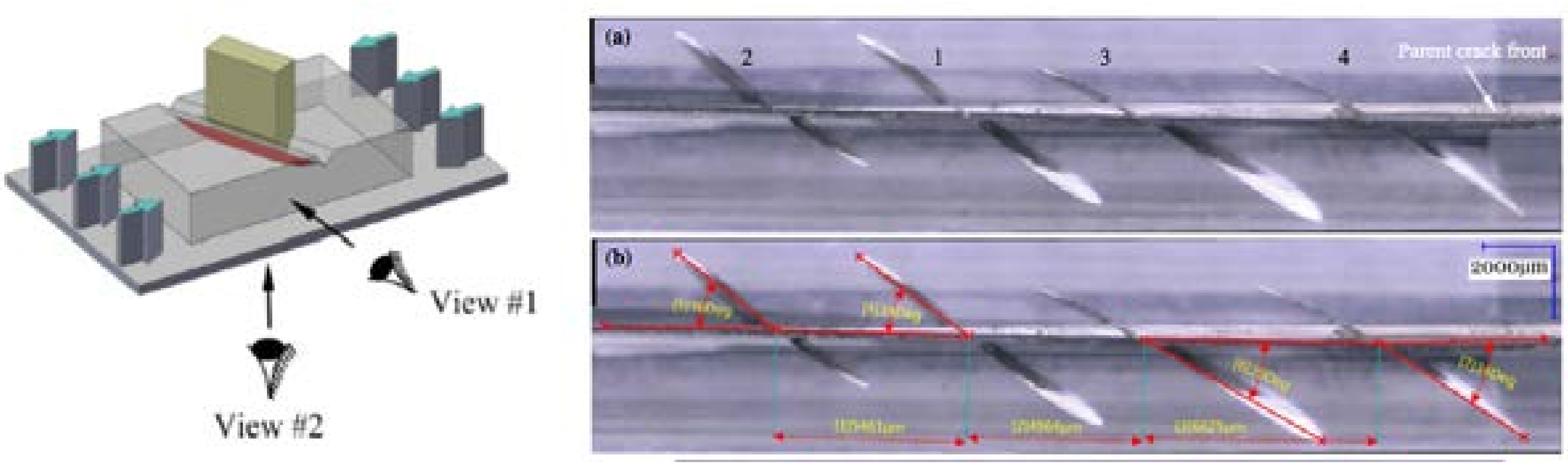




In these experiments, the precrack is not sharp.

Mode I+III. Focus on the initiation of the facets

Pham and Ravi-Chandar (2016)



- Facets are rotated toward the shear-free direction
- The initial spacing between the facets dictated by the thickness of the initial crack.

Mode I+III. Main experimental observations

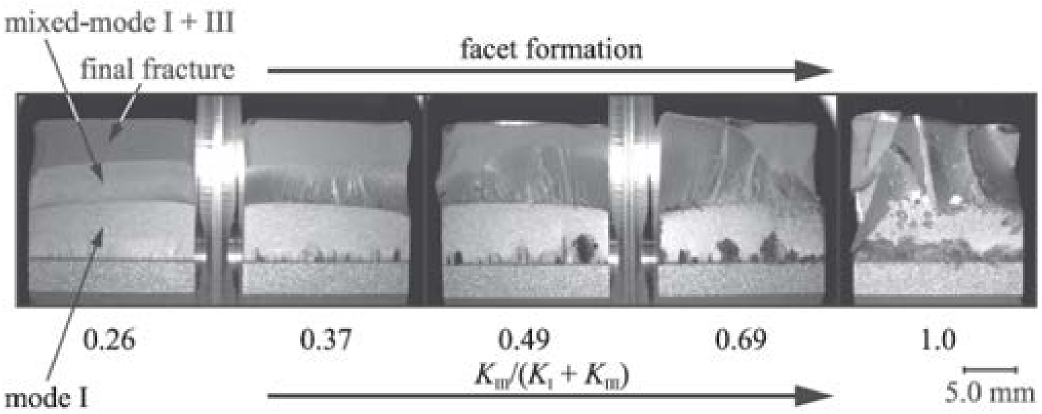
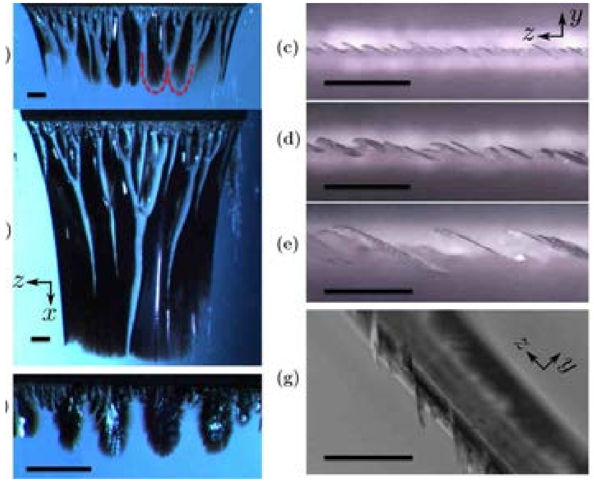


Fig. 6. Facet formation with increasing mode III-part.



- 2 regimes depending on the amount of mode III:
  1. smooth propagation
  2. fragmentation of the initial crack into facets

What governs the transition?

- Facets morphology :
  1. Apparition of small tilted finger shaped facets
  2. Progressive coalescence
  3. Facets are rotated toward the shear-free direction

  Is it possible to predict their shape qualitatively... quantitatively?

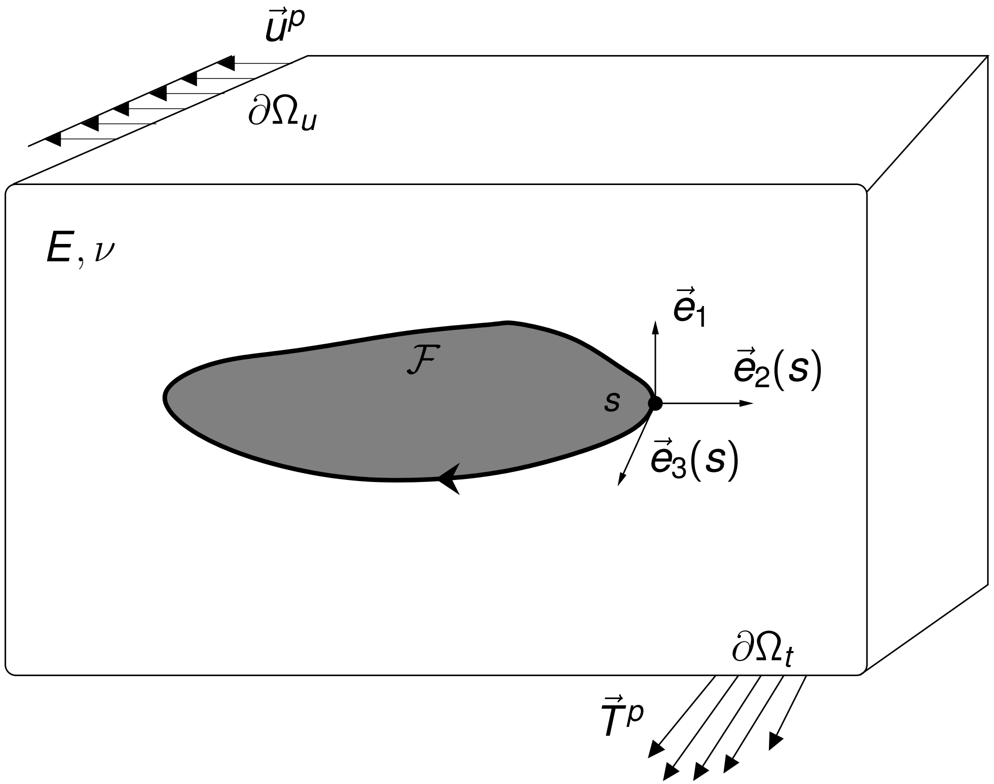
Outline

Experimental observations
- Mode I+II
- Mode I+III

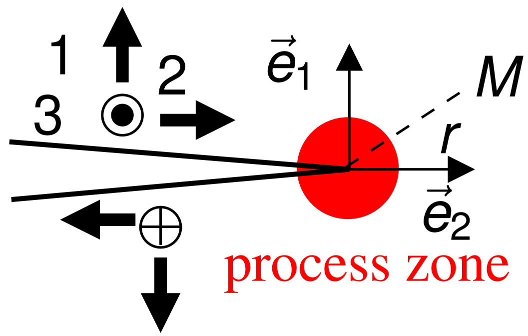
Linear Elastic Fracture Mechanics (LEFM)

Is LEFM able to predict the experimental observations?
- Mode I+II
- Mode I+III

LEFM. Framework



At each point s of the crack front,



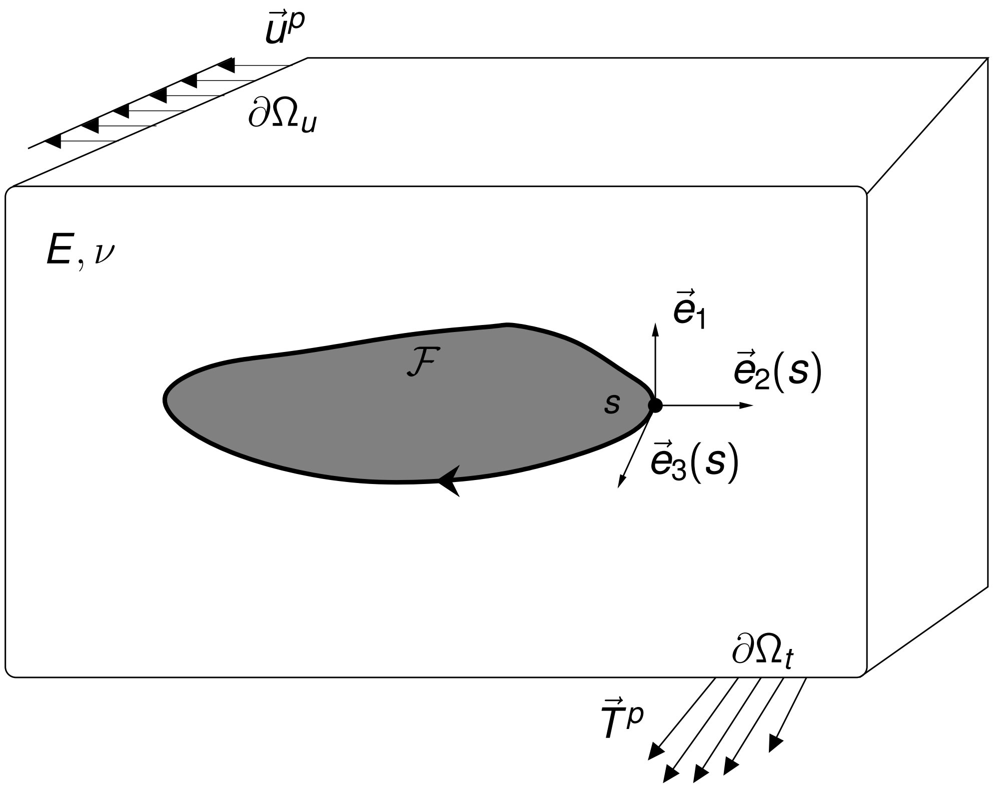
Local loading is given by:

- Stress Intensity Factors: $K_I(s), K_{II}(s), K_{III}(s)$.
- Energy release rate $\mathcal{G}$:

$$\mathcal{G}(s) \quad \equiv \quad -\frac{\mathrm{d}E_{elast}}{\mathrm{d}S} = \frac{1-\nu^2}{E}(K_I(s)^2 + K_{II}(s)^2) + \frac{1+\nu}{E}K_{III}(s)^2$$

Irwin's formula

LEFM. Propagation criteria



At each point s of the crack front,

- Propagation threshold :

$$G(s) = G_c$$

Griffith (1920) criterion

- Propagation direction:

$$K_{II}(s) = 0$$

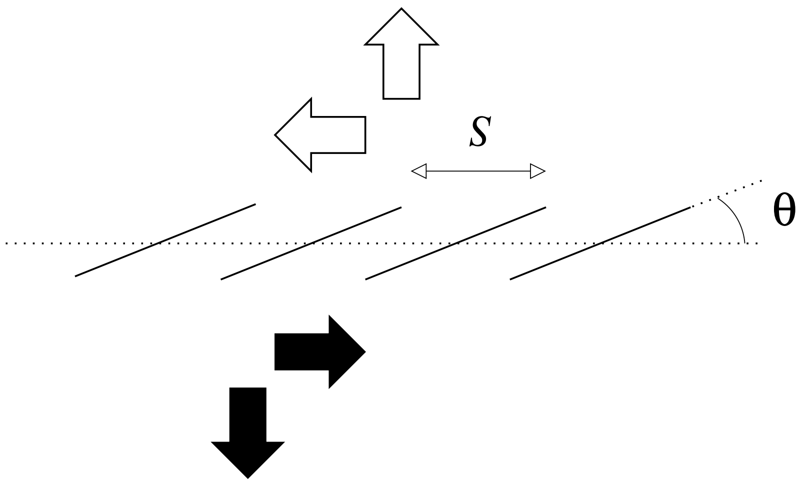
Principle of local symmetry (PLS)

Goldstein and Salganik (1974)

Suitable to predict the propagation of each point of the front...

LEFM. Nucleation of abruptly twisted facets

...but not for the nucleation of abruptly twisted facets.



Direction of the maximum principal stress axis

$$\tan 2\theta = \frac{K_{III}/K_I}{\frac{1}{2} - \nu}$$

Cooke and Pollard (1996)

Outline

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Linear Elastic Fracture Mechanics (LEFM)

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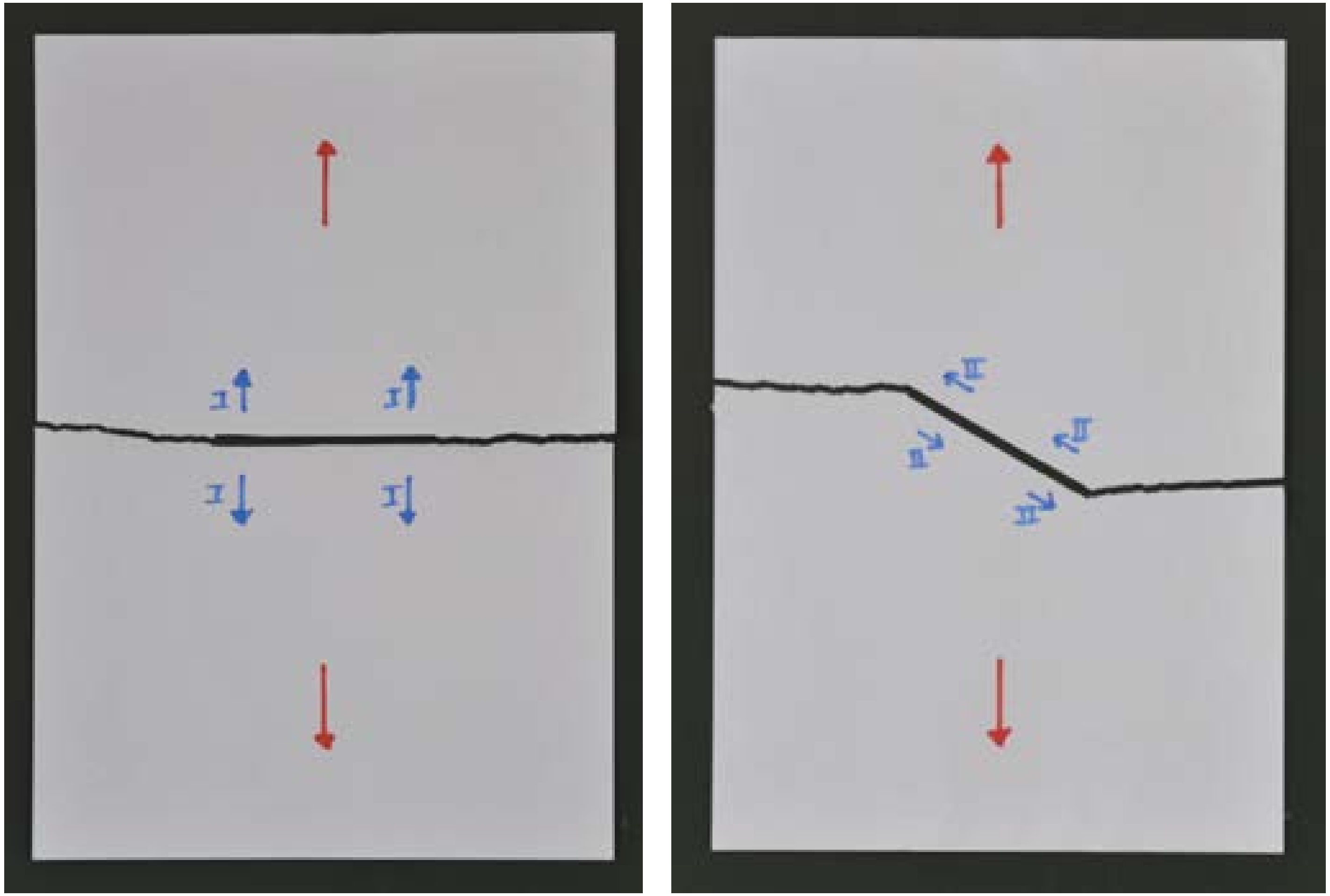
- Mode I+III

Mode I+II. Propagation direction

PLS is verified experimentally



Erdogan and Sih (1963); Flores and Xu (2013)

Mode I: From straight to more complex paths

Yuse and Sano, 1993, 1997; Ronsin et al., 1995; Yang and Ravi-Chandar, 2001

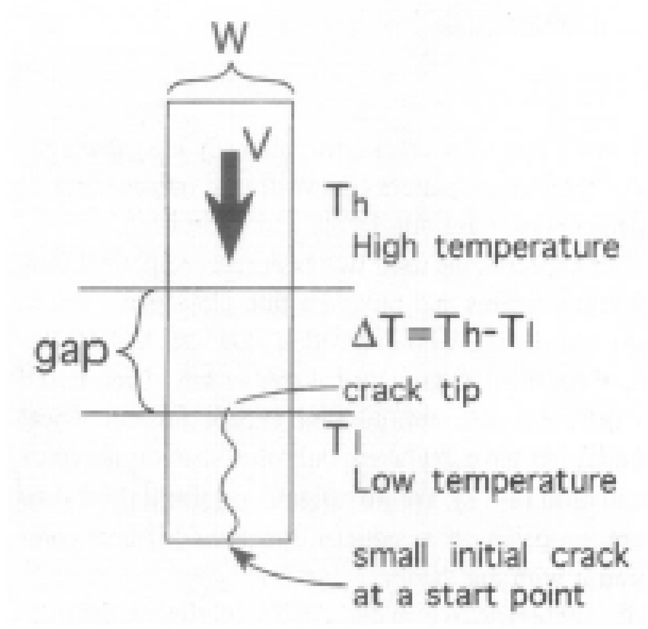
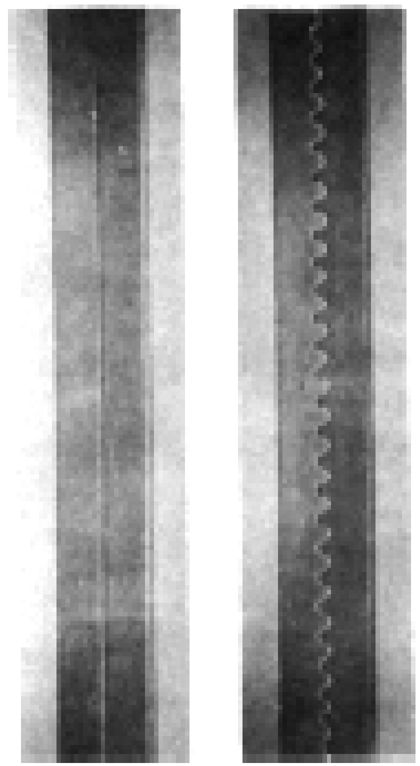
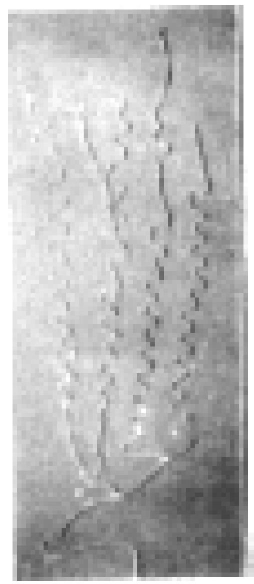


Fig. 1. Temperature configuration of the experiment. A thin sample plate moves slowly across the temperature gradient gap in the direction of the arrow with velocity V.



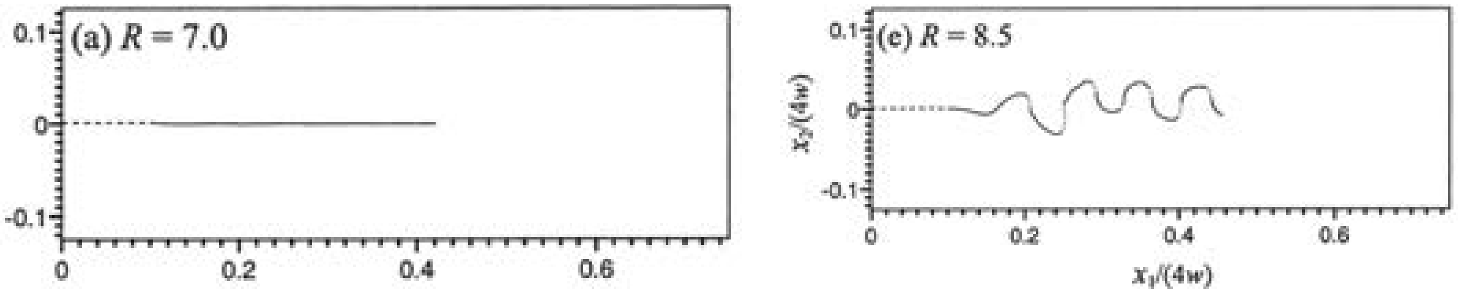


Yuse and Sano (1993)

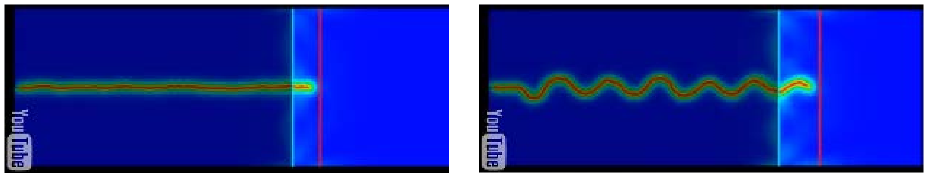
If $V > V_c$ or $\Delta T > \Delta T_c$, the path is no more straight

Mode I: Bifurcation from straight to wavy paths

- The straight propagation is not the unique solution of $K_{II} = 0$.

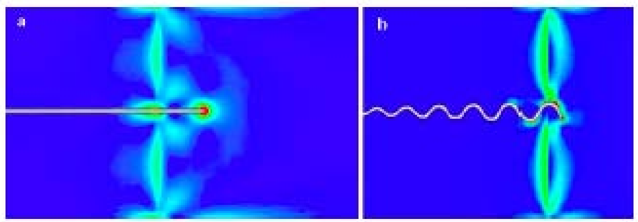


Yang and Ravi-Chandar (2001)



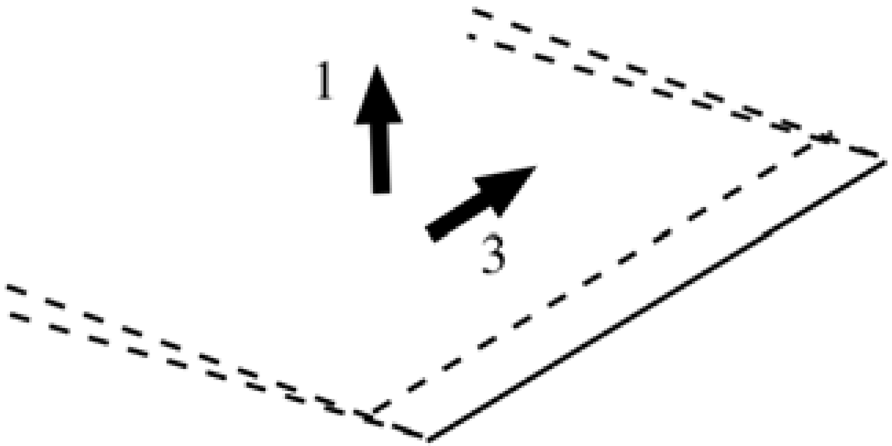
Video on Blaise Bourdin webpage. Bourdin et al. (2008)

- Supercritical bifurcation



Corson et al. (2009)

Mode I+III: a thought experiment



Planar crack with straight front in an infinite and homogeneous media

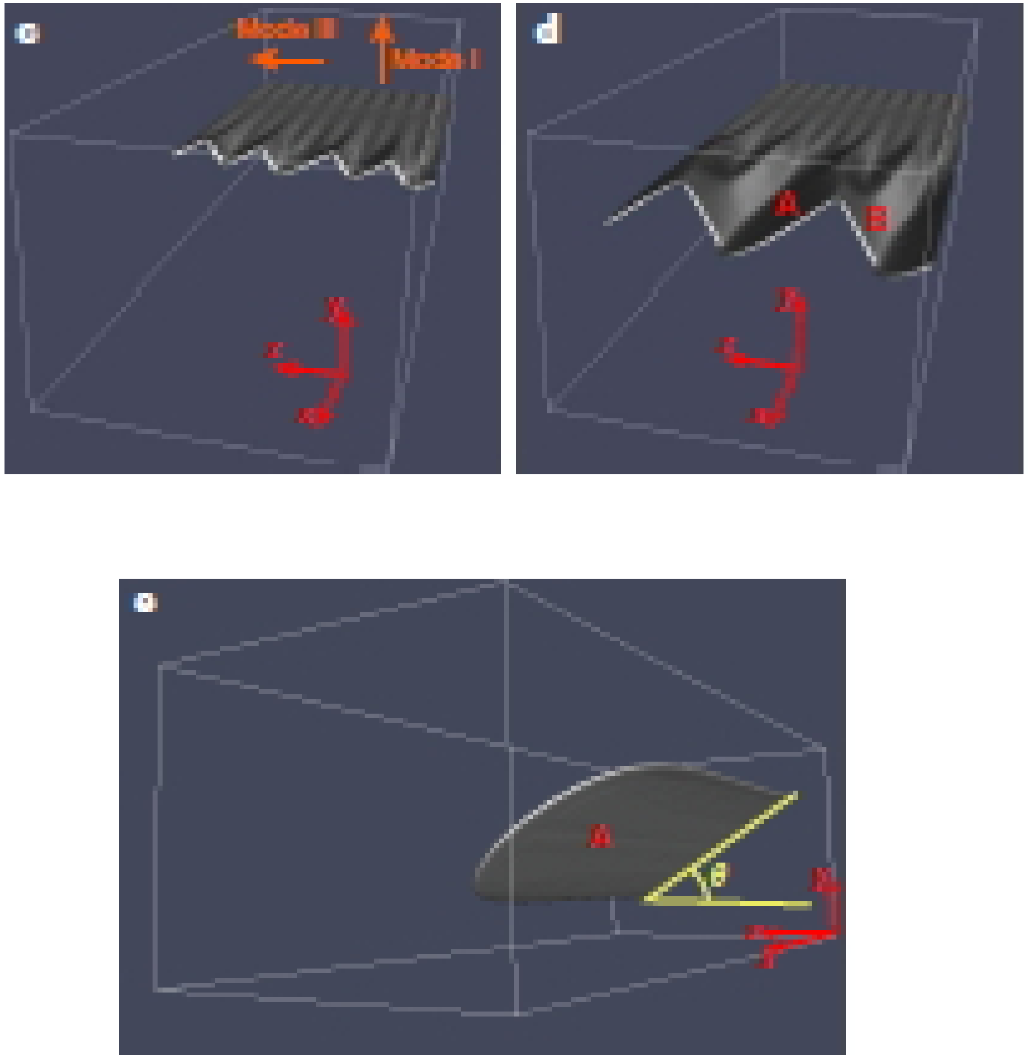
Uniform loading:

$$K_I(s) = K_I$$
$$K_{II} = 0$$
$$K_{III}(s) = K_{III}$$

Straight uniform propagation is a trivial solution of $G = G_c$ and $K_{II} = 0$

But neither unique, nor stable...

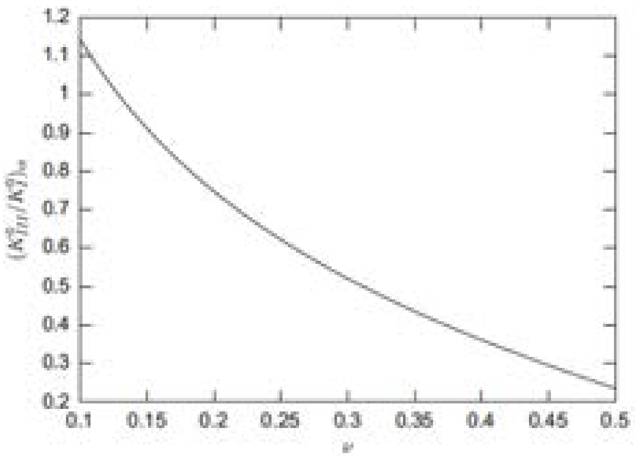
Mode I+III: Helical crack front bifurcation

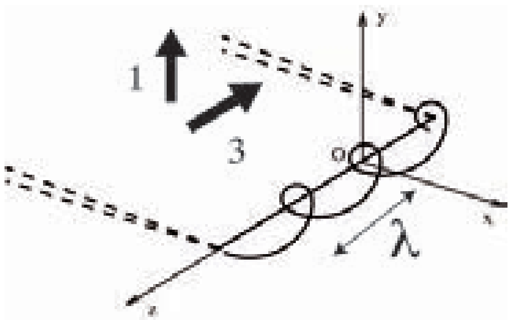


Pons and Karma (2010)

Mode I+III: Linear stability analysis

Leblond, Karma, Lazarus (JMPS, 2011)





For $K_{III}/K_I > (K_{III}/K_I)_c(\nu)$,

the straight propagation is unstable versus wavy out+in-plane perturbations of all wavelength.

$$\delta G = \delta G)_{in-plane} + \delta G)_{out-plane} = 0$$

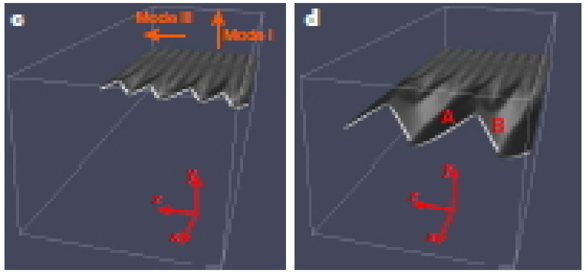
$$\delta K_{II} = \delta K_{II})_{in-plane} + \delta K_{II})_{out-plane} = 0$$

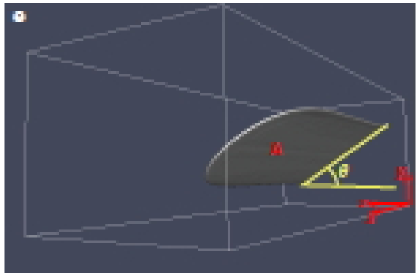
Gao and Rice (1986)

Movchan et al. (1998)

Mode I+III: Non linear analysis

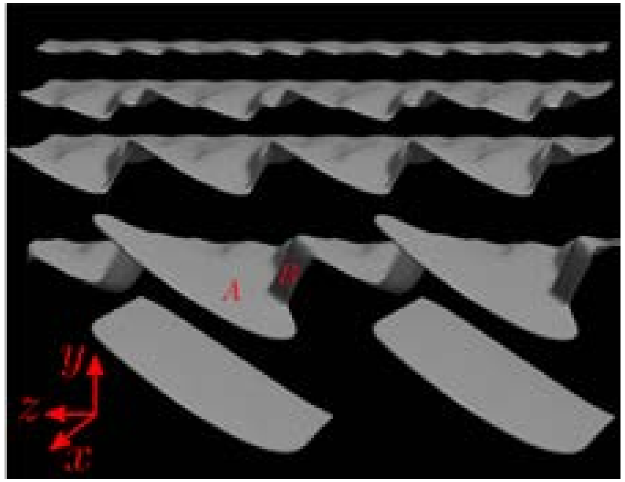
- Above the threshold: Karma and Pons (Nature, 2010)





The propagation is unstable in agreement with linear stability analysis.

- Below the threshold:
  Chen, Cambonie, Lazarus, Nicoli, Pons, Karma (PRL, 2015)



1. Starting from a 'perfectly' straight crack,

   no instability appears;

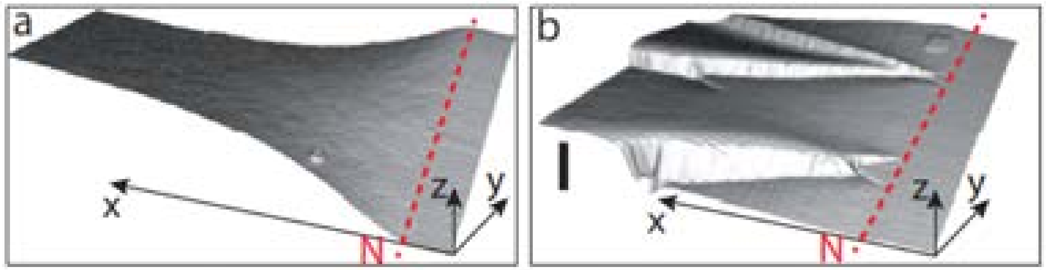
2. The instability can be initiated by decreasing K_{III}/K_I from above to below the threshold.

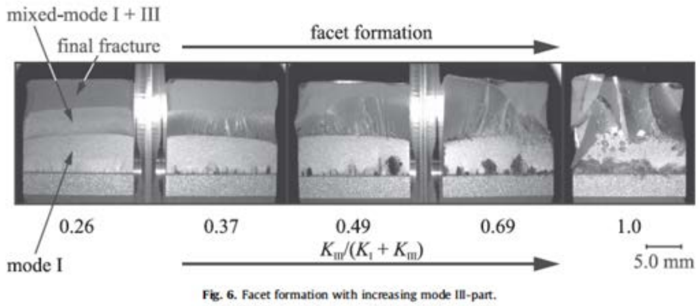
The instability is subcritical and may be initiated by small imperfections (confirmed by Henry (2016))

Mode I+III: subcritical bifurcation/experiments

Subcritical bifurcation implies that the transition is sensitive to defects, and that:

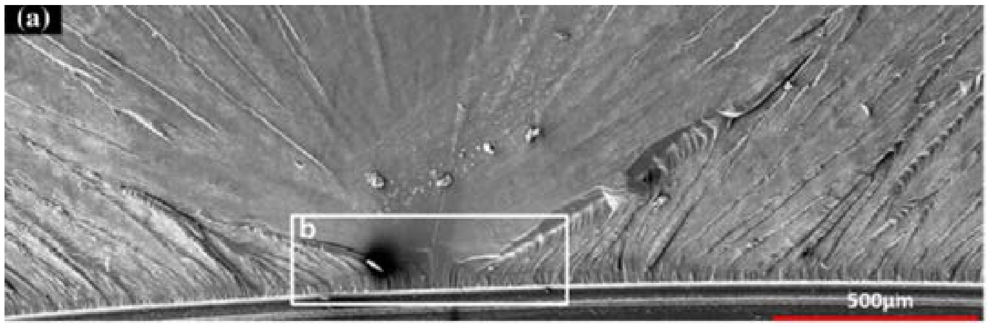
- it may be observed...





Ronsin et al. (2014); Eberlein et al. (2017)

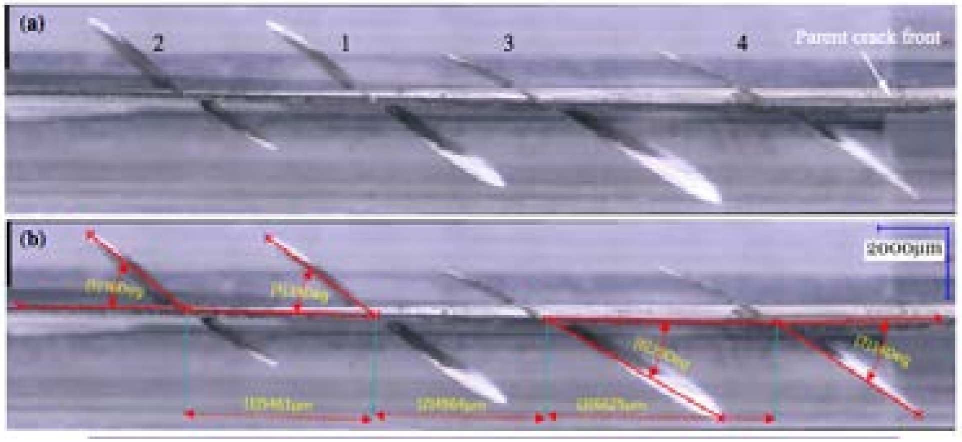
- or not:



Pham and Ravi-Chandar (2014)

Facets morphology at initiation

Pham and Ravi-Chandar (2016)



- Facets are rotated in the shear-free direction given by

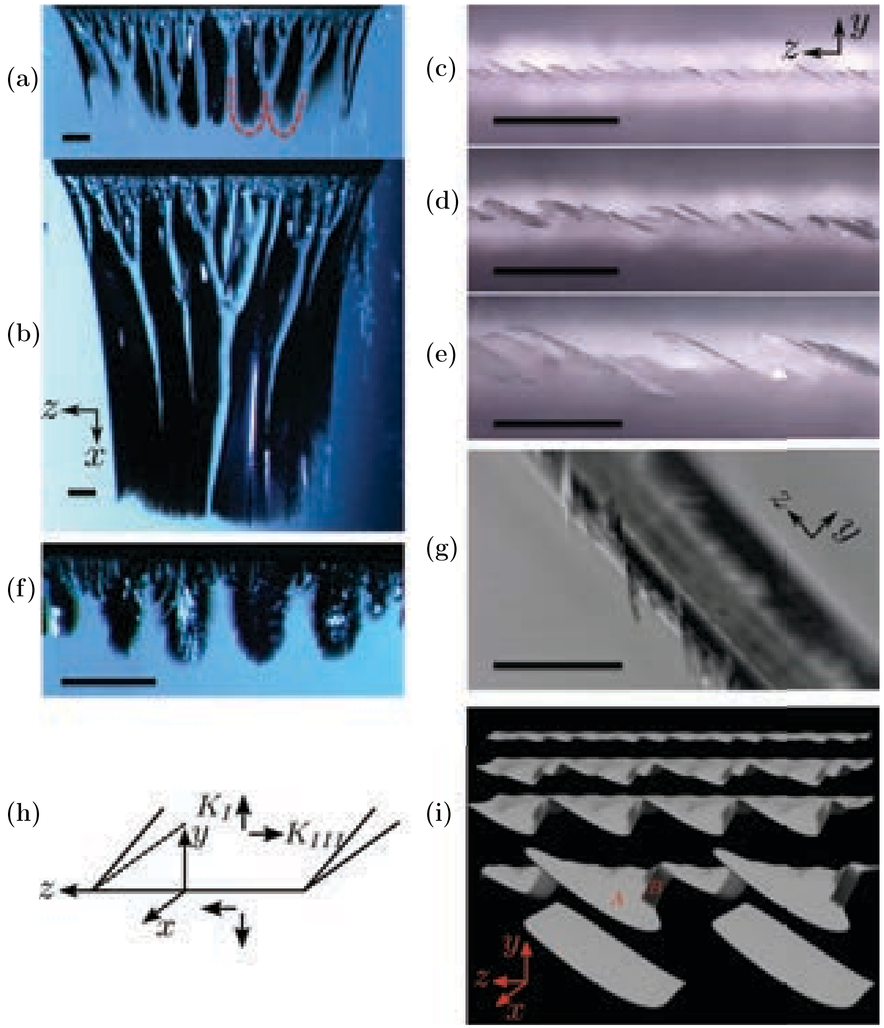
$$\tan 2\theta = \frac{K_{III}/K_I}{\frac{1}{2} - \nu}$$

- The spacing between the facets dictated by the thickness of the initial crack.

Further propagation

Qualitative agreement between experiments and phase-field simulations.

Chen, Cambonie, Lazarus, Nicoli, Pons, Karma (PRL, 2015)



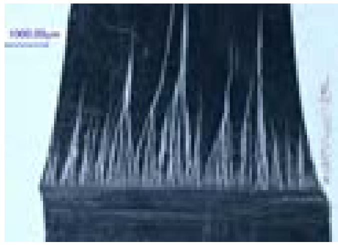
- After initiation, the facets take some finger shape;
- They further coalesce
- The rotation angle is nearly constant

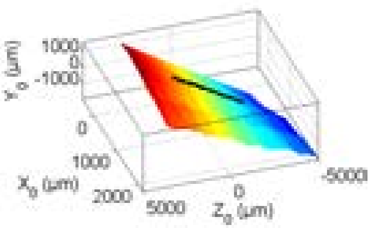
And quantitatively?

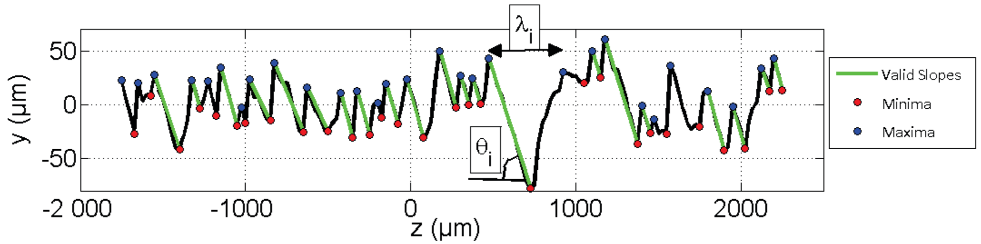
Quantitative description of the crack profile

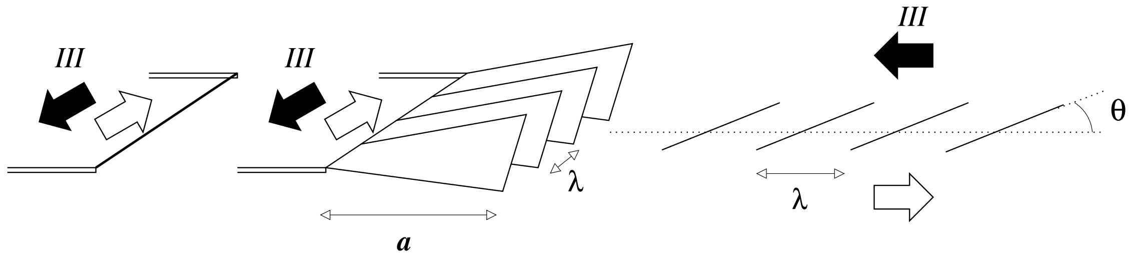
Cambonie and Lazarus (Procedia Materials Science, 2014)

1. Mechanical profilometer to get a mapping of the fracture surface







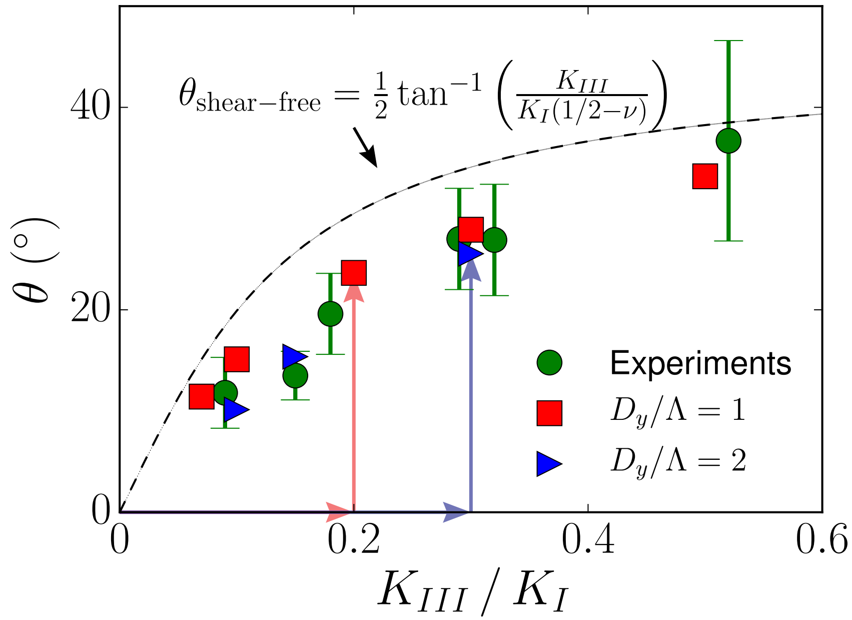


2. We extract:

the facet rotation angle θ

the coarsening rate $\beta \equiv \dfrac{\mathrm{d}\lambda}{\mathrm{d}a}$.

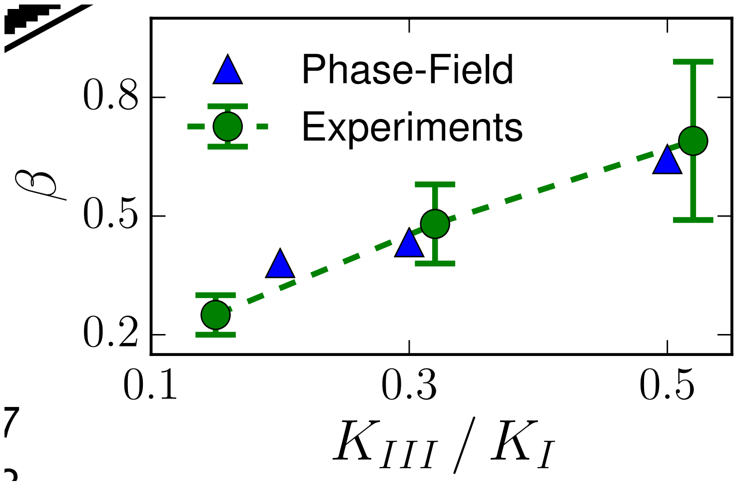
Facet rotation angle. Phase-field/experiments



- quantitative agreement for θ between experiments and PF;
- shear-free orientation overestimates the angle θ.
- discrepancy with Pham and Ravi-Chandar (2016) at initiation

Additional experiments are necessary to conclude.
Interaction between cracks may play a role
(Leblond and Frelat, 2014)?

Coarsening rate

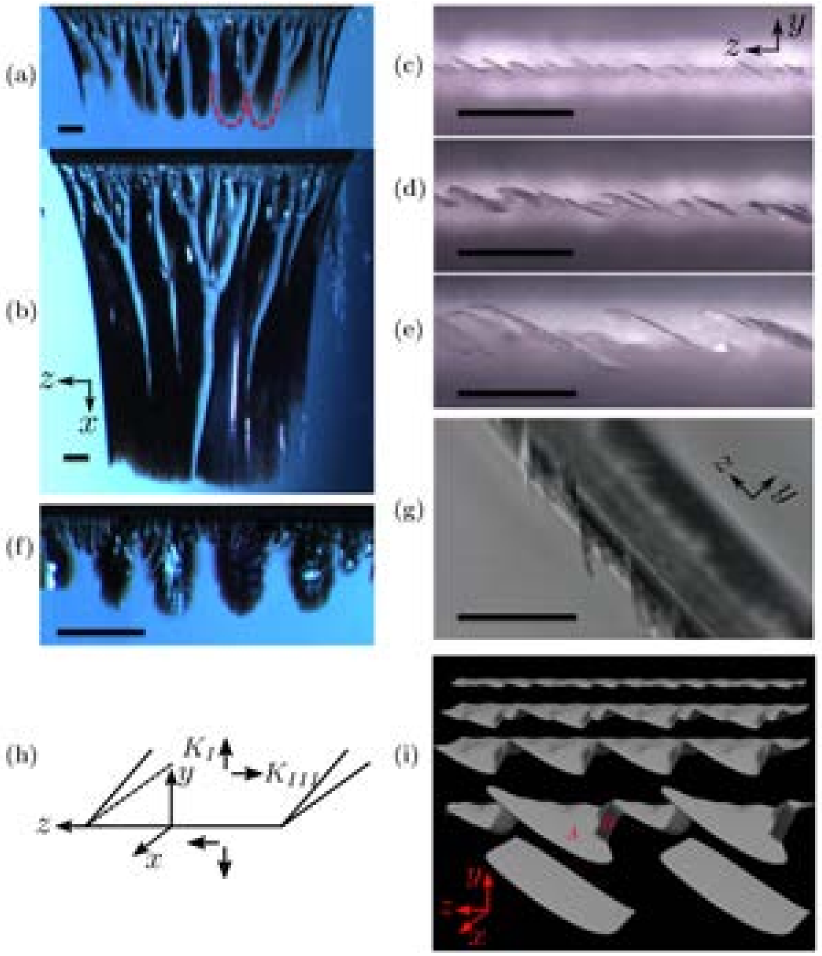


Chen et al. (2015)

- β increases with K_{III}/K_I
- Agreement via an adjustable parameter,

...additional work is necessary.

Conclusion on facets morphology



1. Apparition of small tilted finger shaped facets
2. Facets are rotated toward the shear-free direction
3. Progressive coalescence

LEFM is able to predict the morphology

TODO:

- What determines β?
- Focus on the initiation (initial distance and angle evolution, smooth/abrupt). LEFM limit?

Conclusion on the smooth/facets transition

A subcritical bifurcation has been evidenced by non-linear stability analysis, explaining why a transition may be observed or not.

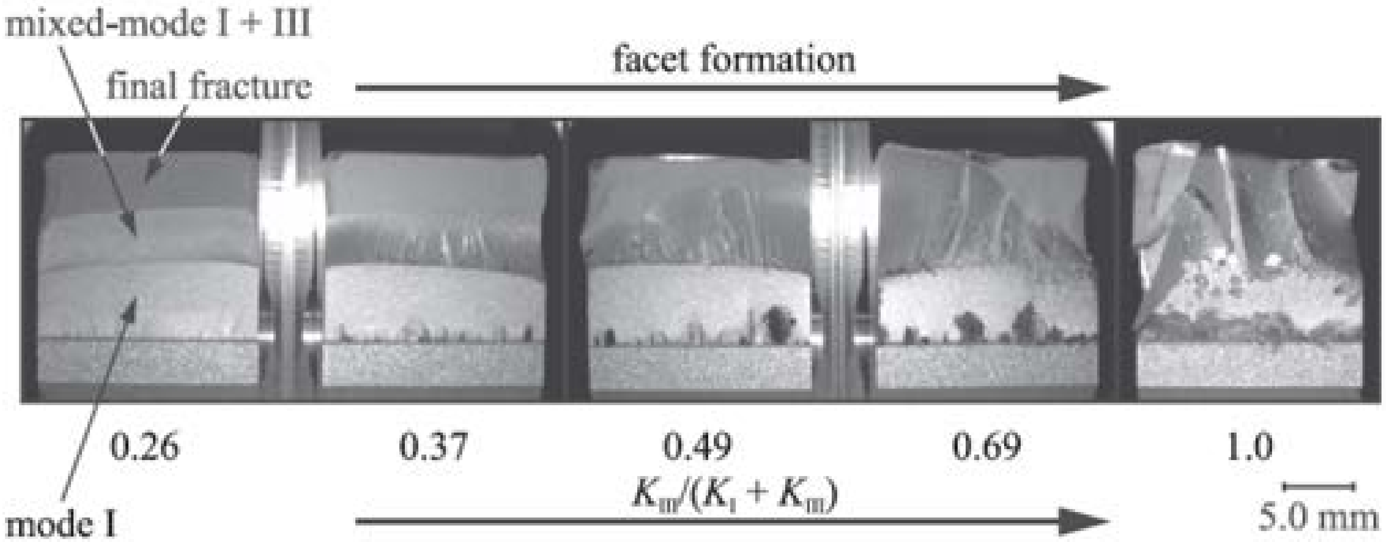


Fig. 6. Facet formation with increasing mode III-part.

Eberlein et al. (2017)

TODO: understand the role of the defects on the onset of the instability?

It may be necessary to focus below the scale of LEFM...

On going work in the LEFM framework

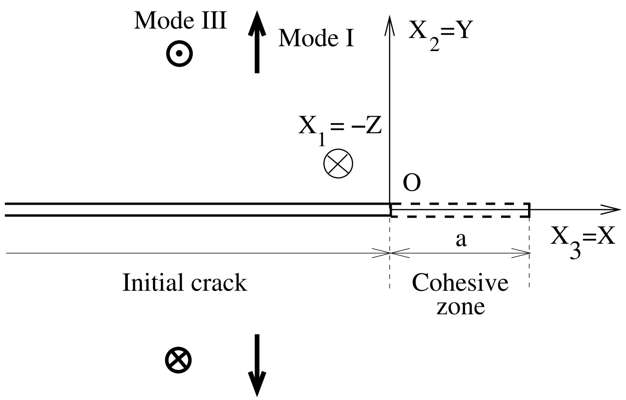
Study

- the morphology
- the impact of facets on the propagation (toughness, velocity)

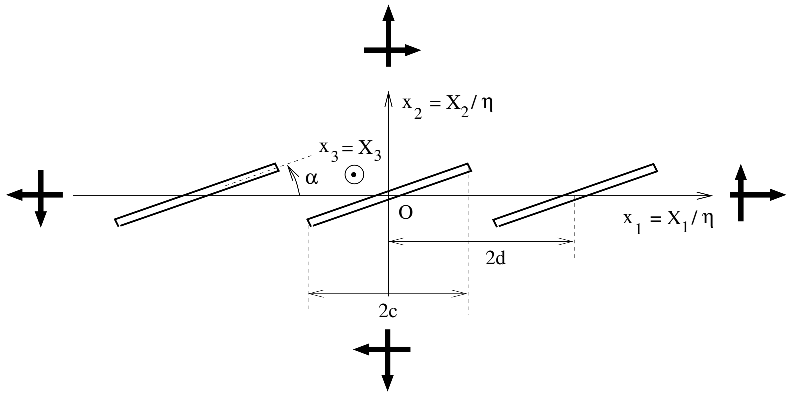
with the use of:

- Additional phase-field simulations
- Additional experiments (3 PB, multiaxial testing machine)
- Multiscale approach:

Macroscopic view: facets appear as a cohesive zone



Microscopic view: facets appear as echelon cracks



Leblond, Lazarus, Karma (IJF, 2015)

That's it for today! Thanks to co-workers and for your attention...
Questions?

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