Toughening effect analysis in problems of propagating cracks interacting with interfaces

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Our collaboration with Prof. F. Duda

Since more than 10 years:

Development of **Phase Field Models (PFM) for brittle fracture** in several solid mechanic problems:

- ✔ Fracture and Plasticity (Int. J. Plasticity, 2015);
- ✔ SCC: solute-assisted brittle fracture in elastoplastic solids (Int. J. Plasticity, 2018);
- ✔ Crack propagation interacting with interfaces (Int. J. Plasticity, 2021)
- ✔ Numerical aspects of PFM (Int. J. Num. Meth. Eng. 2023 – submitted)

Development of multiscale models in the area of thermomechanics problems.

Objectives of this presentation

- ✔ Fracture resistance of bodies with interfaces, how can be increased through the mechanism of **crack propagation shielding**.

Design new material with the objective to enhance resistance to fracture

- ✔ This shielding mechanism is intimately related to both material failure criteria:

crack nucleation governed by strength → σ_c

versus

crack nucleation governed by toughness → $K_{Ic} = \sqrt{EG_c}$

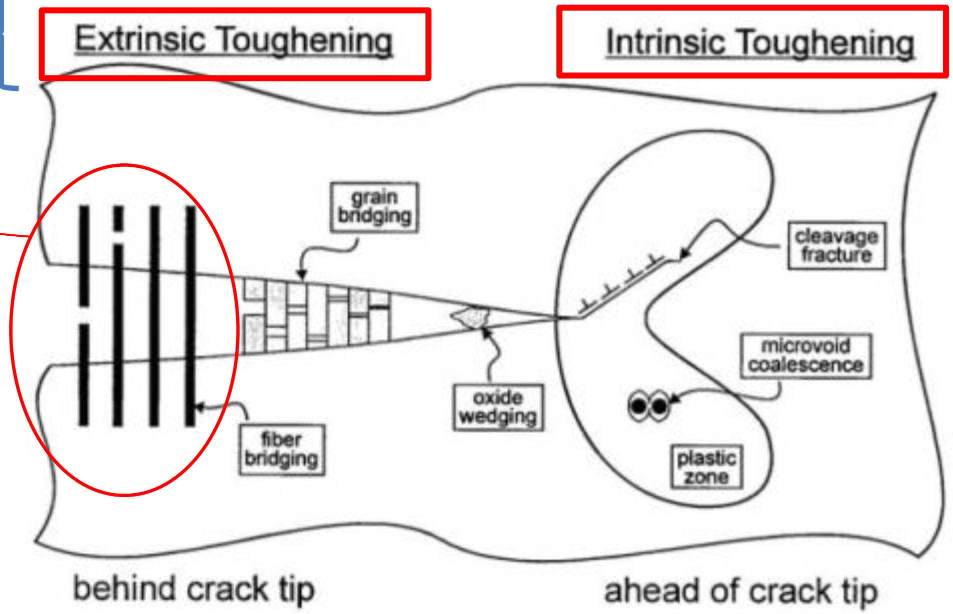
- ✔ Use of Phase Field Models (PFM) is adequate to simulate such phenomenon (PFM have been historically based on the crack nucleation toughness notion)

Mechanisms for fracture resistance increase

(Robert O. Ritchie, University of California, Berkeley)

Wake of a crack tip, associated with **crack-tip shielding**

Ahead of a crack tip, motivated by **plasticity** (Ductile materials)



The main mechanism to increase fracture resistance through extrinsic toughening is **crack deflection and bridging**

Influenced by the micro-architecture — Influenced by the micro-structure

*An outcome of the phenomenon arising between a **propagating crack interacting with an interfaces***

Applications where the mechanisms of ***crack propagation interacting with interfaces*** is relevant

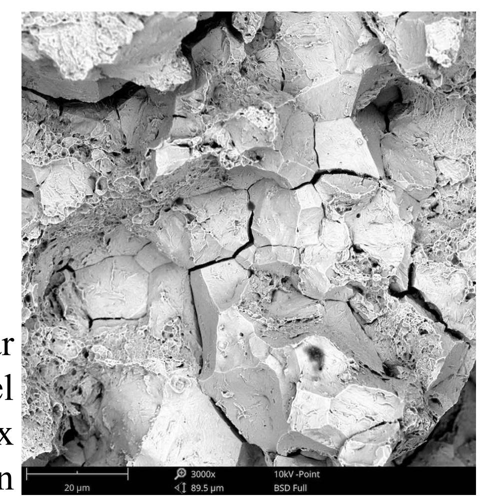
- *Fracking in oil and gas industries: Natural fractures in reservoirs* (complex hydraulic fractures in naturally fractured reservoirs)

- *Composites fracture resistance* (brittle materials such as ceramics, concrete, or epoxies can be toughened by the addition of relatively brittle fibers, provided **crack deflection** occurs at the interfaces between the fibers and the matrix). Laminated composites

- *Intergranular (associated with materials that are prone to corrosion) vs. transgranular (brittle) fracture in polycrystalline materials*

G_s / G_i

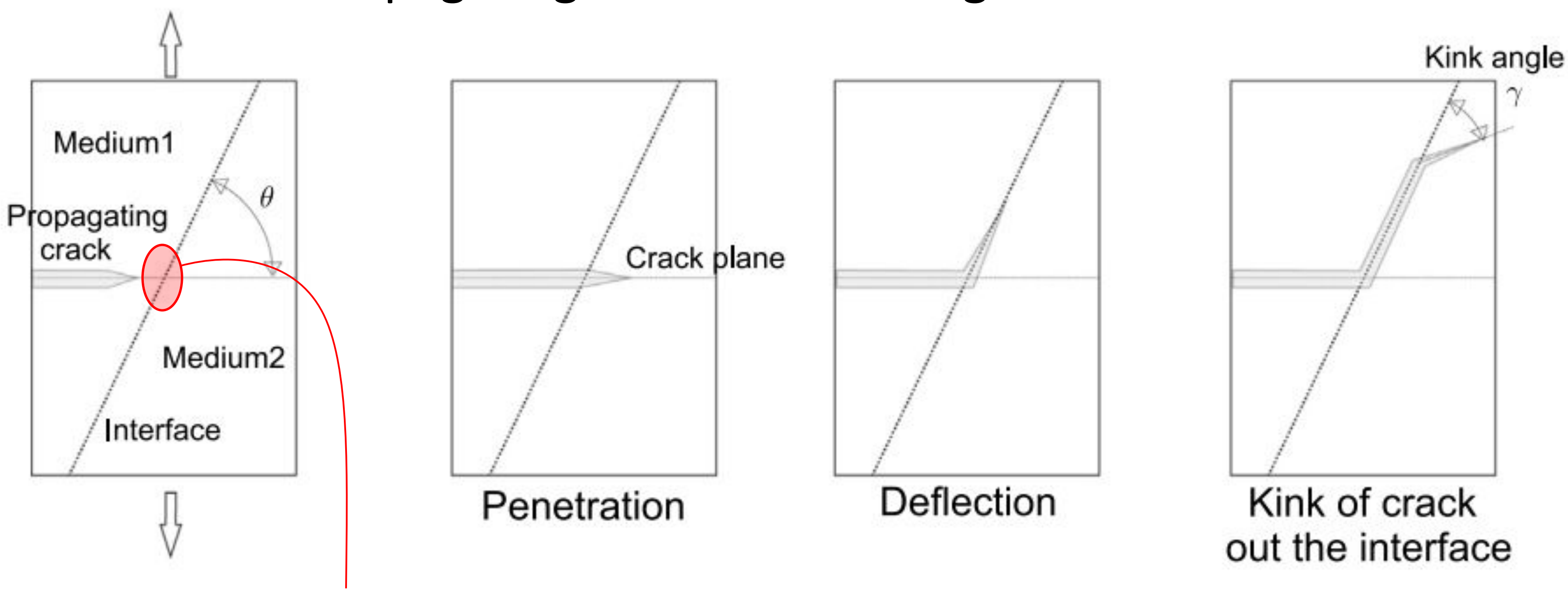
Grain toughness	G_s
Grain boundary toughness	G_i



Intergranular Cleavage in a Steel Bolt at 3000x magnification

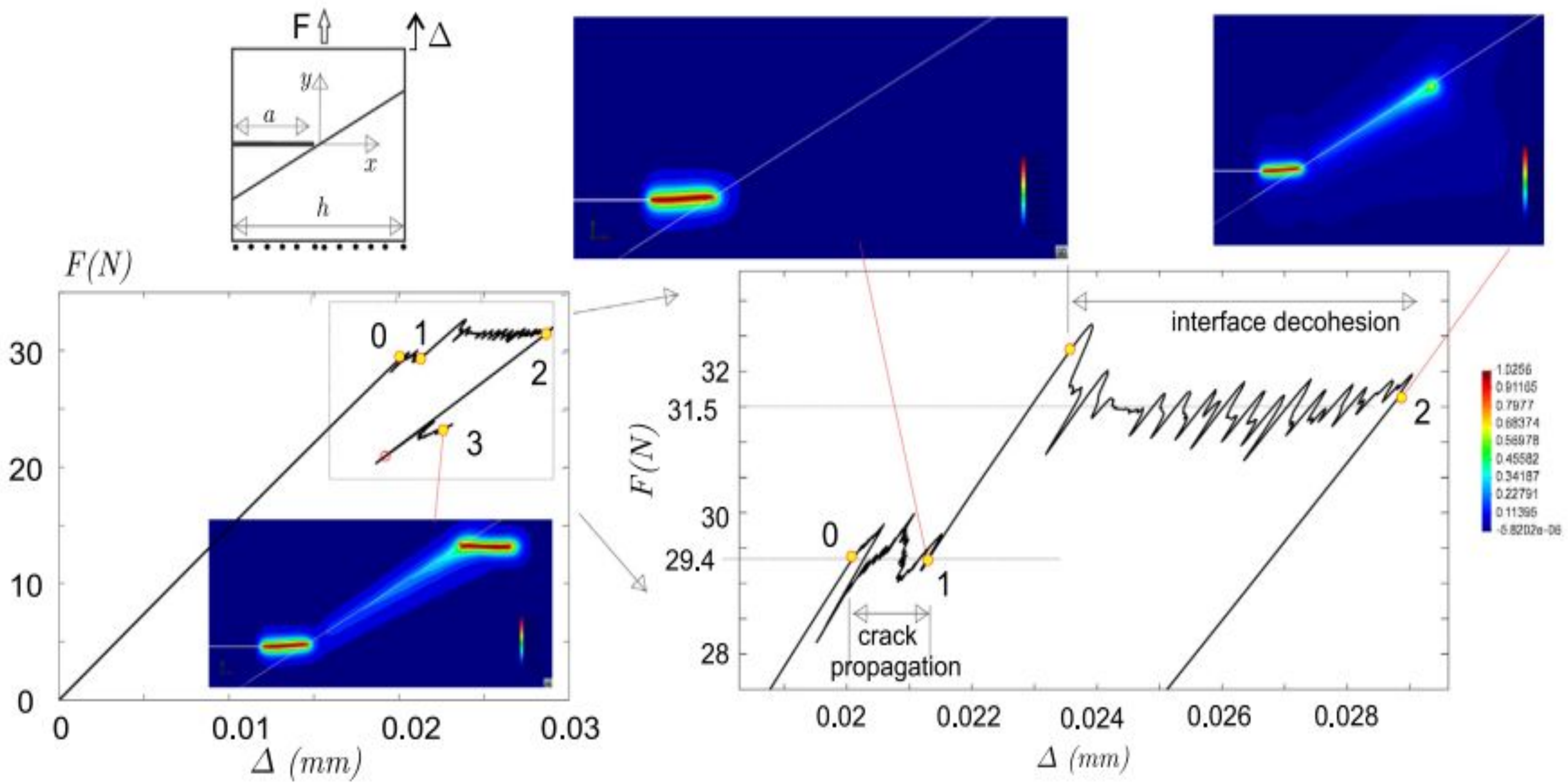
Extrinsic toughening associated with the interface shielding effect on a propagating crack

Propagating cracks interacting with interfaces

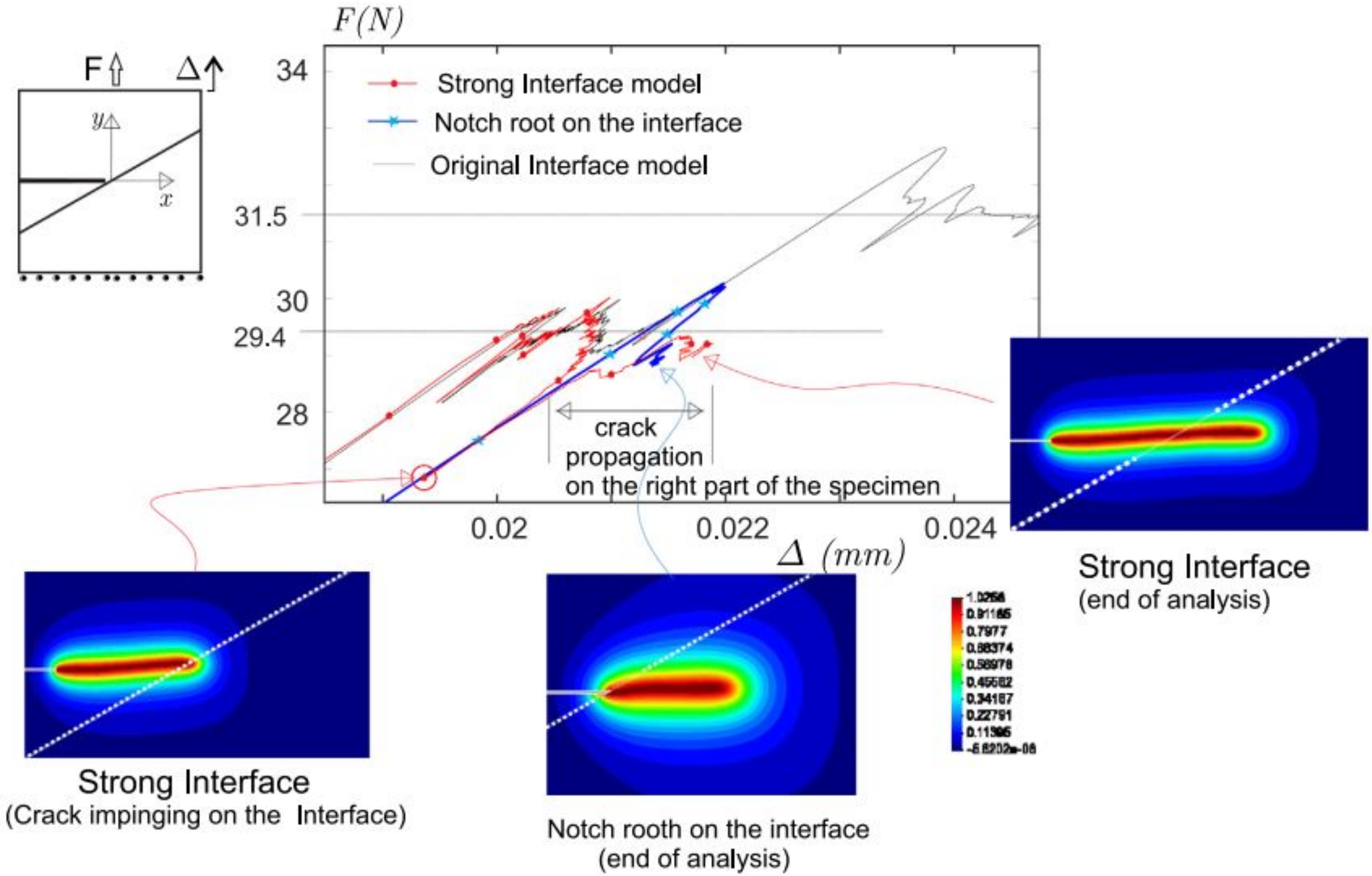


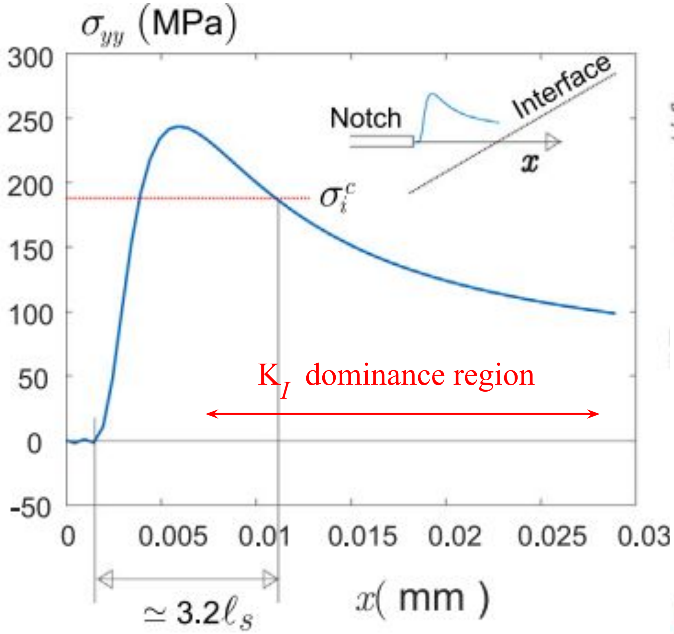
Shielding effect influencing the toughness

Extrinsic toughening associated with the interface shielding effect on a propagating crack



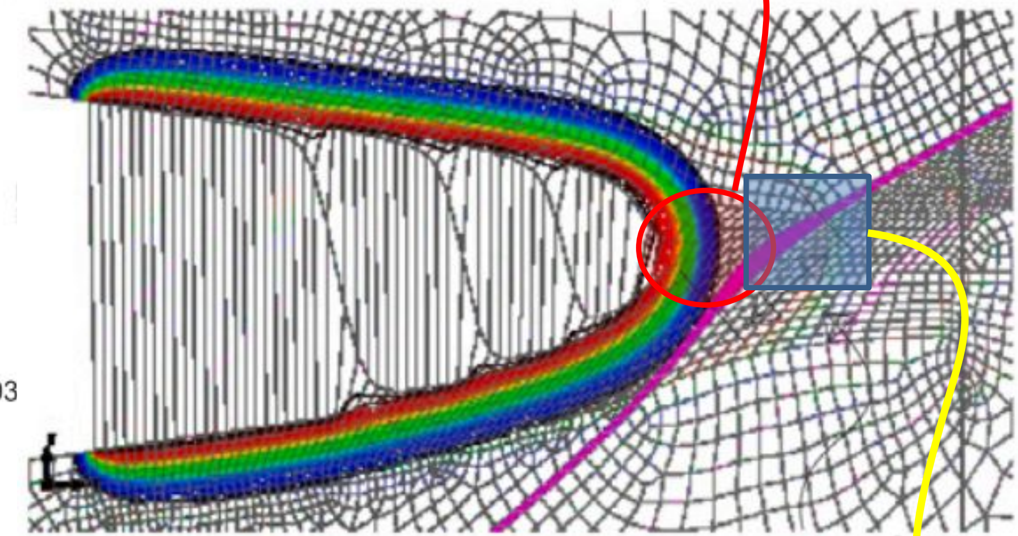
Extrinsic toughening associated with crack-tip shielding



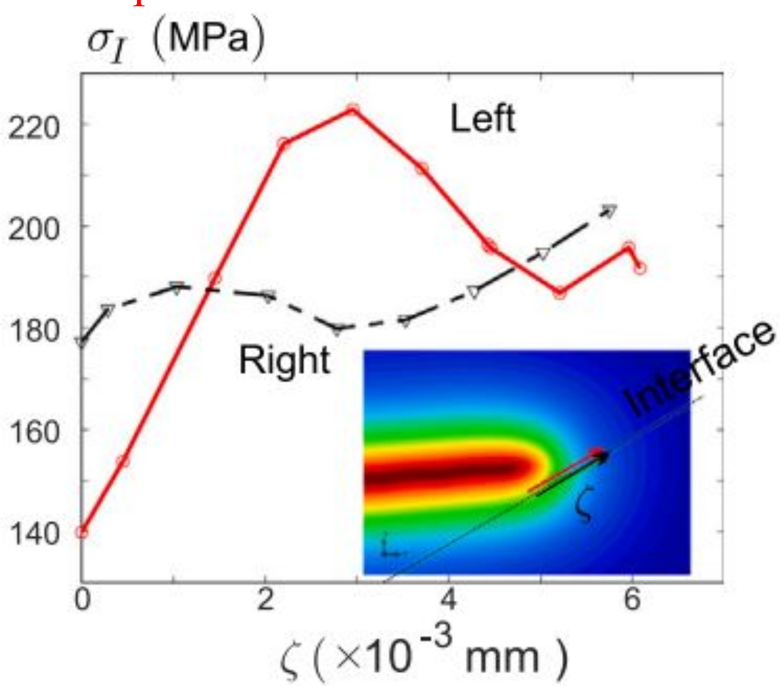


K$_I$ stress dominance region
(**Toughness dominance**)

$$K_{Ic} = \sqrt{EG_c}$$



Principal stress on either side of the interface



Interface degradation induced by stresses **(Strength dominance)**

$$\sigma_c$$

Crack propagation mechanism

↓

Material **toughness**

Interface opening mechanism

↓

Material **strength**

<u>Parameters identifying the interaction mechanisms</u> between propagating crack with interface are strongly related to crack nucleation

(“*Strength or toughness? A criterion for crack onset at a notch*”. <u>D. Leguillon</u>, Eur. J.Mech. Solids A, 2002.)

Two possible competing material failure criteria

Energy criterion:

$$-\frac{\partial W_{\mathrm{p}}}{\partial S} = G \geqslant G_{\mathrm{c}}$$

Fracture energy (G_{c})

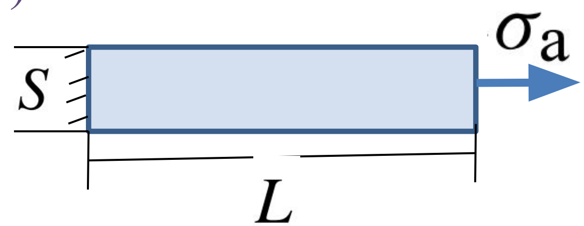
Energy release per unit of crack area (G)

Strength criterion: $\sigma \geqslant \sigma_{\mathrm{c}}$

Assessing fracture resistance using an incorrect criterion can result in inconsistencies:

Bar failure, <u>toughness criterion</u> (energy criterion):

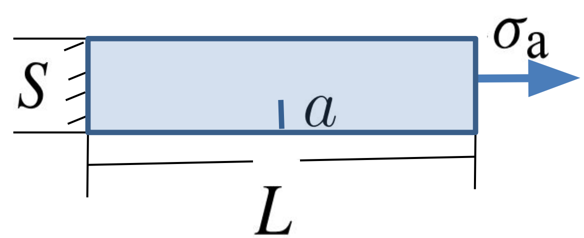
$$-\delta W_{\mathrm{p}} = W_{\mathrm{p}} = \frac{1}{2} S L \sigma_{\mathrm{a}} \varepsilon_{\mathrm{a}} = \frac{1}{2} S L \frac{\sigma_{\mathrm{a}}^2}{E}$$



$$\frac{1}{2} S L \frac{\sigma_{\mathrm{a}}^2}{E} \geqslant G_{\mathrm{c}} S \quad \Rightarrow \quad \sigma_{\mathrm{a}} \geqslant \sqrt{\frac{2 E G_{\mathrm{c}}}{L}}. \quad \Rightarrow$$

$$L \to \infty \quad \Rightarrow \quad \sigma_{\mathrm{a}} \to 0$$

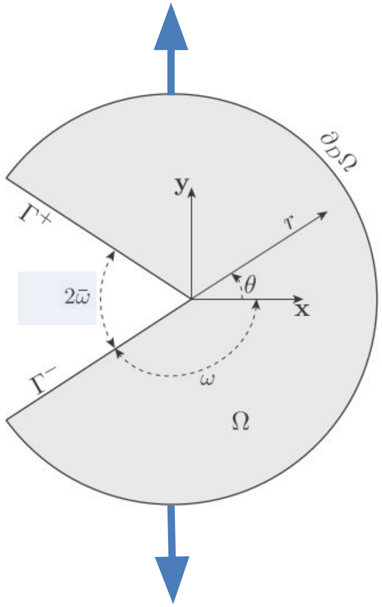
Notched bar failure, <u>strength criterion</u>:



$$\sigma = \alpha\left(\frac{a}{S}\right) \frac{\sigma_{\mathrm{a}}}{\sqrt{r}} > \sigma_c$$

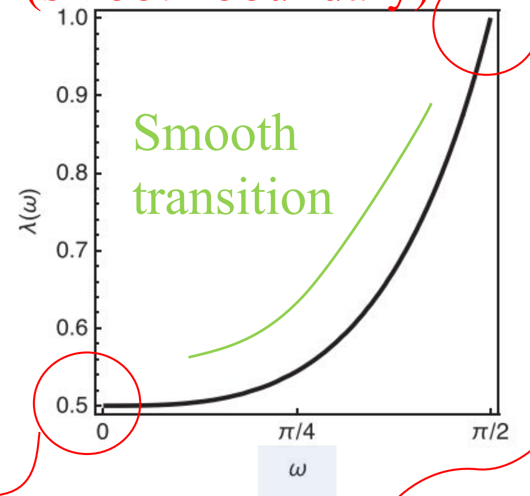
$\sigma_{\mathrm{a}} \to 0$ satisfies the failure criterion

Notch with angle □



$$\sigma_{\theta\theta} = k r^{\lambda-1} F(\theta)$$

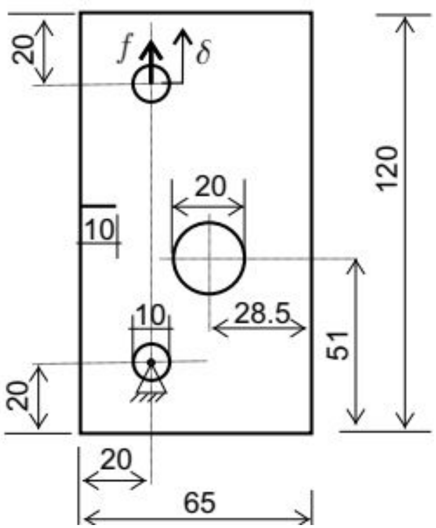
Regular stress
(smooth boundary)



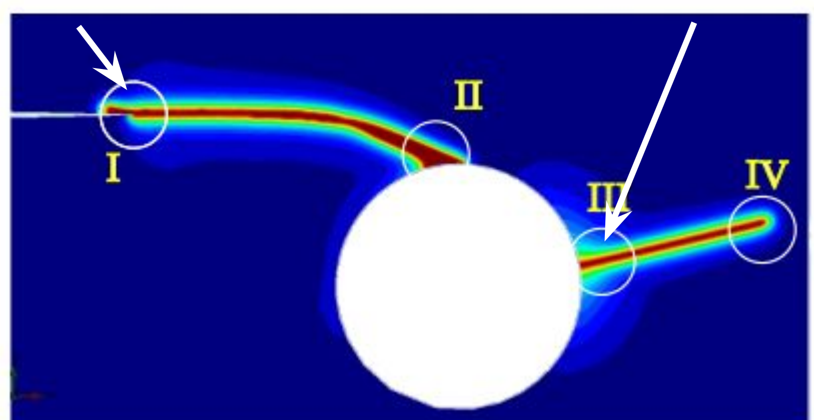
Singular stress
(sharp crack)

Crack onset criterion: toughness □=0 ; strength □=□/2

Notched plate with hole



Crack nucleation governed by toughness

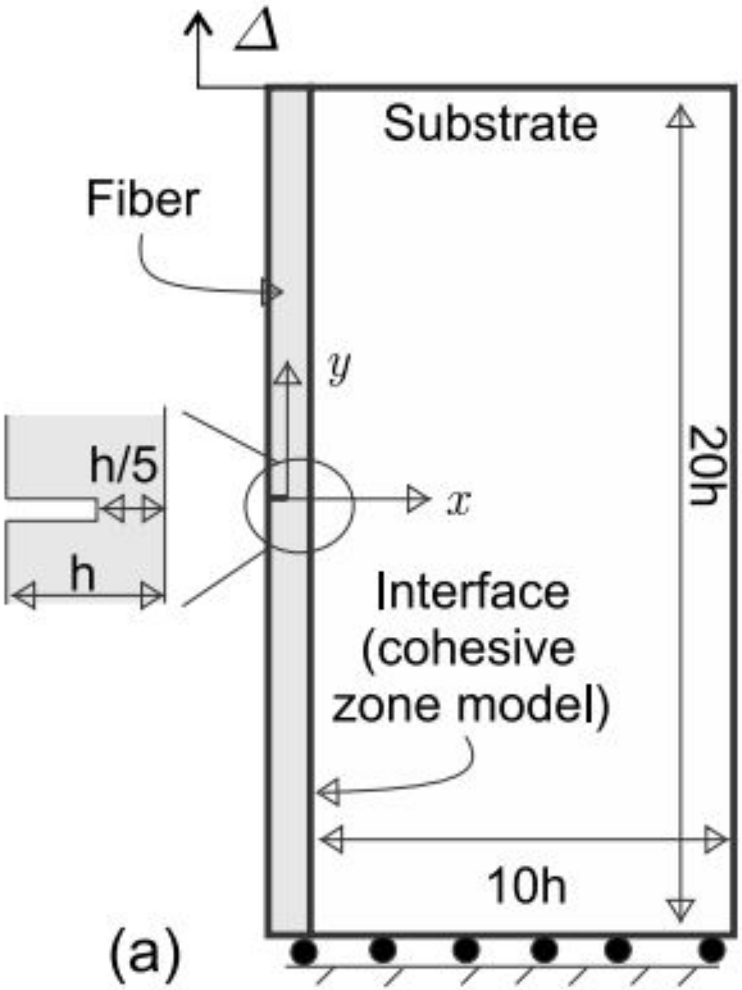


Crack nucleation governed by a critical stress (strength)

As a conclusion

Determining which of both criteria, strength vs. toughness, **describes the material resistance mechanism** can be challenging, as they may interact in complex ways and be influenced by various factors.

Interaction mechanisms between a propagating crack (brittle solids) and an interface



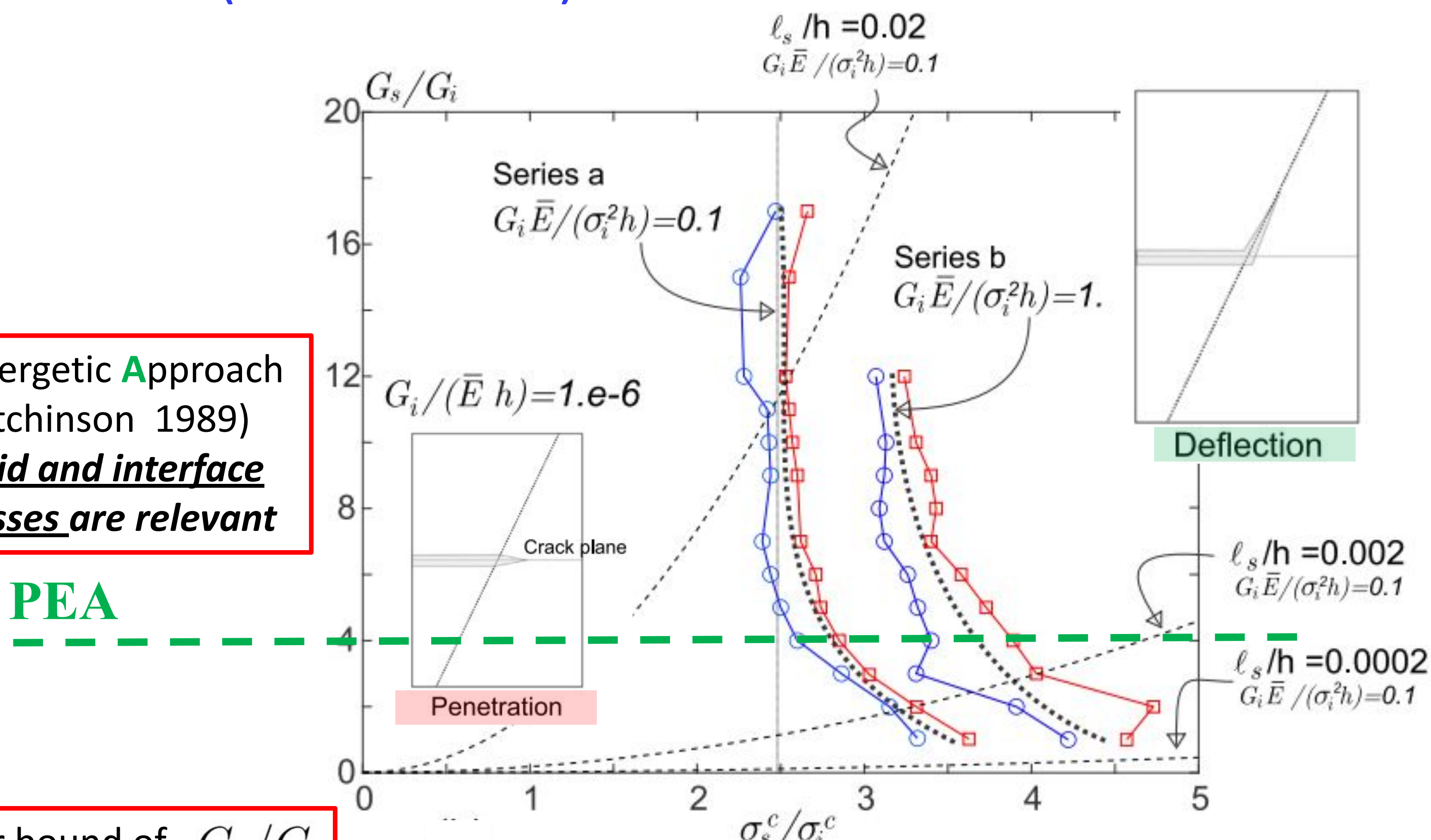
Parametric study of the interaction mechanism
Penetration vs. deflection

Fiber = Substrate

Relevant parameters:

- Bulk toughness G_s
- Interface toughness G_i
- Bulk critical stress σ_s^c,
- Interface critical stress σ_i^c

Interaction mechanisms between a propagating crack (brittle solids) and an interface



Purely **E**nergetic **A**pproach
(He-Hutchinson 1989)
Only solid and interface toughnesses are relevant

No lower bound of G_s/G_i guarantees penetration.

There is a lower bound σ_s^c/σ_i^c guaranteeing penetration.

Further analysis of extrinsic toughening (crack-tip shielding)

Bulk toughness G_s
Interface toughness G_i

Bulk critical stress σ_s^c,
Interface critical stress σ_i^c

Applied load for crack propagation

Stress intensity factor

$$K_I = 1.197\sigma_0\sqrt{\pi h}$$

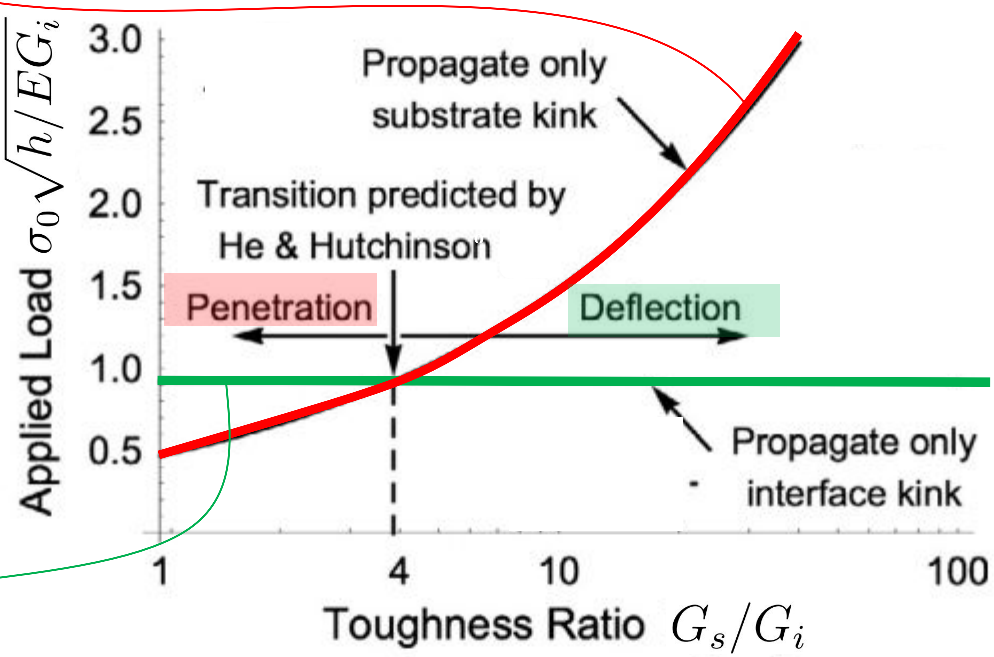
$$K_{Ic} = \sqrt{EG_c}$$

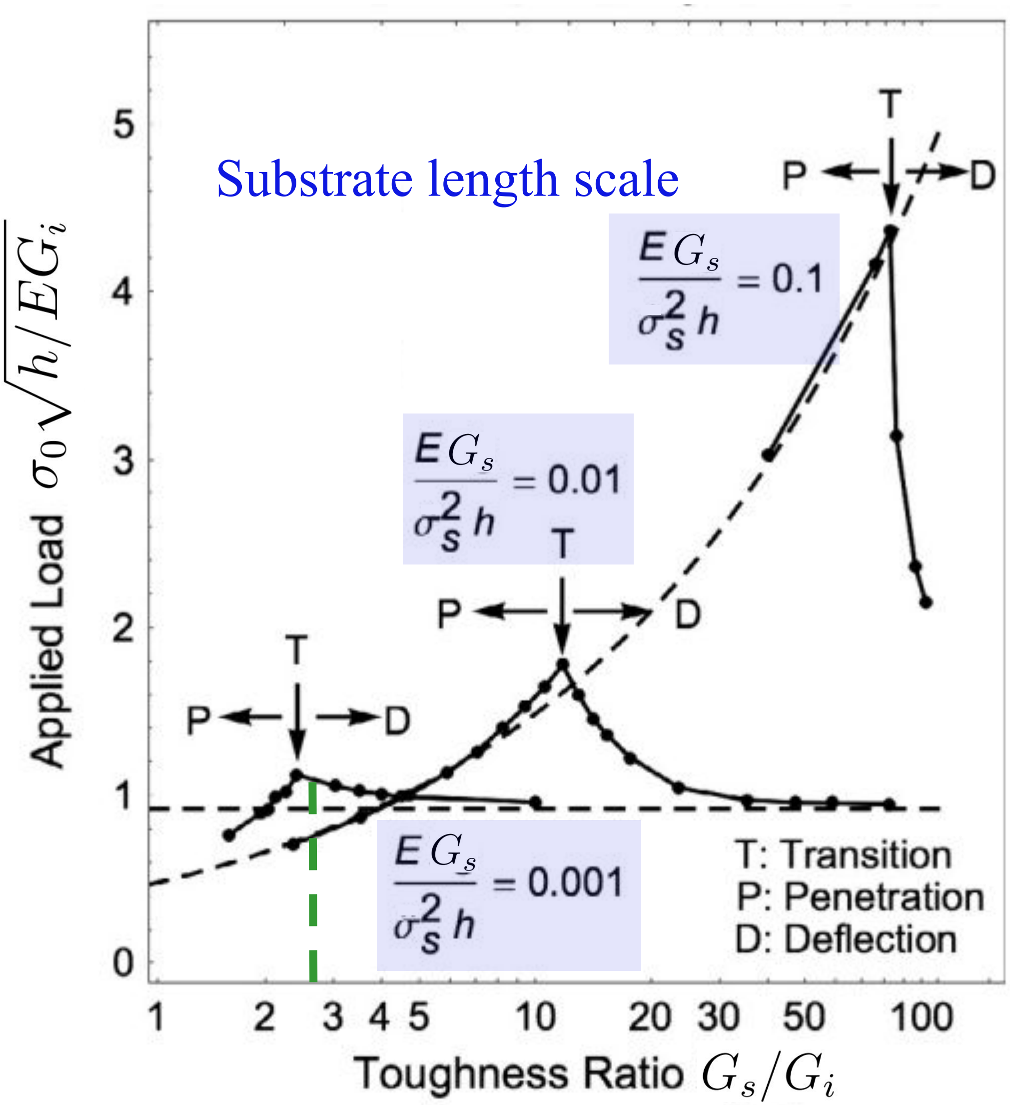
$$\sigma_0\sqrt{\frac{h}{EG_i}} = \frac{1}{1.197\sqrt{\pi}}\sqrt{\frac{G_s}{G_i}}$$

Applied load for crack deflection

$$\sigma_0\sqrt{\frac{h}{EG_i}} = 0.923$$

PEA He-Hutchinson 1989





Strom and Parmigiani, Eng.Fracture Mech. 2014

Bulk toughness	G_s
Interface toughness	G_i

Bulk critical stress	σ_s ,
Interface critical stress	σ_i

Interface length scale is hold constant $\frac{E G_i}{\sigma_i^2 h} = 0.01$

Bulk toughness is hold constant $\frac{G_s}{E h} = 10^{-6}$

Numerical modeling of interaction mechanisms

Cohesive Zone Model

(Parmigiani et al. 2007)

Interface elements (IE) with a CZM

Parameters defining the CZM: (G_i ; σ_i^c)

Kink-out

A drawback of using an IE methodology is that the crack propagates in a zig-zag (following the interface elements). **The angle of the crack which kinks out the interface is determined by the mesh.**

Kinking of a crack out of an interface

An alternative solution: Phase Field Model

Phase Field model coupled with interface models (CZM)

(Zambrano et al. 2022)

<u>Main features</u>

Assumed as a material parameter

Bulk modeled with a phase field approach (G_s , ℓ_s); → $\sigma_s^c = \xi \sqrt{\frac{G_s E}{\ell_s}}$

Interface modeled with a CZM (G_i , σ_i^c) → $\ell_i = 0.53 \frac{E_i G_i}{(\sigma_i^c)^2}$

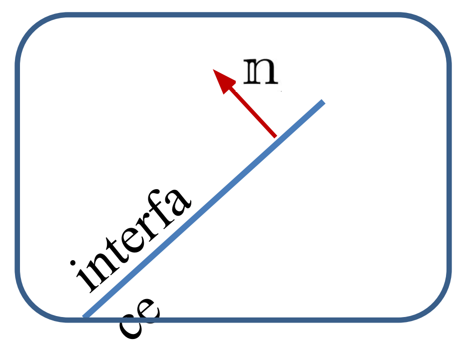
φ : phase field

$\xi = G_s \ell_s \nabla \varphi$: microforce

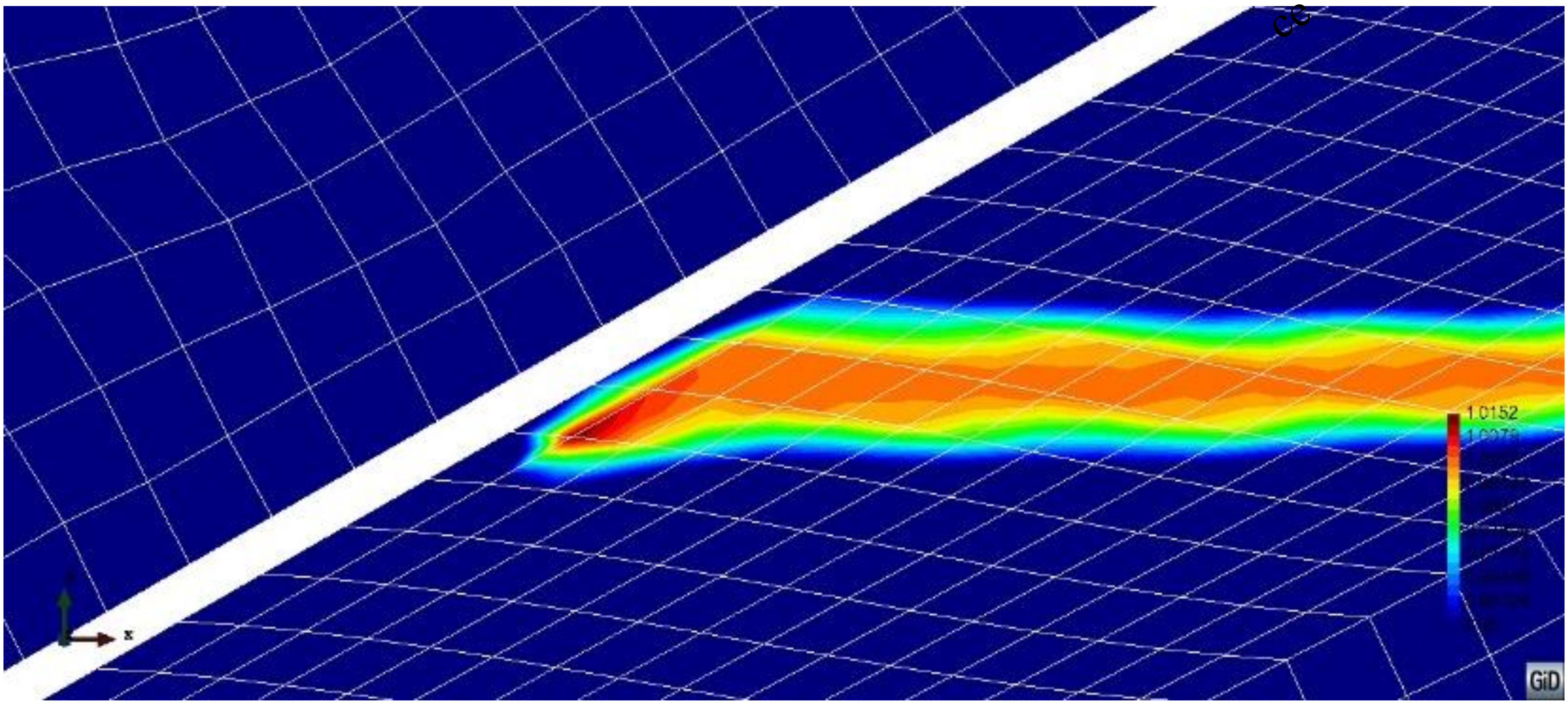
Continuity conditions across the interface

$$[\![\xi \cdot \mathbb{n}]\!] = 0$$

$$[\![\varphi]\!] = 0$$



Kinking of a crack out of an interface



Conclusions

Phase field models may handle problems with crack nucleation based on strength or toughness criterion. To achieve accurate predictions, it is essential to **enhance the model with a critical stress parameter** that can be associated with the order parameter of the phase field model.

This approach has been assumed by several authors (Tanné, Li, Bourdin, J.J. Marigo, and C. Maurini. Crack nucleation in variational phase-field models of brittle fracture. *J.Mech. Phys. Solids*, 2018)

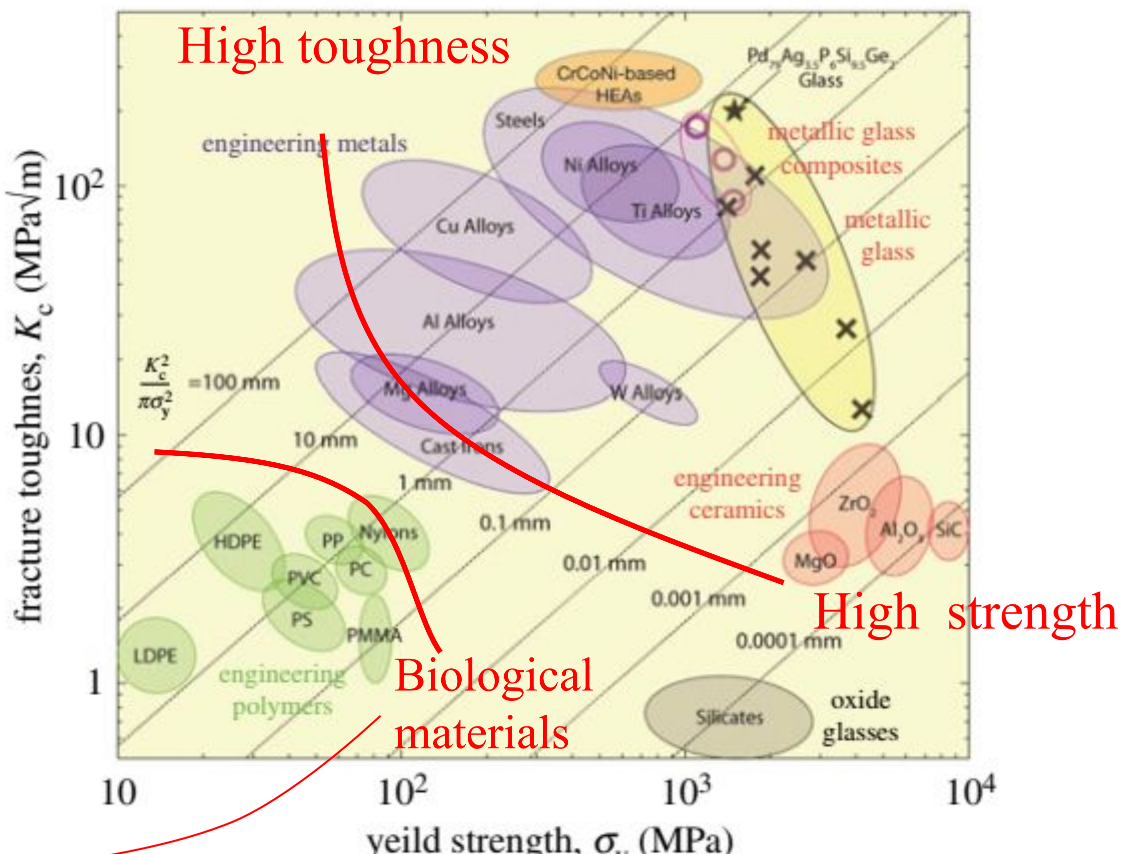
Possible further development of PFM for fracture resistance assessment (**including SCC problems**)

Additional crack nucleation issues (multiple material failure strength criteria) can be incorporated through **new degradation functions and driving force terms** (Kumar A, Bourdin B, Francfort GA, Lopez-Pamies O. Revisiting nucleation in the phase-field approach to brittle fracture. J.Mech. Phys. Solids, 2020)

a subtle difference with the original contribution of Bourdin, Francfort and Marigo

→ **Formulation based on the Euler Lagrange equations of the PFM**

Conflict between **toughness and strength**



Hierarchichal structures: develop different toughening mechanisms at different length scales