SiliconPV 2013
3rd International Conference on Crystalline Silicon Photovoltaics
Advanced technologies and materials for crystalline Si solar cells and modules
March 25-27, 2013 · Hamelin, Germany

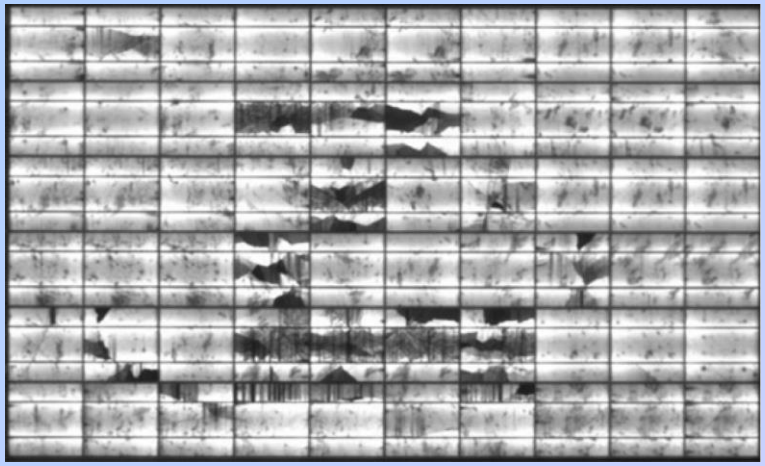
Numerical modelling of microcracking in PV modules induced by thermo-mechanical loads

Marco Paggi, Alberto Sapora

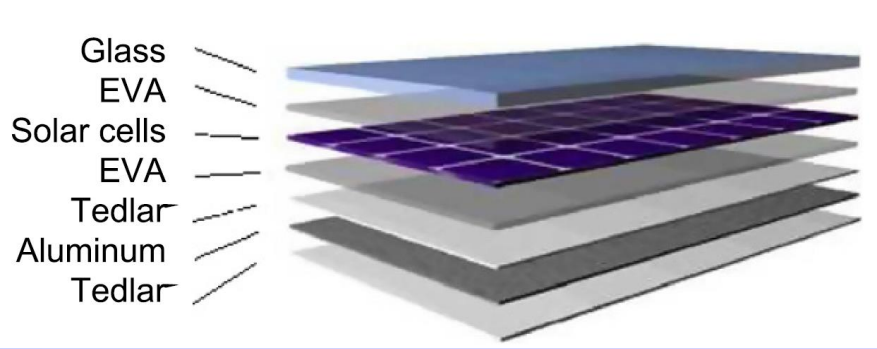
Department of Structural, Geotechnical and Building Engineering
Politecnico di Torino, Italy

Outline

- **A multi-physics and multi-scale computational approach**
- **Micro-cracking in polycrystalline Silicon cells**
- **A thermo-mechanical nonlinear fracture mechanics model**

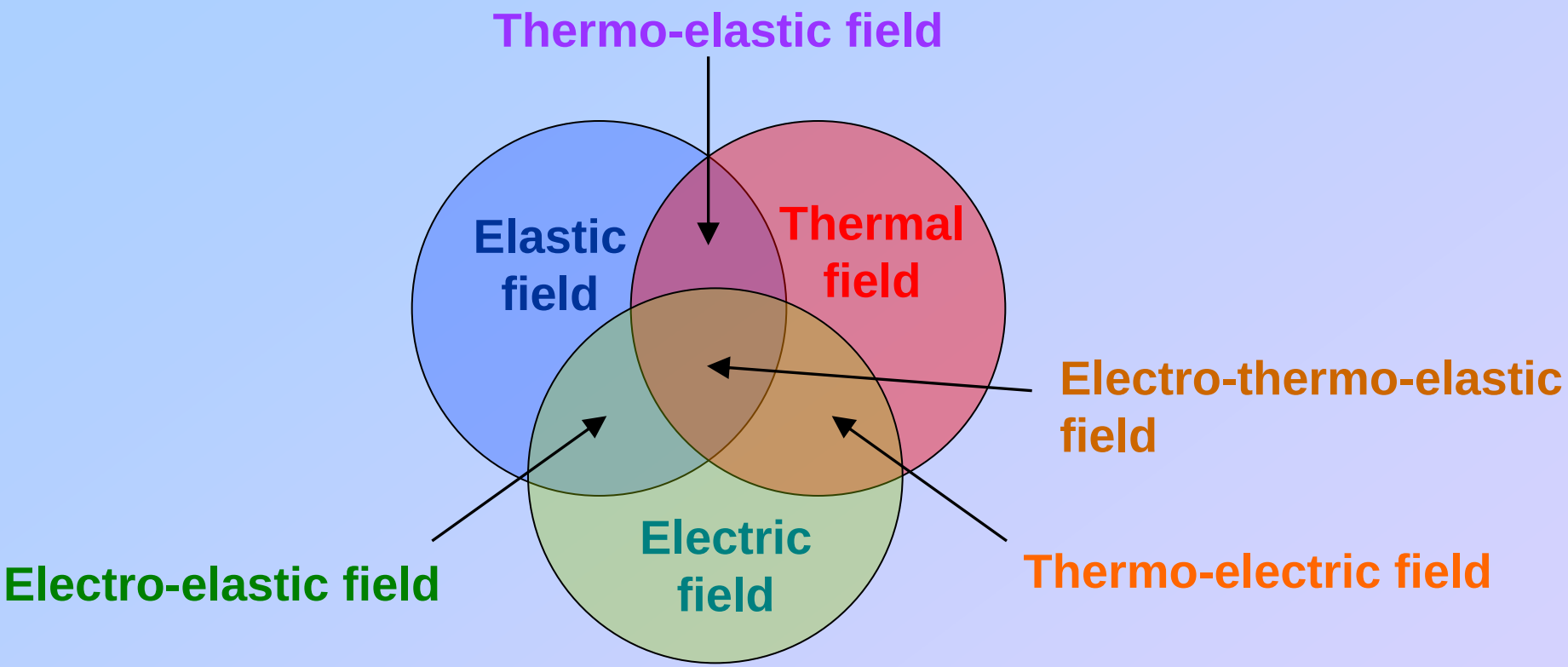


Kajari-Schröder et al., 2011
Köntges et al., 2011
Kajari-Schröder et al., 2012



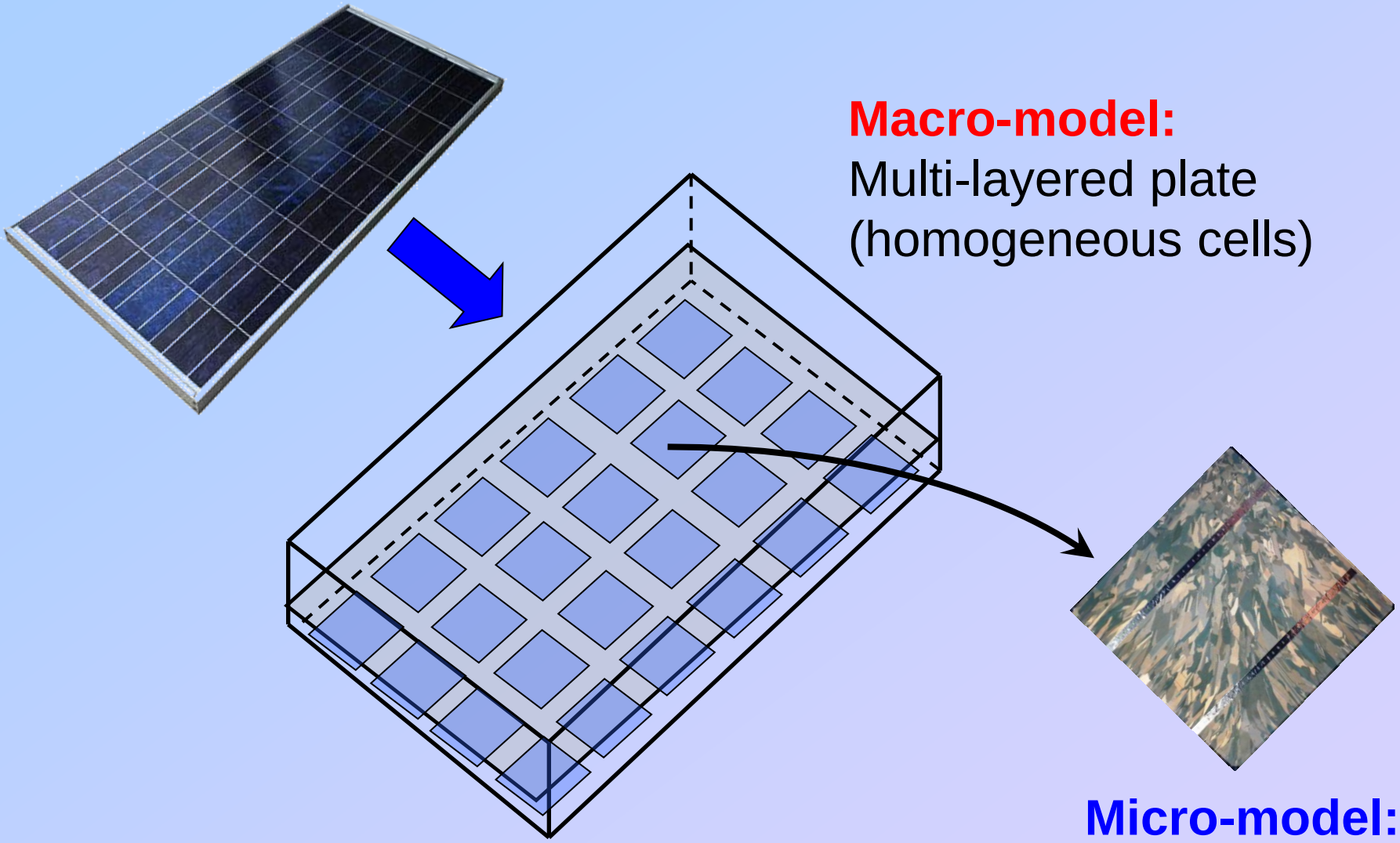
Paggi, Kajari-Schröder, Eitner, 2011

A multi-physics approach



- **Thermo-elastic field: coupling due to thermoelasticity**
- **Thermo-electric field: coupling in the Schrödinger equation**
- **Electro-elastic field: coupling due to microcracks**

A multi-scale solution strategy



Macro-model:
Multi-layered plate
(homogeneous cells)

Micro-model:
Polycrystalline Si cells
with grain boundaries

Paggi et al., Comp. Struct., 2013

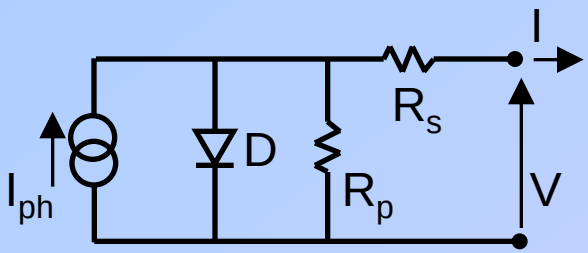
A multiscale-multiphysics finite element model

Macro-model of the PV panel:

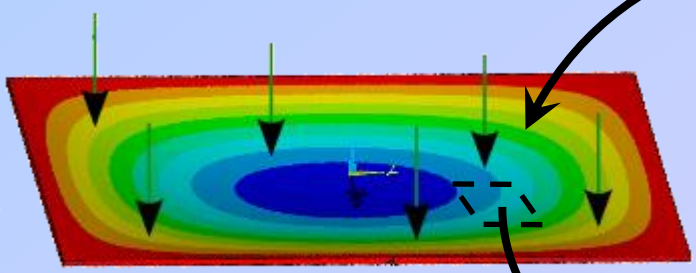
- Multi-layered plate
- Compute displacements
- Compute power-loss

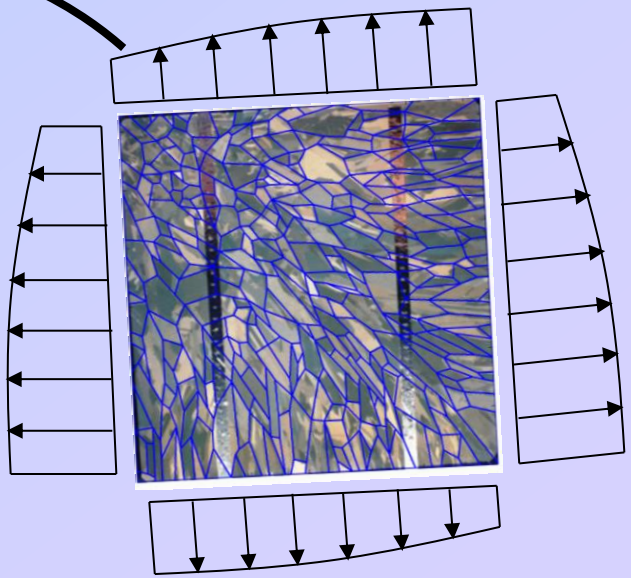
Micro-model of the Si cell:

- Heterogeneous with interfaces
- Micro-cracks
- Compute inactive area
- Update cell stiffness



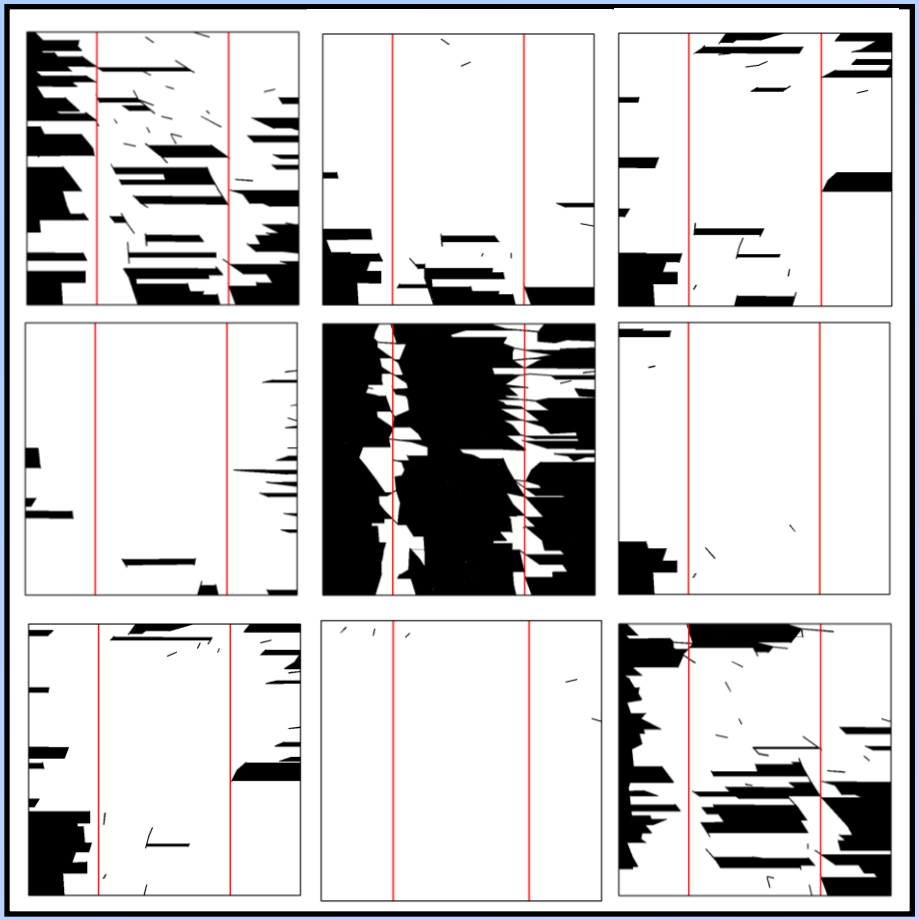
Updated stiffness,
thermal properties,
inactive cell area

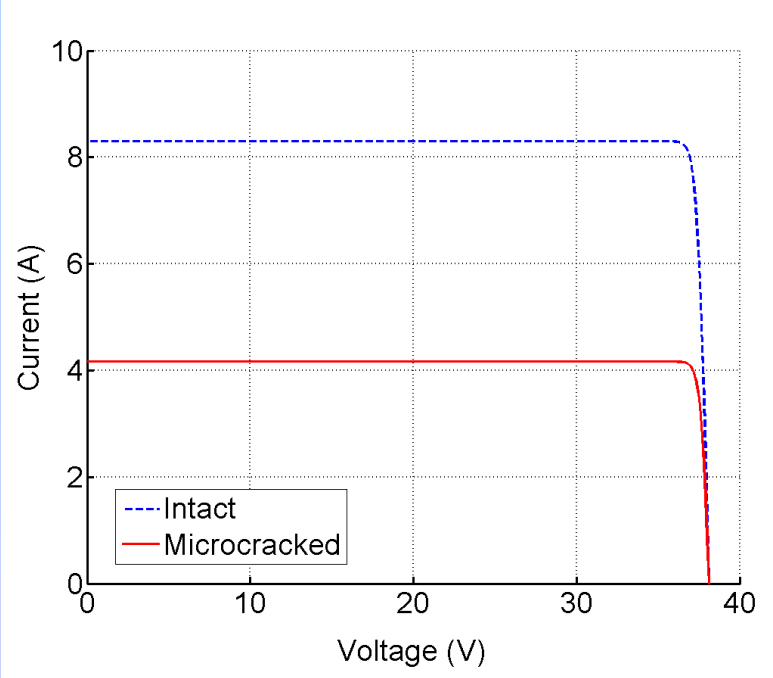




Displacement BCs,
thermal field

Electrically inactive cell areas: numerical results





Paggi et al., 2013

Open issues:

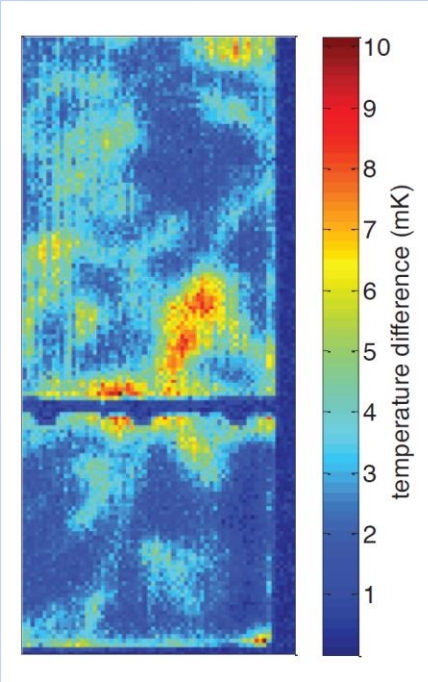
- **Limit case scenario of perfectly insulated cracks**
- **Model parameter identification**

Effect of cracking on the thermal field

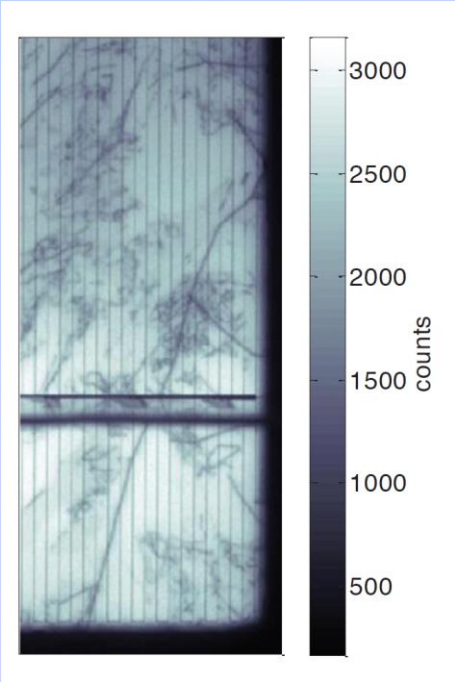
In-situ thermal image

Munoz et al., 2011

Dark lock-in thermography



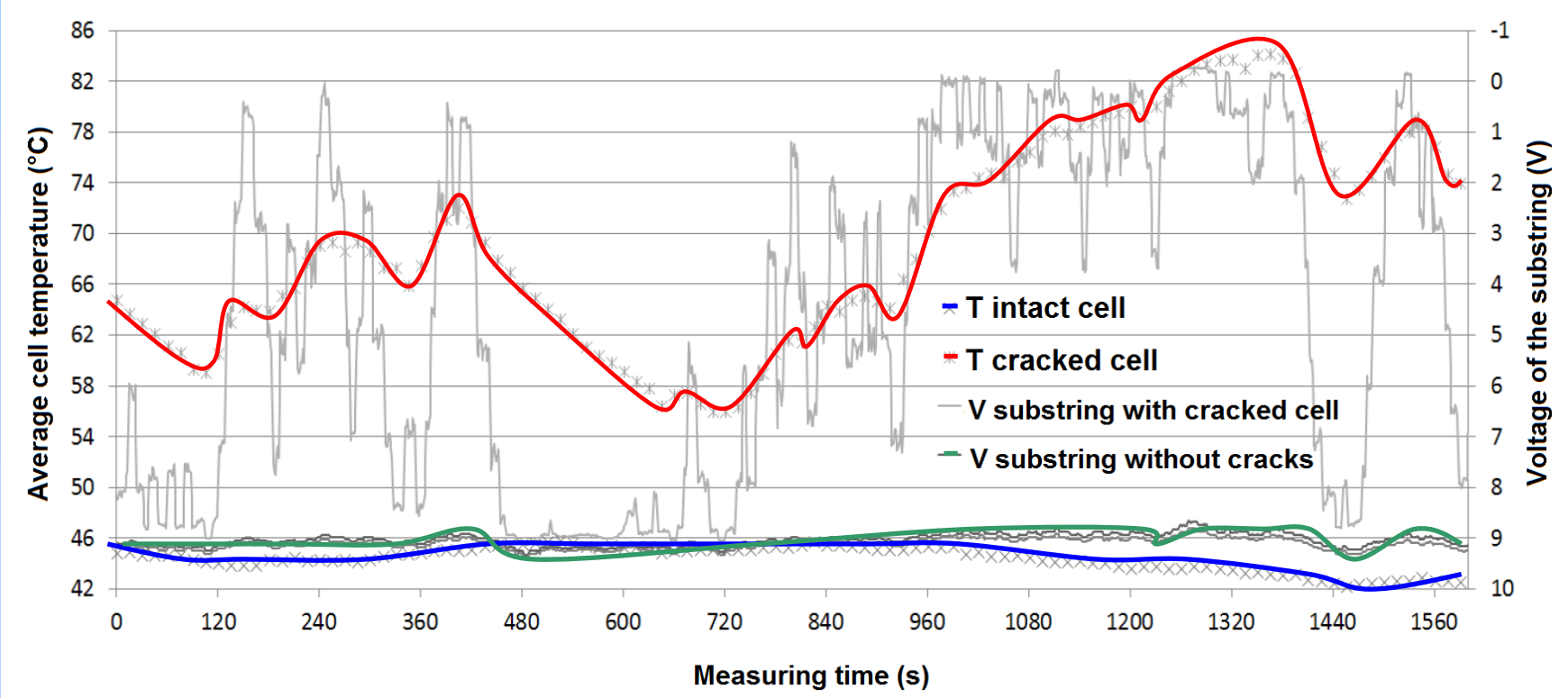
EL image

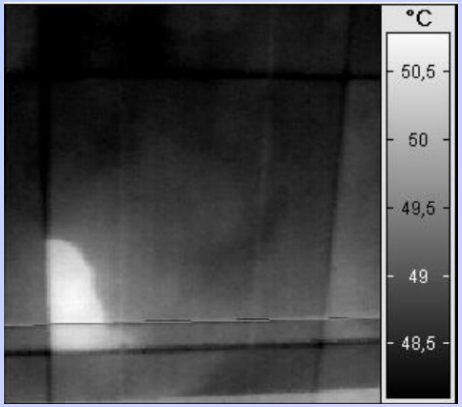


van Mölken et al., 2012

- **High temperature near cracks (additional thermal resistance)**
- **Cracks are source of ricombination effects**

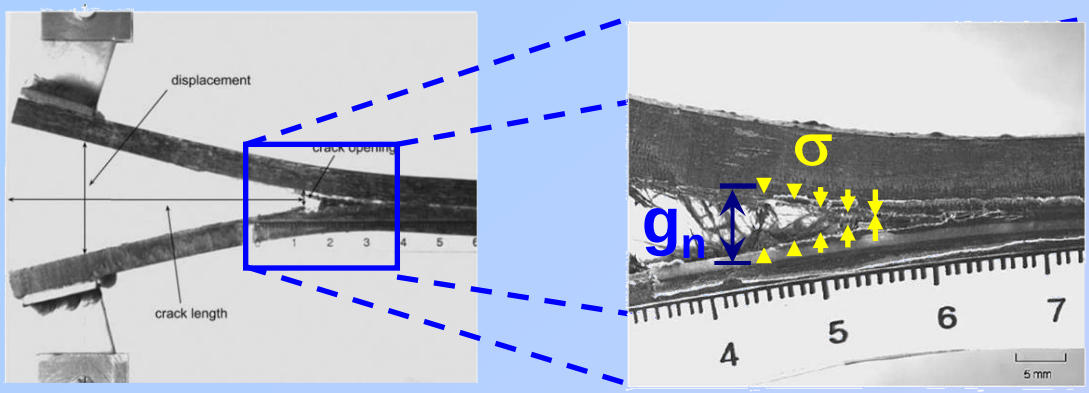
Interaction between thermal and elastic fields



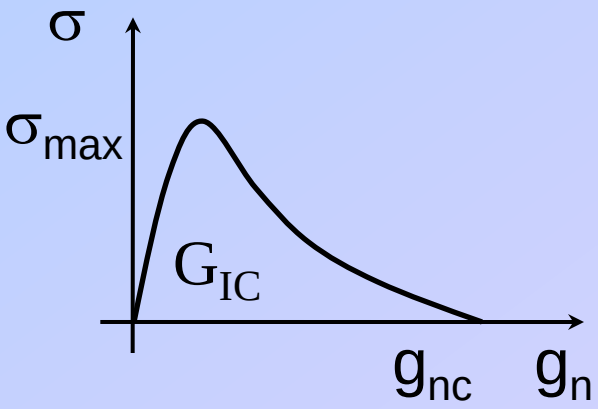


Weinreich et al., 2011

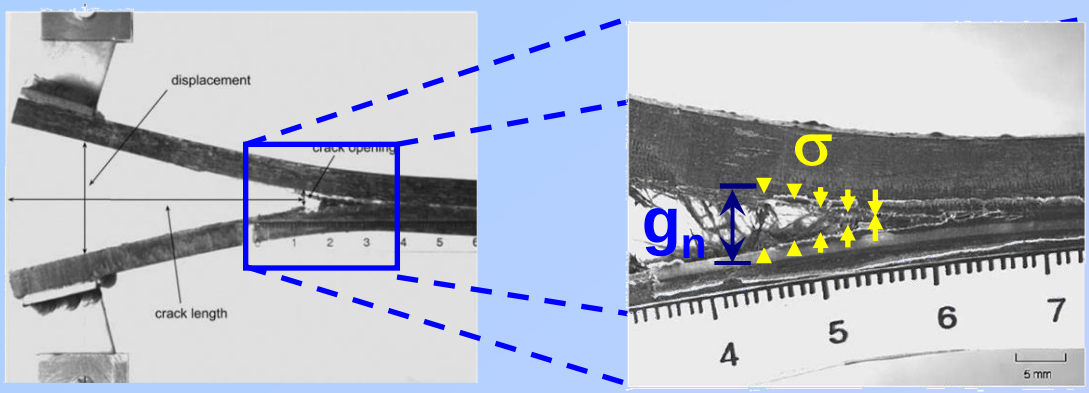
A thermo-mechanical cohesive zone model



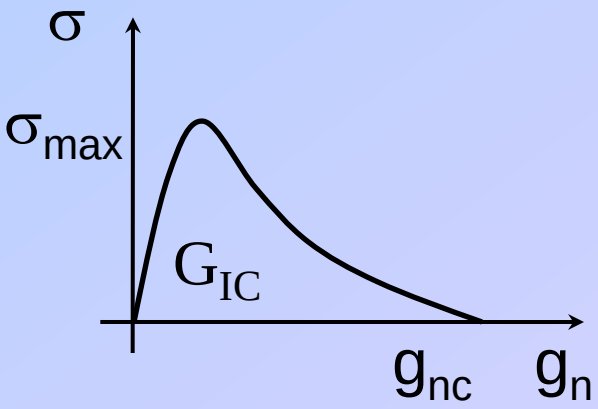
$\sigma = \sigma(g_n)$

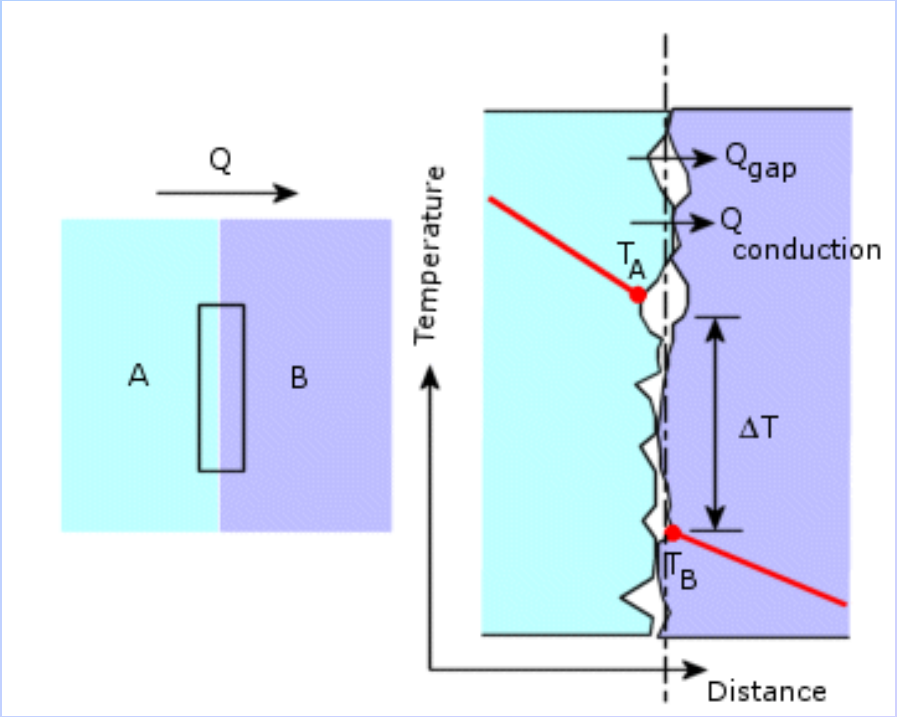


A thermo-mechanical cohesive zone model

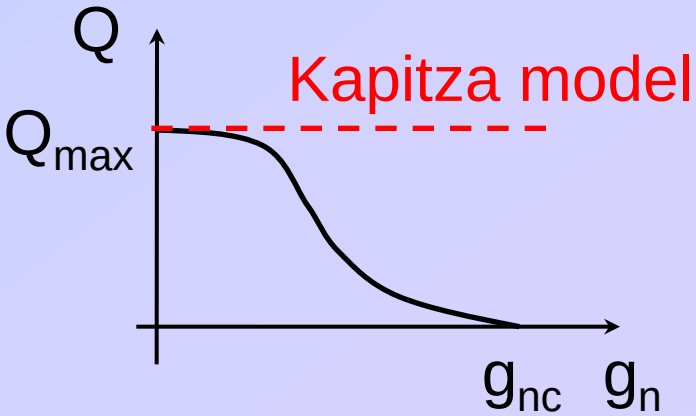


$$\sigma = \sigma(g_n)$$

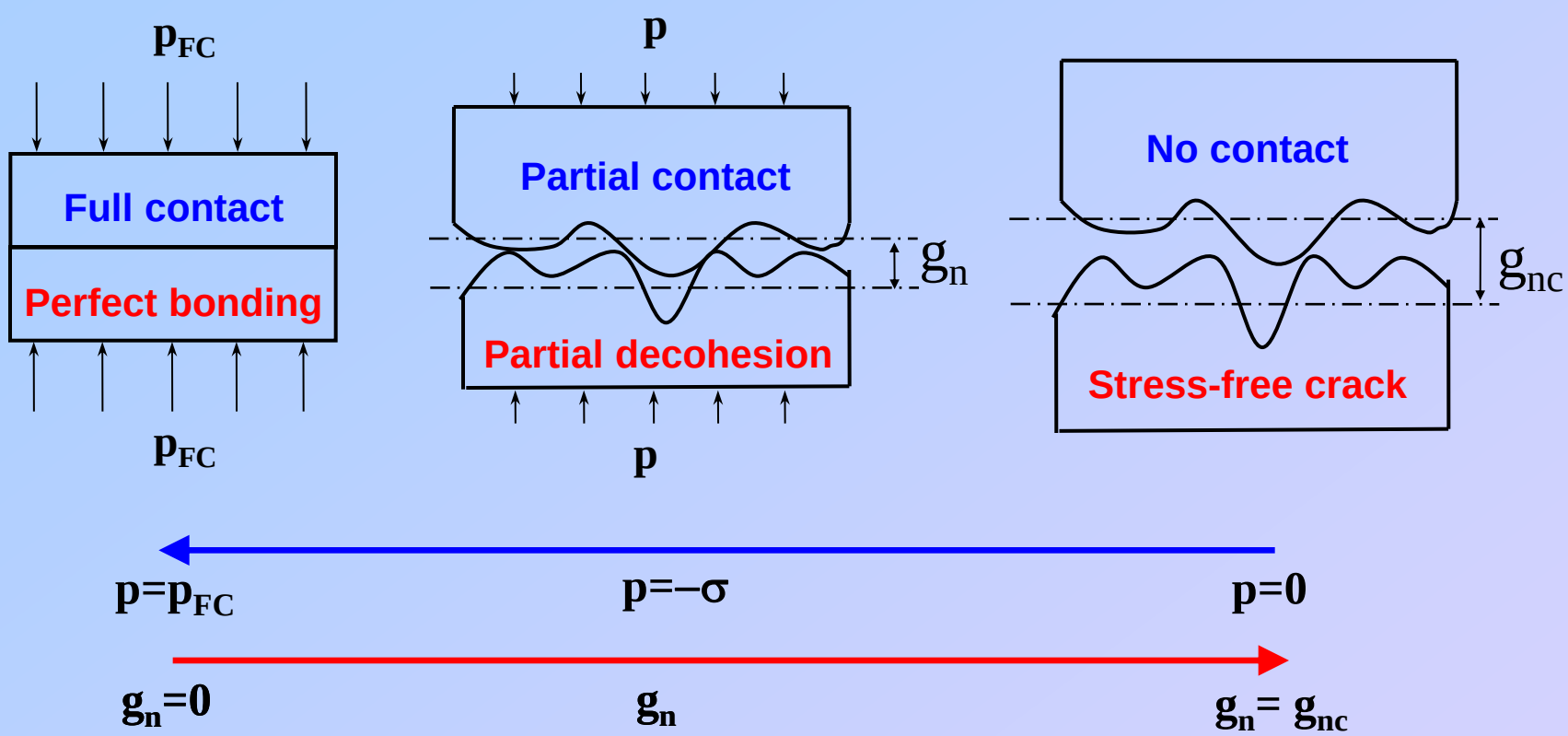




$$Q = -k_{int}(g_n)\,\Delta T$$



Analogy between fracture and contact mechanics

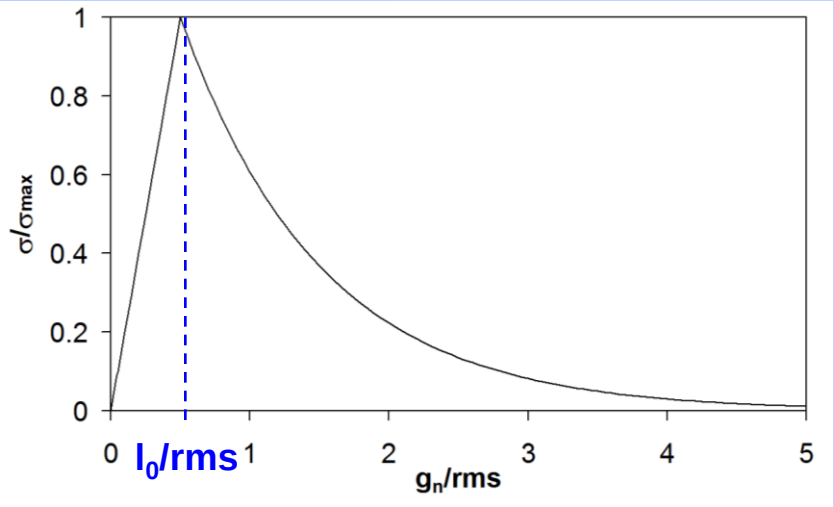


Hypotheses:

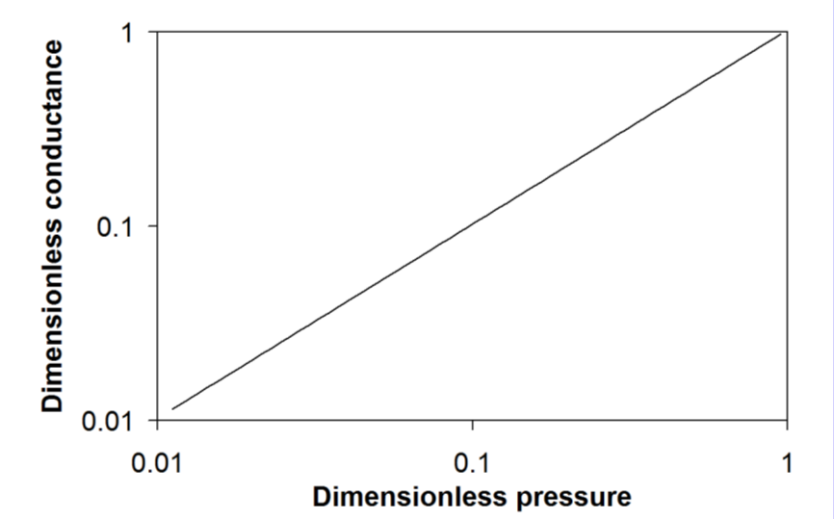
- Estimate cohesive tractions from a micromechanical contact model (Greenwood & Williamson, 1966)
- Interface conductance proportional to the normal stiffness (Paggi & Barber, 2011)

A thermo-mechanical cohesive zone model

$$\sigma = \begin{cases} \sigma_{\max} \exp\left(\dfrac{-l_0 - g_t}{rms}\right)\dfrac{g_n}{l_0}, & 0 \le \dfrac{g_n}{rms} < \dfrac{l_0}{rms} \\ \sigma_{\max} \exp\left(\dfrac{-g_t - g_n}{rms}\right), & \dfrac{l_0}{rms} \le \dfrac{g_n}{rms} < \dfrac{g_{nc}}{rms} \\ 0, & \dfrac{g_n}{rms} \ge \dfrac{g_{nc}}{rms} \end{cases}$$



$$k_{\text{int}} = \begin{cases} \dfrac{1}{\rho_{\text{int}}}, & 0 \le \dfrac{g_n}{rms} < \dfrac{l_0}{rms} \\ \dfrac{2\sigma}{\rho_{\text{int}} E_{\text{int}}\, rms}, & \dfrac{l_0}{rms} \le \dfrac{g_n}{rms} < \dfrac{g_{nc}}{rms} \\ 0, & \dfrac{g_n}{rms} \ge \dfrac{g_{nc}}{rms} \end{cases}$$



Model parameters: l_0, rms, σ_{max} + (ρ_{int}, E_{int})

Weak form of the problem and solution scheme

$$\int_V \boldsymbol{\sigma}^T (\nabla \delta \mathbf{u}) \mathrm{d}V = \int_V \mathbf{f}^T (\delta \mathbf{u}) \mathrm{d}V + \int_{\partial V} \bar{\sigma}^T (\delta \mathbf{u}) \mathrm{dS} + \int_S \mathbf{t}^T (\delta \mathbf{g}) \mathrm{dS}$$

$$\int_V \mathbf{q}^T (\nabla \delta T) \mathrm{d}V = \int_V \rho_V c_V \dot{T} \delta T \, \mathrm{d}V + \int_{\partial V} \bar{q} \delta T \, \mathrm{d}S + \int_S q \delta g_T \, \mathrm{d}S$$

Cracks contribution

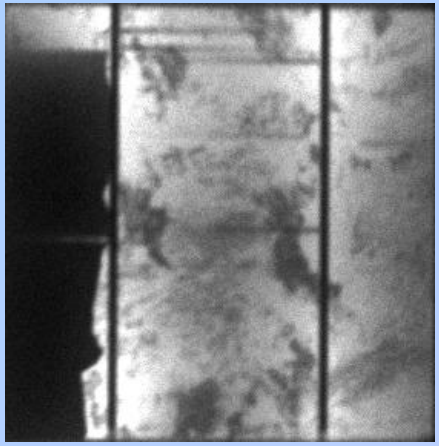
Staggered solution scheme:

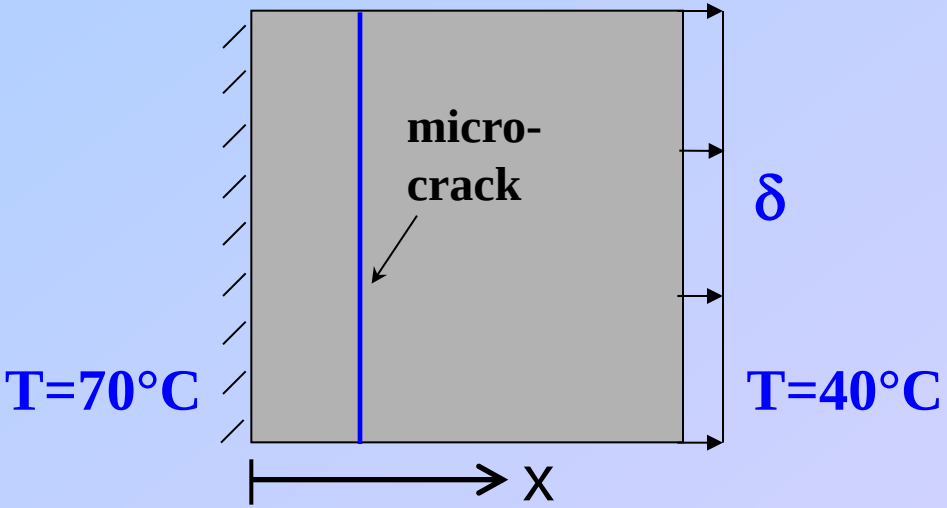
(1) SOLVE the thermal problem (freezing the elastic one)

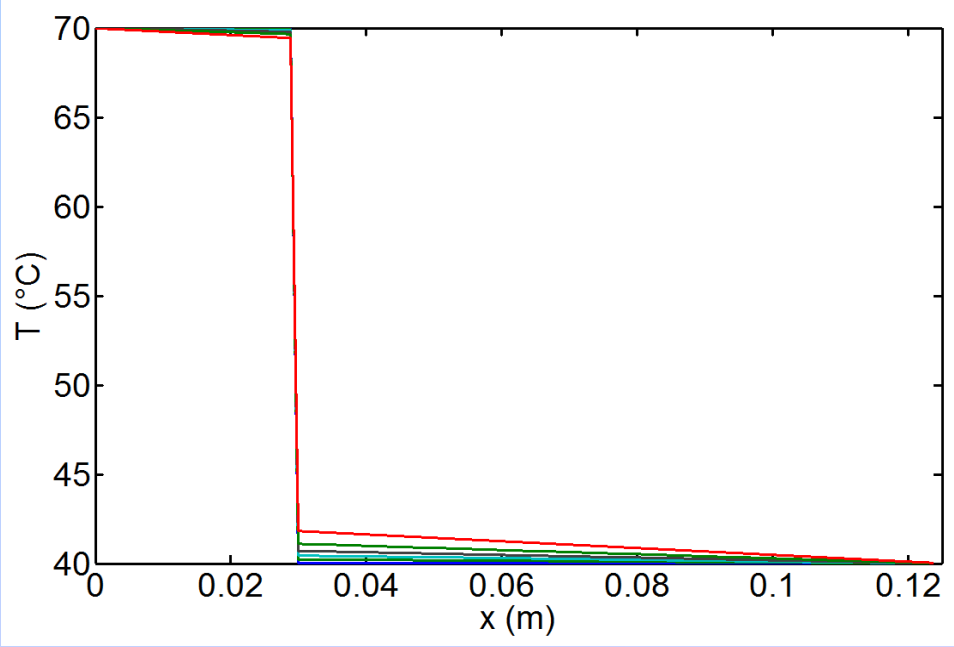
(2) SOLVE the thermo-elastic problem, determine crack opening and update the crack conductance

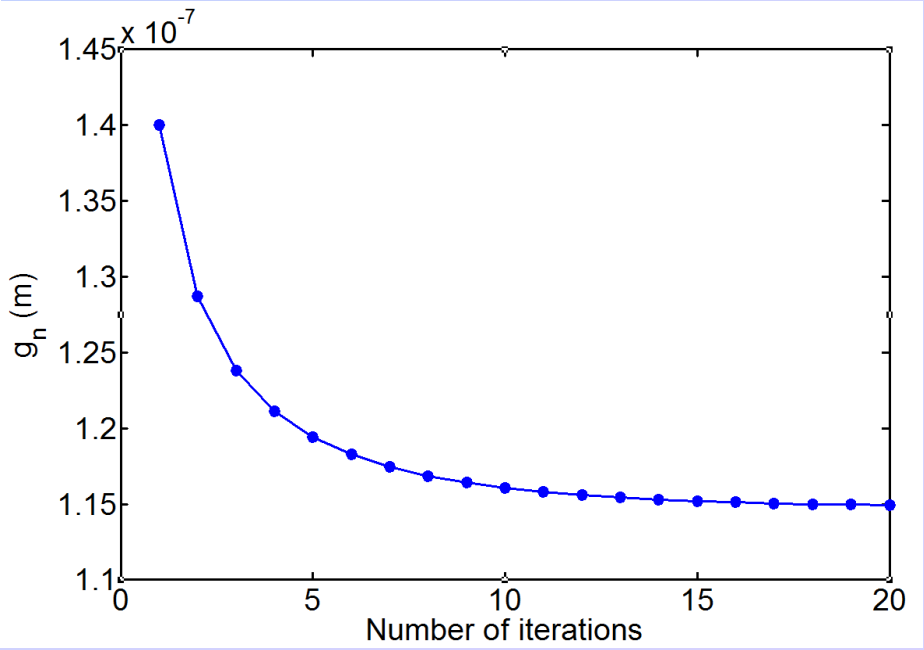
(3) ITERATE (1) and (2) until convergence

Numerical example









Conclusions and future developmens

- **A thermo-mechanical cohesive zone model for polycrystalline Silicon has been proposed**
- **Due to the analogy with contact mechanics, only 3 model parameters need to be identified by experiments**
- **Future developments will concern the coupling with the electric field and the experimental validation of the multiphysics computational approach**

Acknowledgements

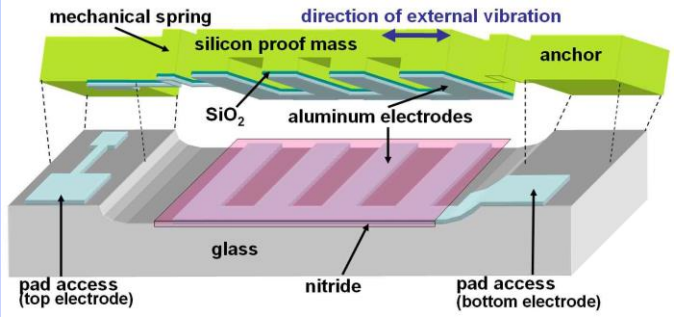
European Research Council
Supporting top researchers from anywhere in the world

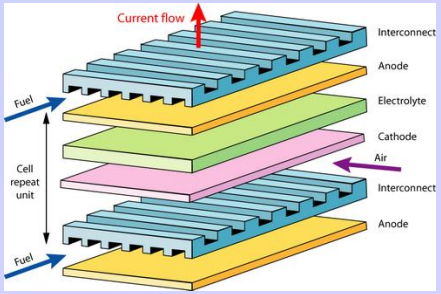
ERC Starting Grant IDEAS 2012

Multi-field and multi-scale Computational Approach to Design and Durability of PhotoVoltaic Modules

FIRB Future in Research 2010

Structural mechanics models for renewable energy applications





marco.paggi@polito.it