“Impact of mechanical and thermal loads on the long term stability of PV modules”
November 5, 2013, ISFH

An-Institut der Leibniz Universität Hannover

Modelling of cracking in PV modules: Physical aspects and computational methods

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In collaboration with:

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Motivations and tasks

Understand and avoid the phenomenon of cracking in PV modules using multi-scale and multi-physics computational methods

Paggi et al., Composite Struct. 2013

Tasks:

1. Develop nonlinear fracture mechanics models based on experimental evidence of cracking in solar cells

2. Simulate cracking due to thermo-mechanical loads by considering the whole PV module as a composite

3. Predict the electric response resulting from cracking, damage and impurities in solar cells

Outline

- **Part I: experimental evidence of thermo-electro-mechanical coupling**
- **Part II: constitutive modelling of cracks**
- **Part III: electric model for a defective cell**

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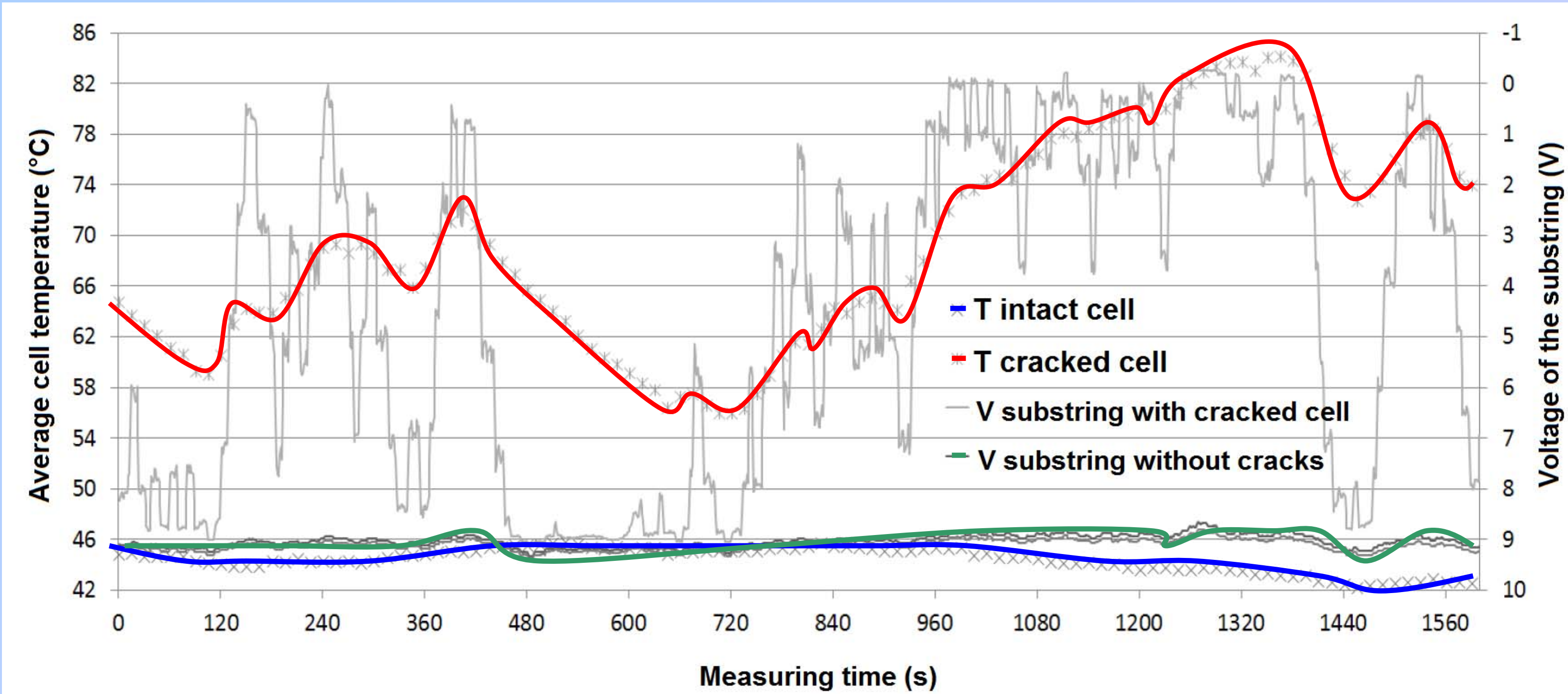
ERC Starting Grant IDEAS 2012
http://staff.polito.it/marco.paggi/CA2PVM.htm

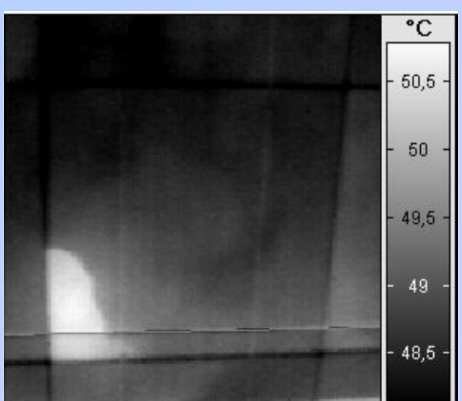
FUTURO IN RICERCA

FIRB Future in Research 2010
http://staff.polito.it/marco.paggi/FIRB.htm

Experimental evidence of thermo-electro-mechanical coupling and crack closure effects

Oscillating behaviour of cracked cells

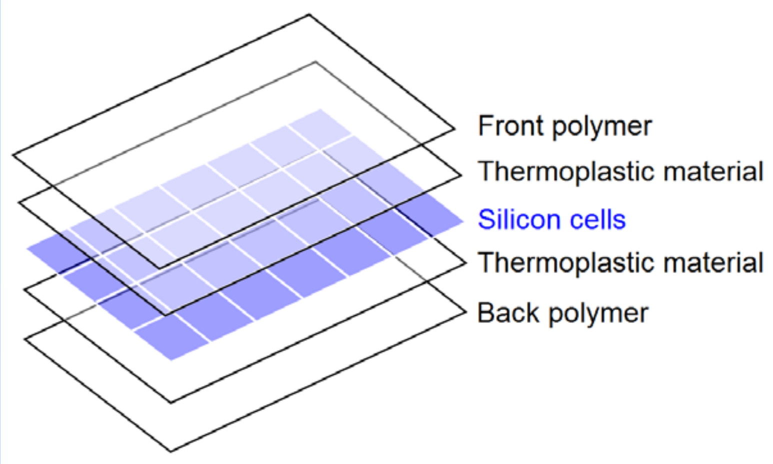




- Strong coupling between thermal and electric fields
- Self-healing of the cell due to thermoelastic deformation (crack closure & contact)?

Weinreich et al., 2011

A simple test on a “flexible” PV panel in bending



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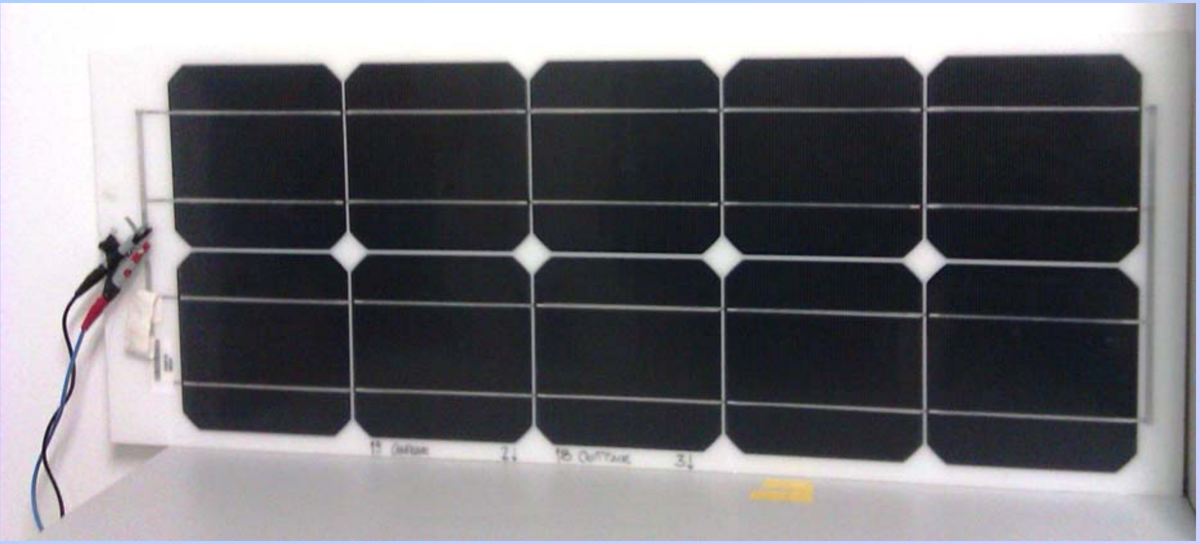
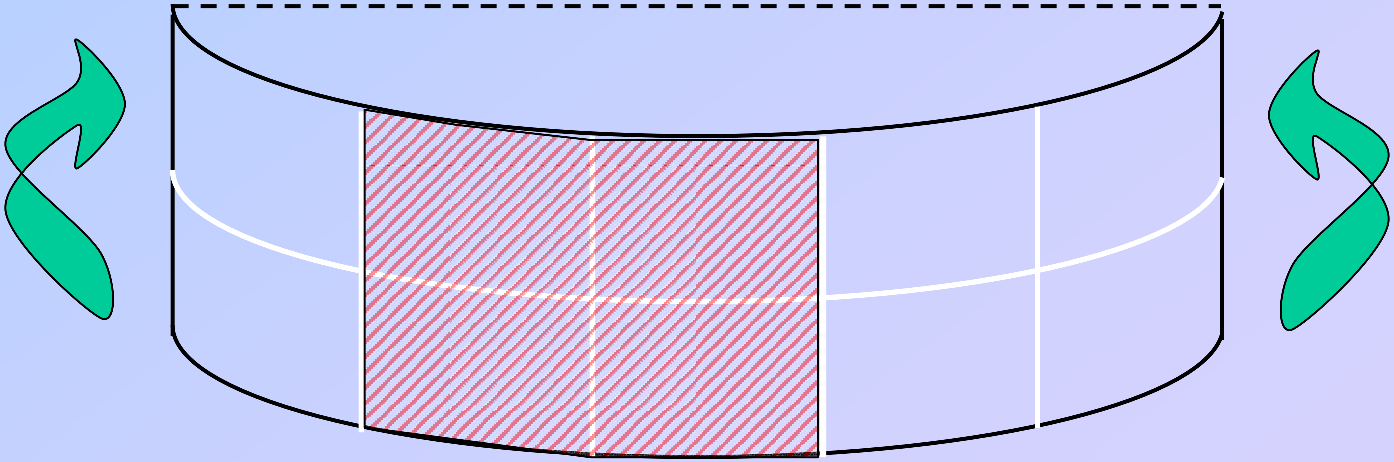
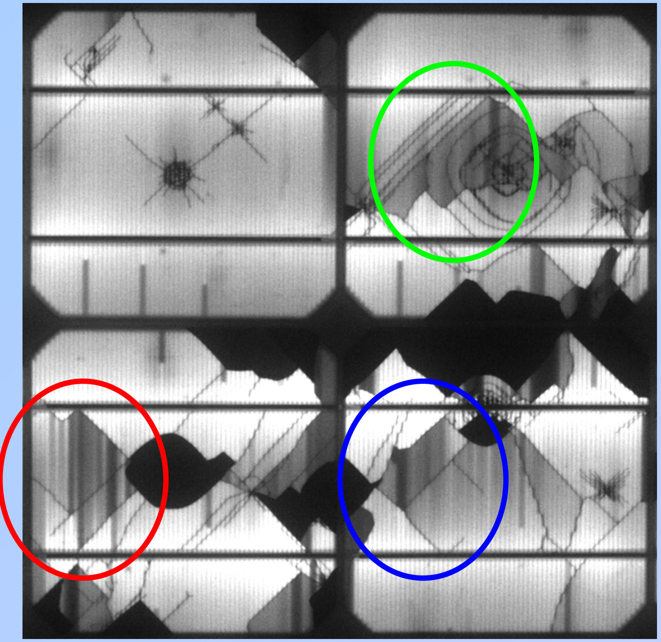
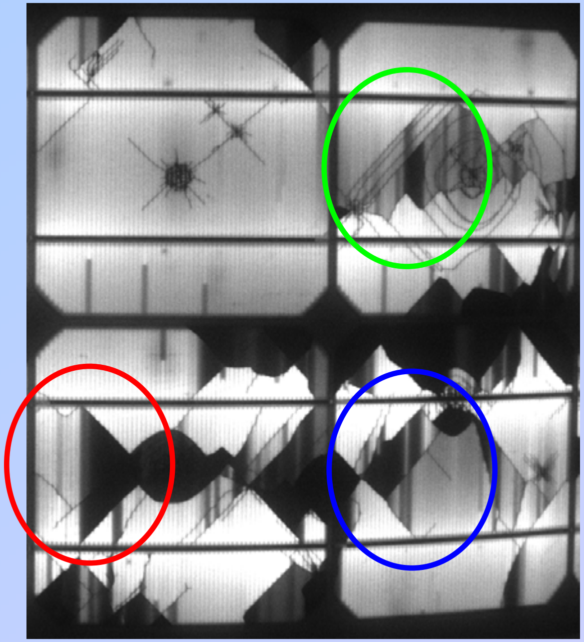
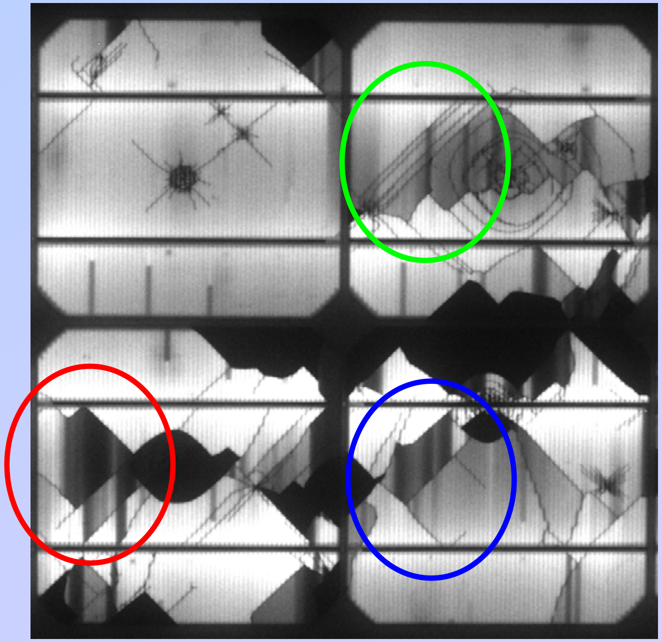




A simple test on a “flexible” PV panel in bending


Initial flat configuration


Max deflection


Final flat configuration

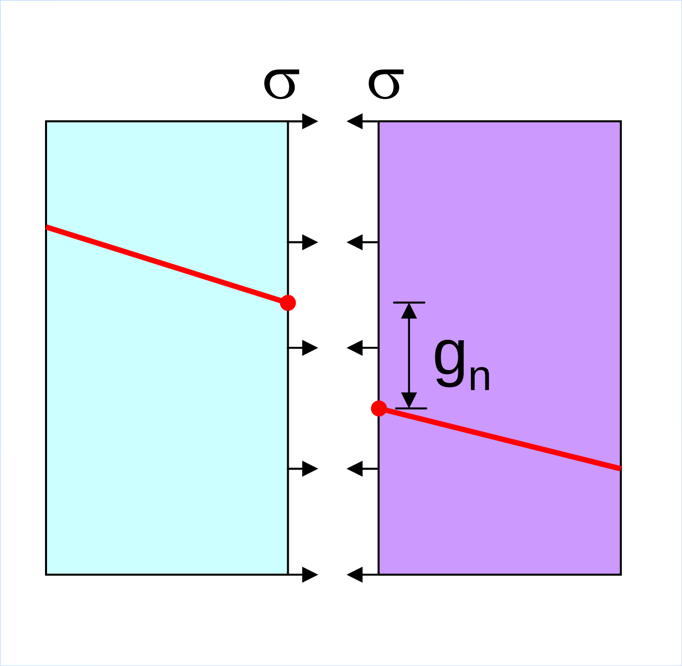
- **Some electrically inactive areas conduct again after unloading (self-healing due to crack closure & contact)**

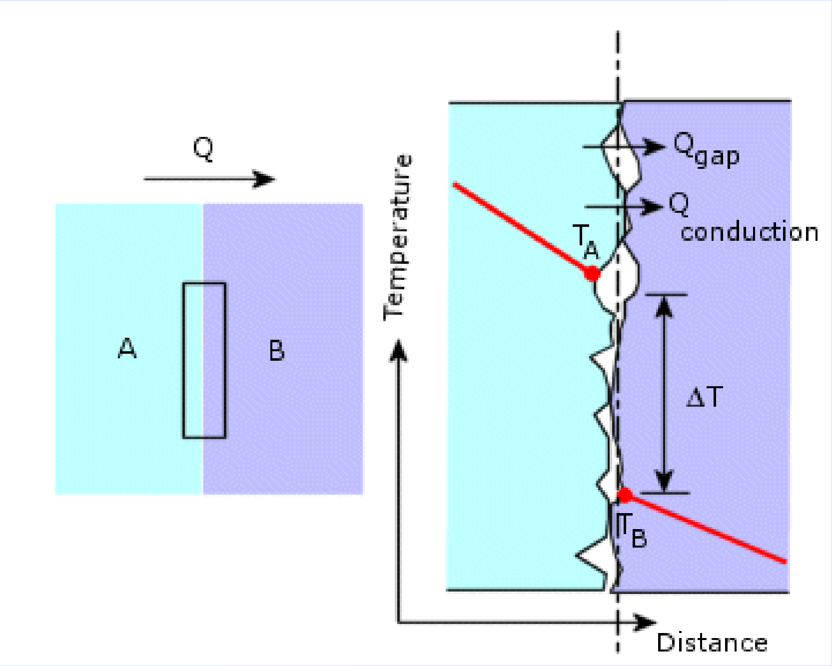
- **The amount of electrically inactive areas increases after the loading cycle (fatigue effects)**

Part II: constitutive modelling of cracks

A thermomechanical cohesive zone model based on an analogy between fracture and contact mechanics

Modelling of discrete cracks: thermoelastic CZM





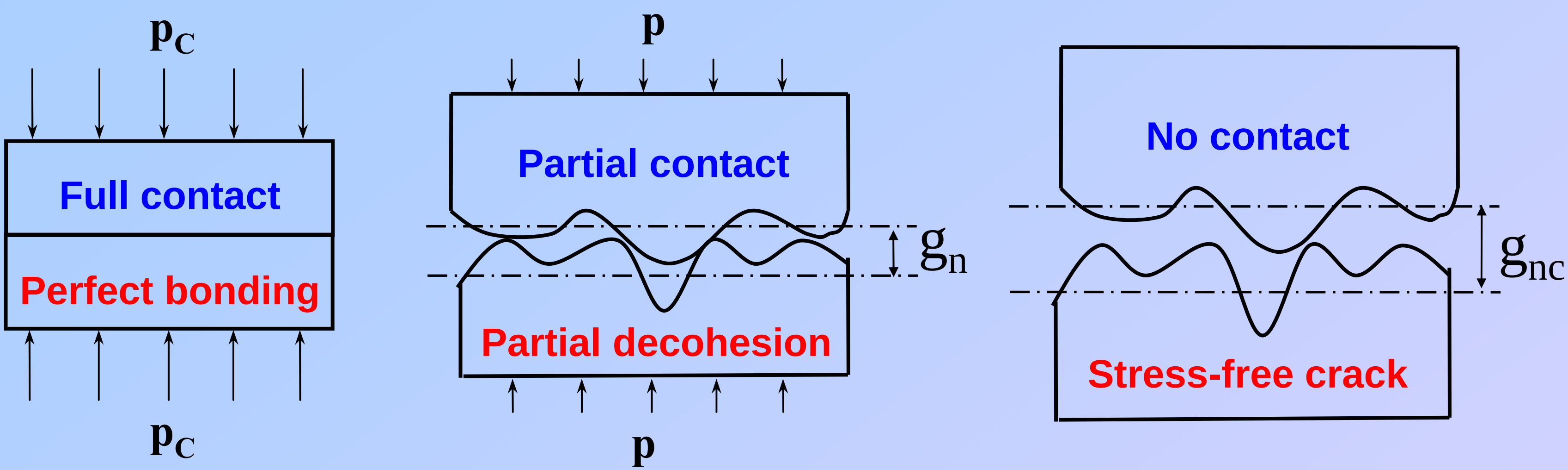
$\sigma = \sigma(g_n)$

$Q = Q(\Delta T, g_n)$

- **Cohesive tractions opposing to crack opening and sliding**
- **Thermal flux dependent on the temperature jump and on the crack opening**

Sapora and Paggi, Comp. Mech., 2013

Modelling of discrete cracks: thermoelastic CZM

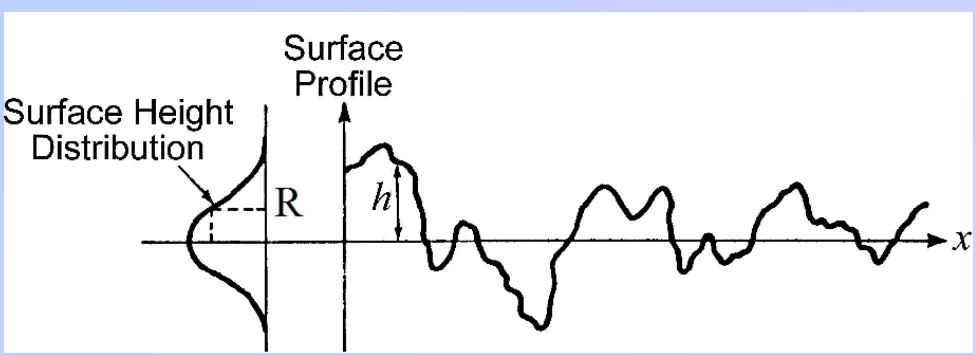


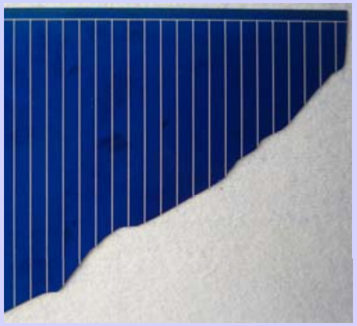
CONTACT

$p=p_C$ $p=-\sigma$ $p=0$

FRACTURE

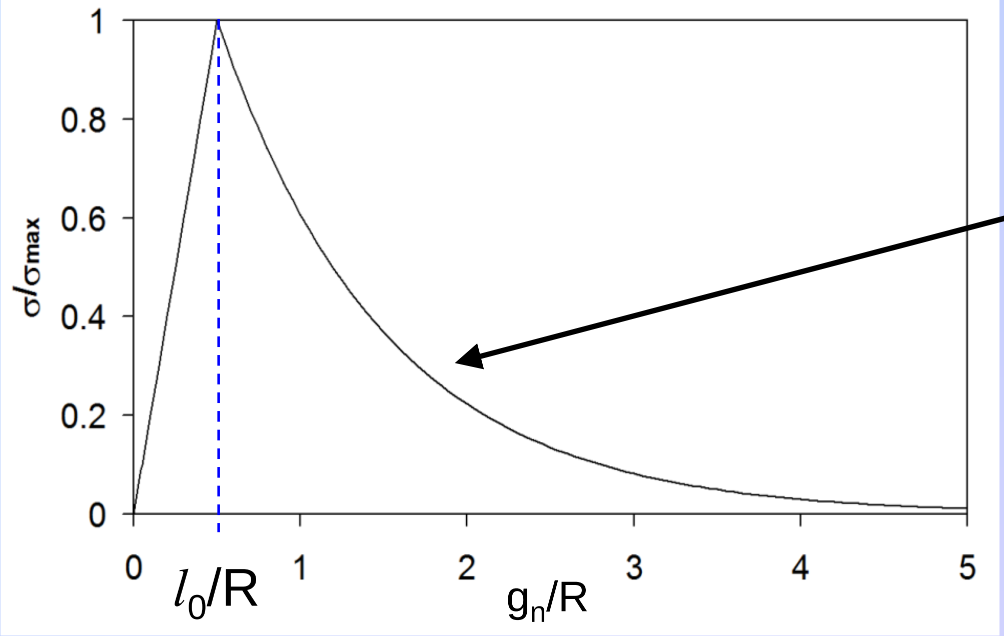
$g_n=0$ g_n $g_n= g_{nc}$





Modelling of discrete cracks: thermoelastic CZM

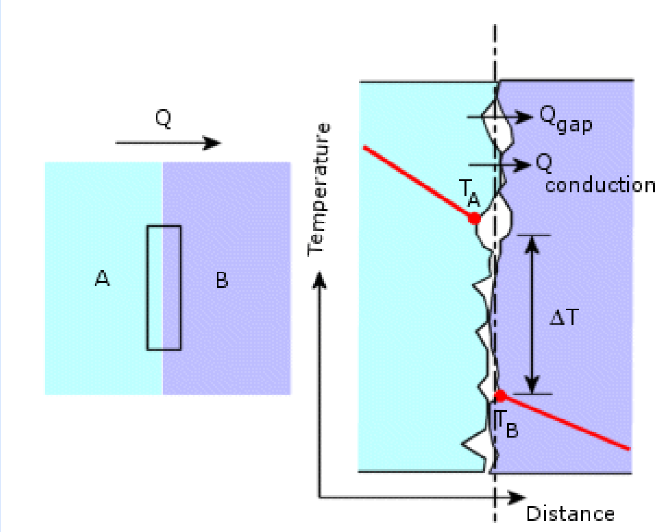
$$\sigma = \begin{cases} \sigma_{\max} \exp\left(\dfrac{-l_0 - |g_\mathrm{t}|}{R}\right) \dfrac{g_\mathrm{n}}{l_0}, & \text{if} \quad 0 \le \dfrac{g_\mathrm{n}}{R} < \dfrac{l_0}{R} \\ \sigma_{\max} \exp\left(\dfrac{-g_\mathrm{n} - |g_\mathrm{t}|}{R}\right), & \text{if} \quad \dfrac{l_0}{R} \le \dfrac{g_\mathrm{n}}{R} < \dfrac{g_\mathrm{nc}}{R} \\ 0, & \text{if} \quad \dfrac{g_\mathrm{n}}{R} \ge \dfrac{g_\mathrm{nc}}{R} \end{cases}$$

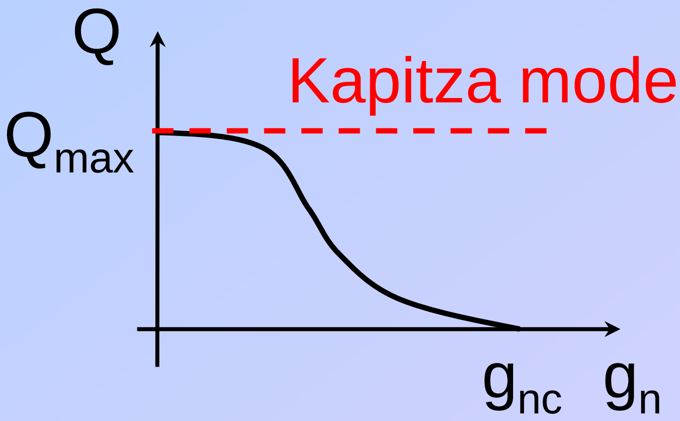


Exponential decay inspired by micromechanical contact models:

Greenwood & Williamson, *Proc. R. Soc. London* (1966)
Lorenz & Persson, *J. Phys. Cond. Matter* (2008)

Modelling of discrete cracks: thermoelastic CZM





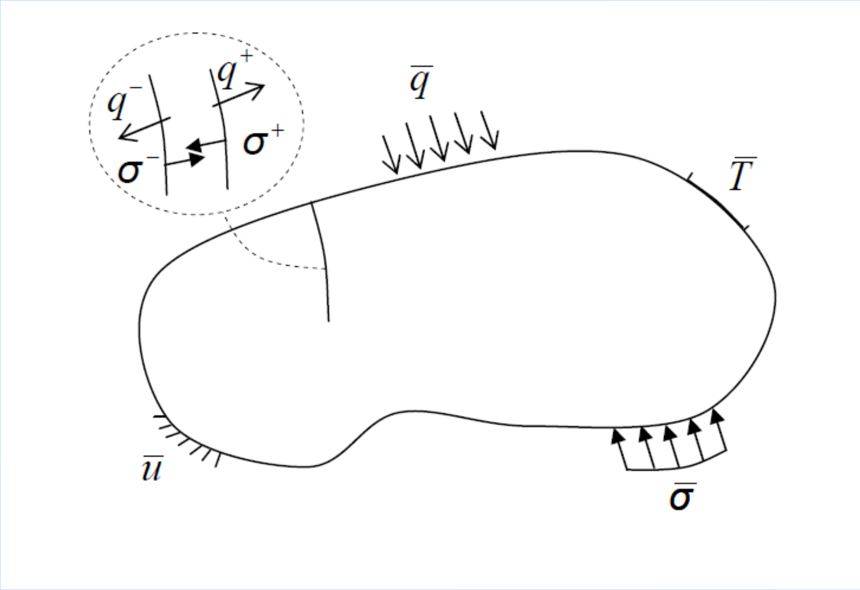
Thermal conductance proportional to the normal stiffness:

$$
k_{\mathrm{int}} = \begin{cases} \dfrac{1}{\rho_{\mathrm{int}}}, & \text{if} \quad 0 \leq \dfrac{g_{\mathrm{n}}}{R} < \dfrac{l_0}{R} \\ \dfrac{2\sigma}{\rho_{\mathrm{int}} E_{\mathrm{int}} R}, & \text{if} \quad \dfrac{l_0}{R} \leq \dfrac{g_{\mathrm{n}}}{R} < \dfrac{g_{\mathrm{nc}}}{R} \\ 0, & \text{if} \quad \dfrac{g_{\mathrm{n}}}{R} \geq \dfrac{g_{\mathrm{nc}}}{R} \end{cases}
$$

$$Q = -k_{\mathrm{int}}(g_{\mathrm{n}})\,\Delta T$$

Paggi & Barber, IJHMT (2011)

Finite element formulation



V: volume

S: surface

S: Cauchy stress tensor

f: body force vector

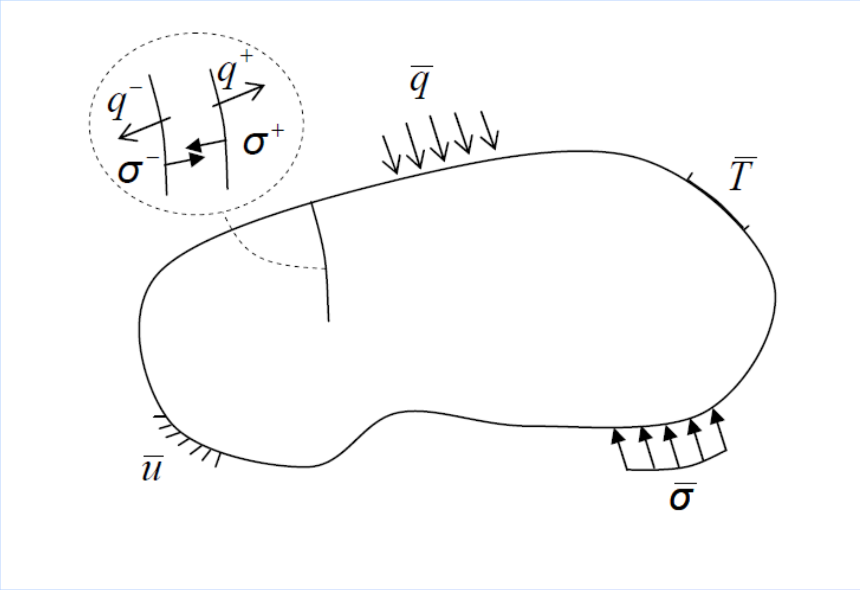
w: displacement vector

Strong form: $\nabla^T \mathbf{S} + \mathbf{f} = \mathbf{0}$

Weak form:

$$\int_V \mathbf{S} : \nabla(\delta \mathbf{w}) \mathrm{d}V = \int_V \mathbf{f}^T (\delta \mathbf{w}) \mathrm{d}V + \int_S \bar{\boldsymbol{\sigma}}^T (\delta \mathbf{w}) \mathrm{dS} + \int_{S_{\mathrm{int}}} \boldsymbol{\sigma}^T (\delta \mathbf{w}) \mathrm{dS}$$

Finite element formulation



V: volume

S: surface

q: heat flux vector

Q: heat generation

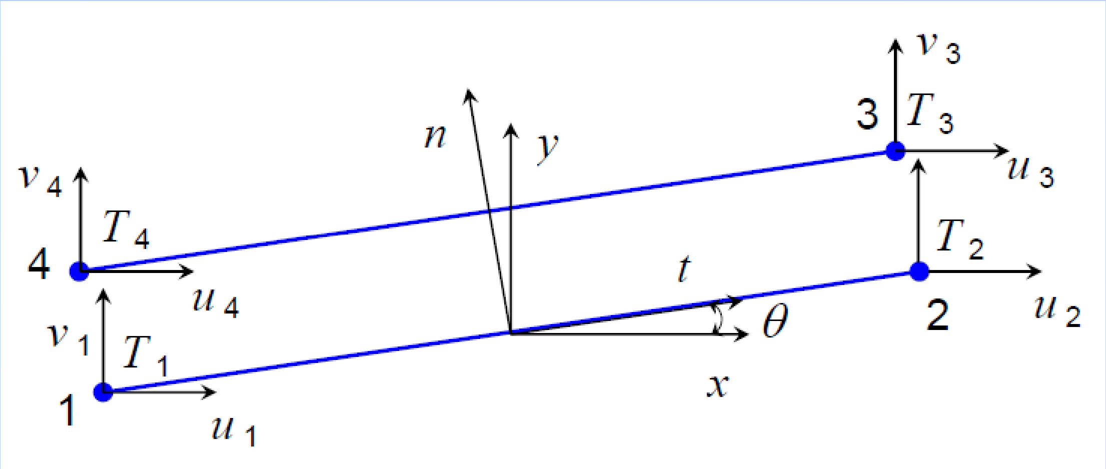
T: temperature

Strong form: $$-\nabla^T \mathbf{q} + Q = \rho c \dot{T}$$

Weak form (energy balance):

$$\int_V \mathbf{q}^T \nabla(\delta T)\mathrm{d}V = \int_V (\rho c \dot{T} - Q)\delta T \,\mathrm{d}V + \int_S \bar{\mathbf{q}}^T (\delta \mathbf{w})\,\mathrm{dS} + \int_{S_{\mathrm{int}}} q(\delta T)\,\mathrm{dS}$$

Finite element formulation



Gap vector:
$\boldsymbol{g}=(g_t,g_n,g_T)^T$

Traction and flux vector:
$\boldsymbol{p}=(\tau,\sigma,q)^T$

Weak form for the interface elements: $$\delta G_{\text{int}} = \int_{S_{\text{int}}} \delta \mathbf{g}^T \mathbf{p} \, \mathrm{d}S$$

Consistent linearization of the interface constitutive law (implicit scheme):

$$\mathbf{p} = \mathbf{C}\,\mathbf{g} \quad \Longrightarrow \quad \delta G_{\text{int}} = \int_{S_{\text{int}}} \delta \mathbf{g}^T \mathbf{C}\,\mathbf{g} \, \mathrm{d}S$$

Paggi, Wriggers, *Comp. Mat. Sci.* (2011); *JMPS* (2012)

Finite element formulation

$$\mathbf{C} = \left[\begin{array}{cc:c} \dfrac{\partial \tau}{\partial g_t} & \dfrac{\partial \tau}{\partial g_n} & 0 \\ \dfrac{\partial \sigma}{\partial g_t} & \dfrac{\partial \sigma}{\partial g_n} & 0 \\ \hdashline \dfrac{\partial q}{\partial g_t} & \dfrac{\partial q}{\partial g_n} & \dfrac{\partial q}{\partial g_{\mathrm{T}}} \end{array}\right]$$

Mechanical part

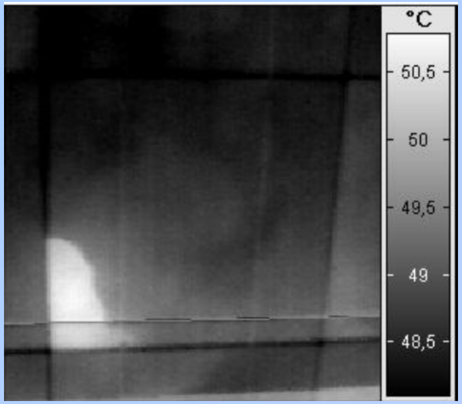
Thermoelastic part with coupling

If *k_{int}=const* (Kapitza model): $\dfrac{\partial q}{\partial g_t} = \dfrac{\partial q}{\partial g_n} = 0$

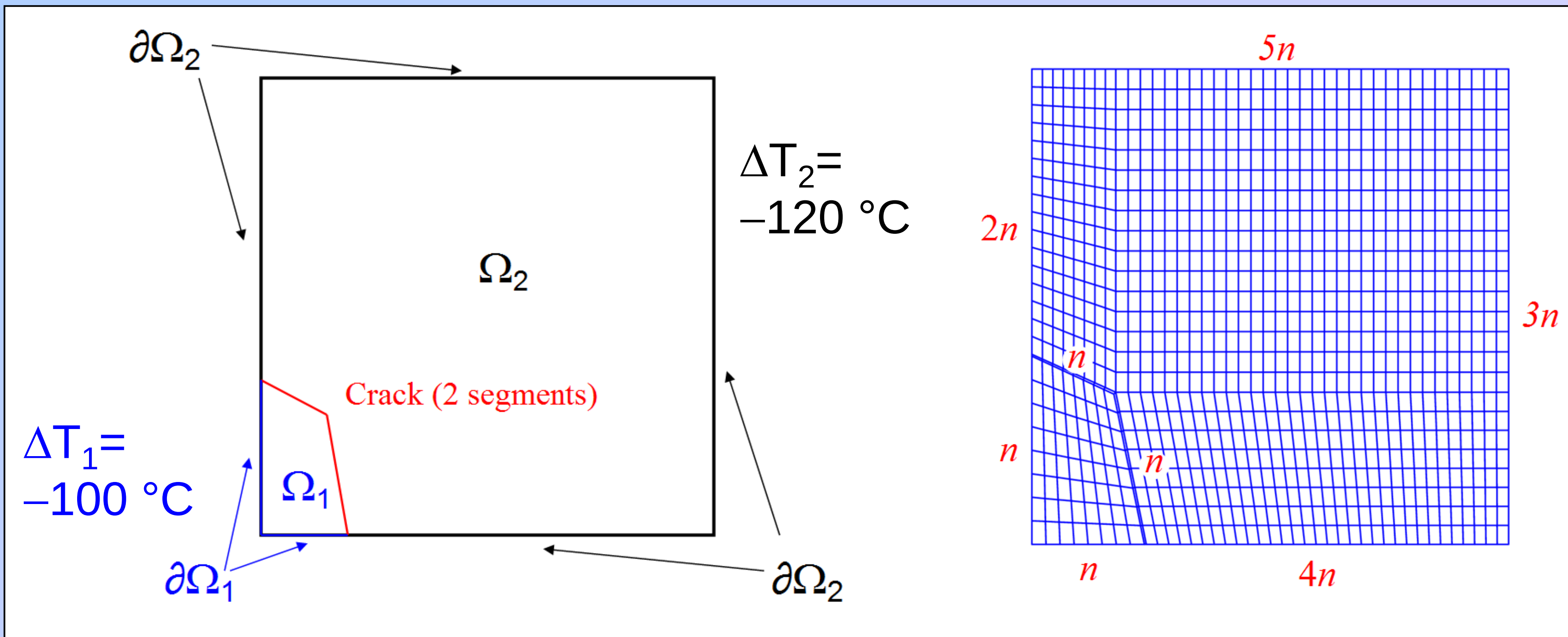
Tangent matrix for the Newton-Raphson algorithm:

$$\mathrm{K} = \mathrm{R}^T \int_{S_{int}} \mathrm{B}^T \mathrm{C} \mathrm{B} \, dS \mathrm{R}$$

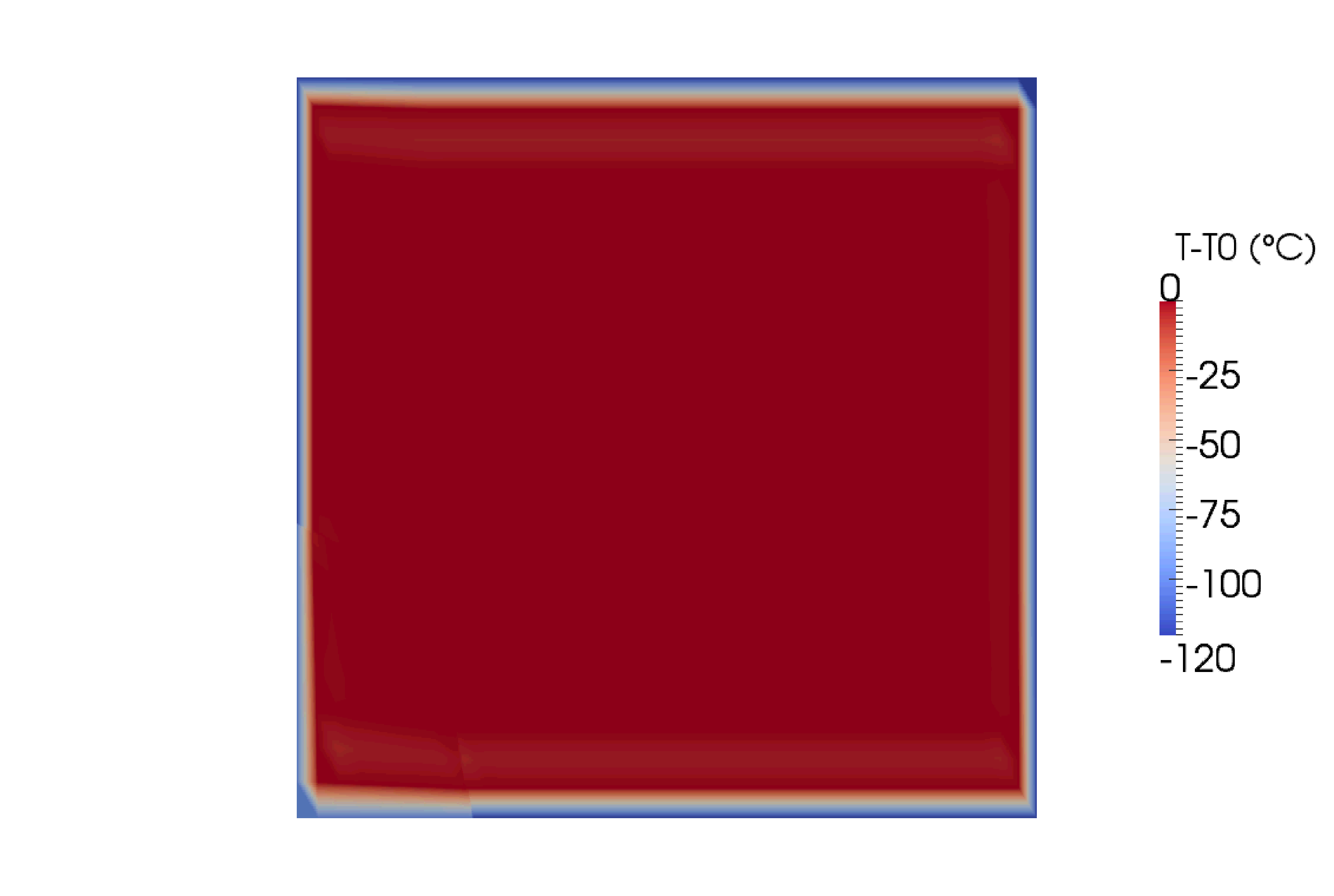
Numerical example



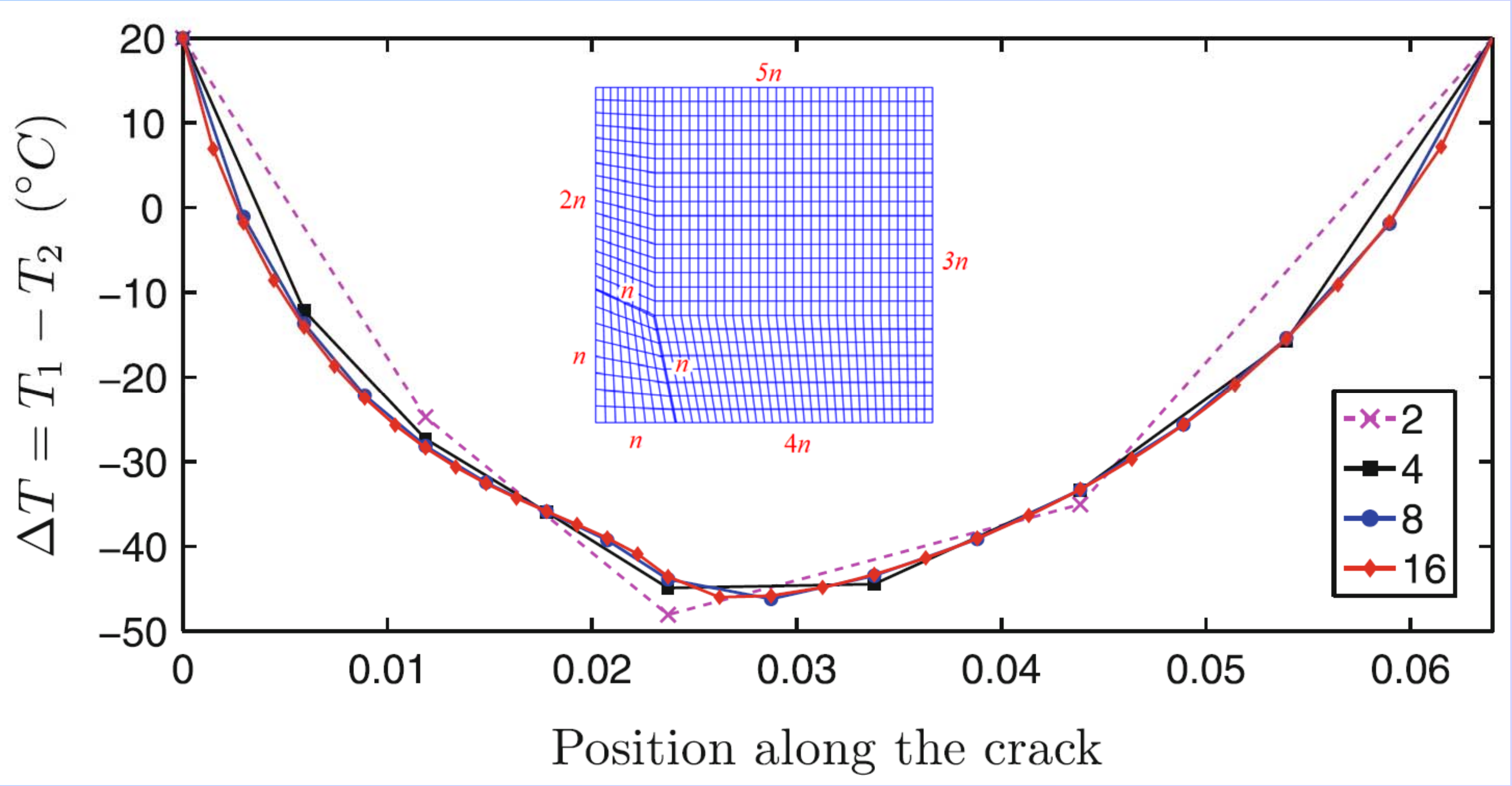
Stress-free temperature coincident with the lamination temperature (T_0=150°C)



Numerical example



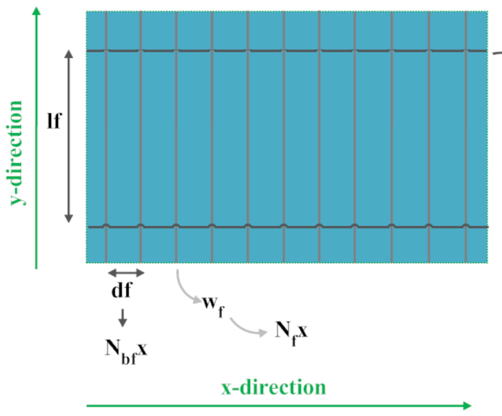
Mesh convergence study

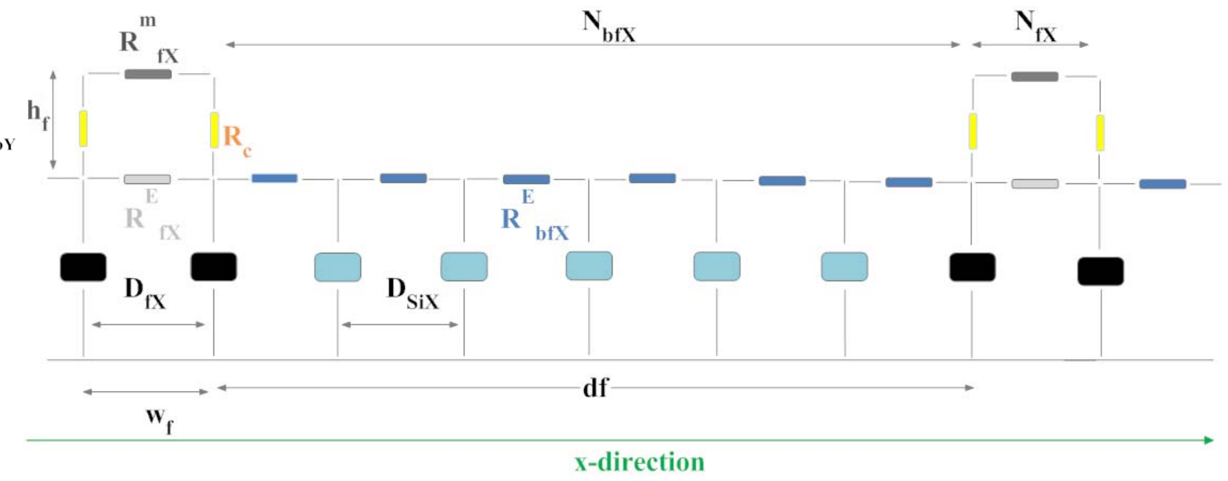


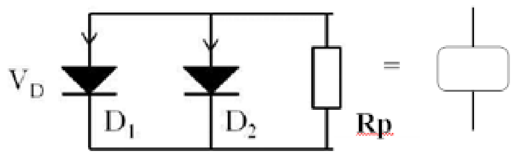
Part III: the electric model

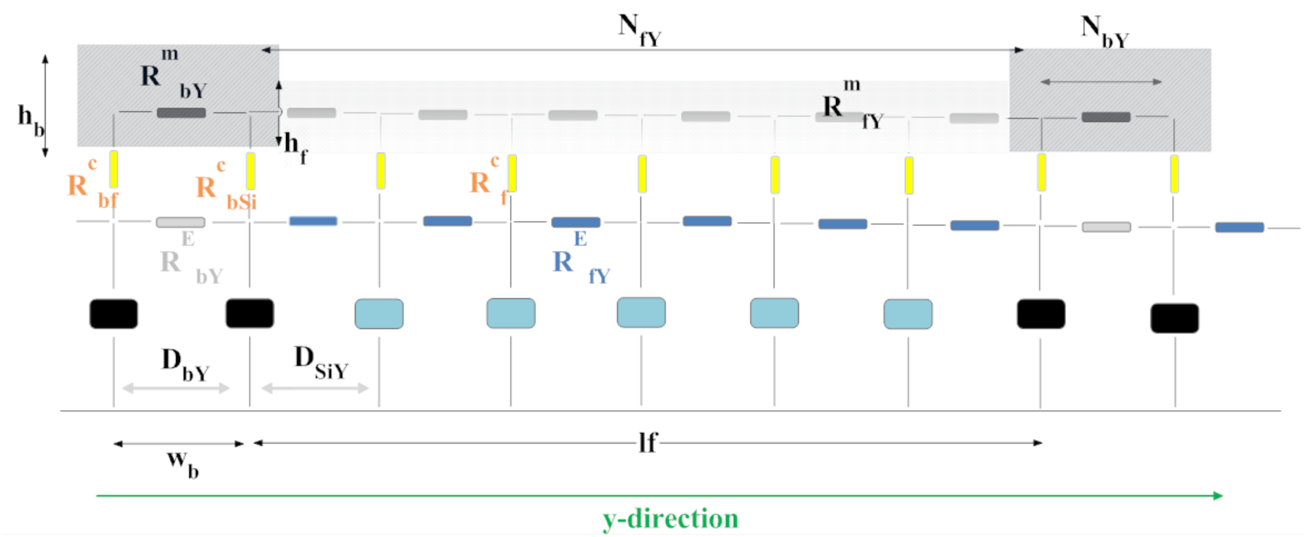
A 2D electric model for a cracked cell

The electric model



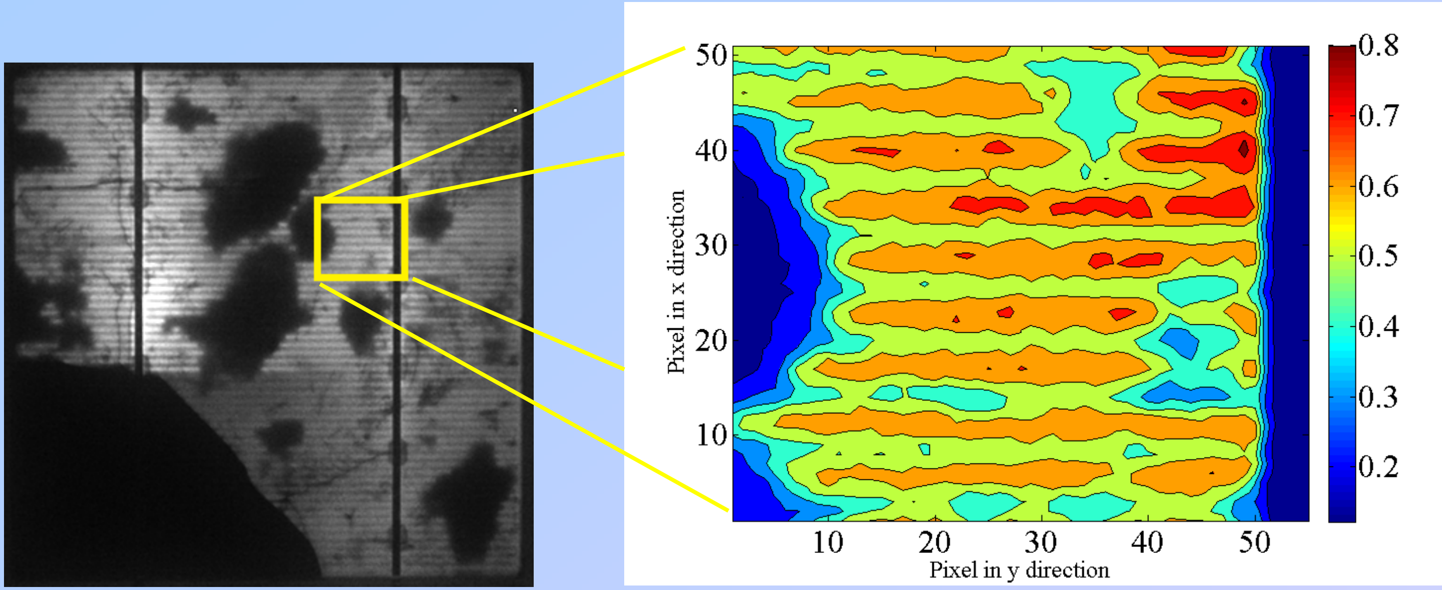




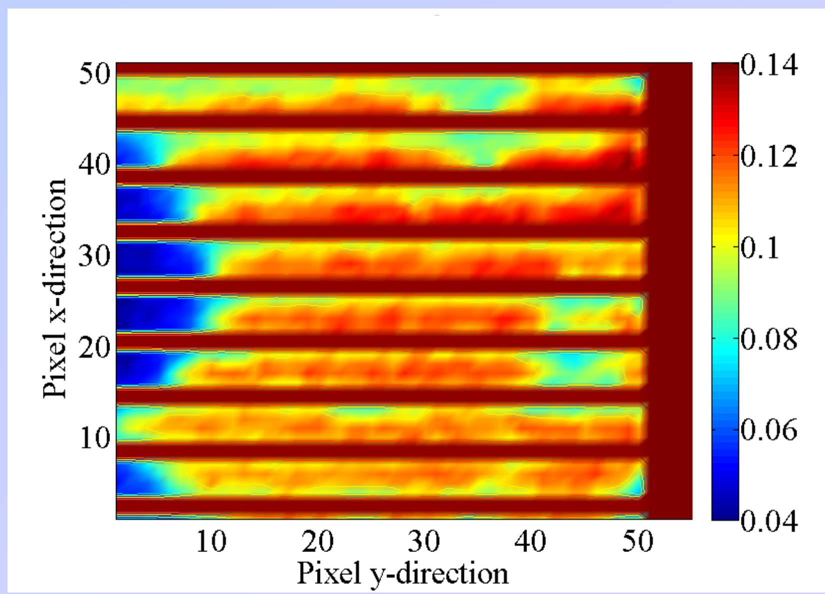


D. Grote, PhD thesis, University of Konstanz, Germany, 2010

Parameters identification via inverse analysis



EL image (a.u.)



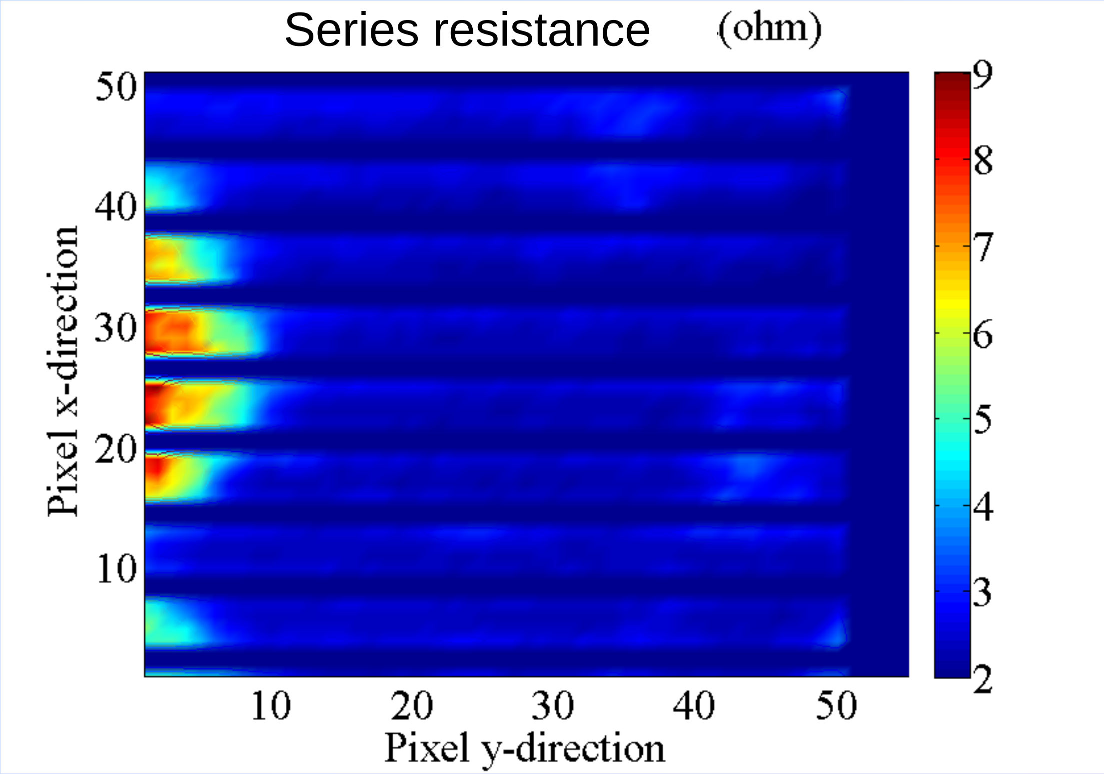
Current from EL image (A)

Fuyuki et al. (2007) ***J. Appl. Phys.***

Trupke et al. (2007) ***Appl. Phys. Lett.***

Potthoffy et al. (2010) ***Prog. Photov.***

Parameters identification via inverse analysis



- Different resistance values can be identified and associated to cracks, defects, grain boundaries, etc. (**learning stage**)
- Those values can be assigned to cracks and other numerically simulated defects (**predictive stage**)

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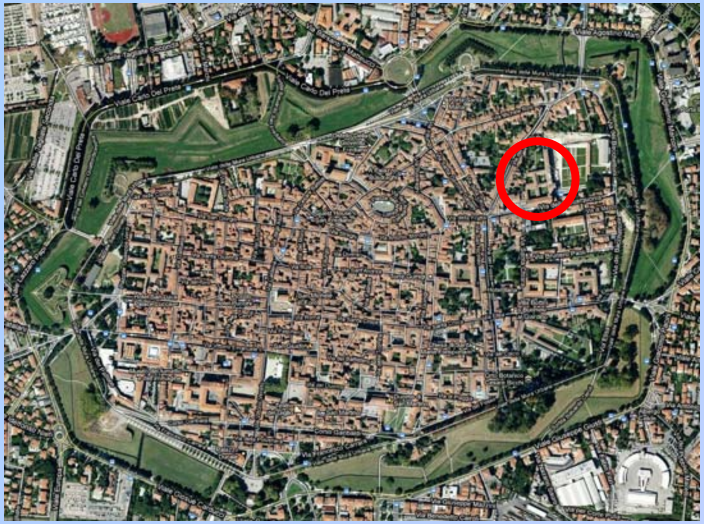

SEM with tensile stage

Profilometer

Testing machine

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