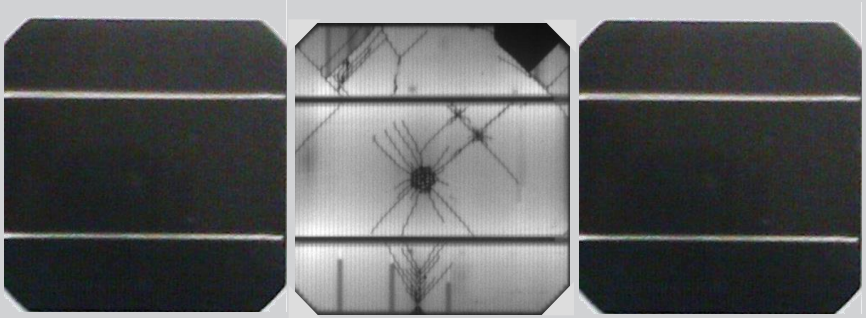
Quantitative analysis of cracking in photovoltaic modules using a multi-physics approach



Prof. M. Paggi
IMT Institute for Advanced Studies Lucca

I. Berardone, A. Infuso, M. Corrado, A. Sapora
Politecnico di Torino

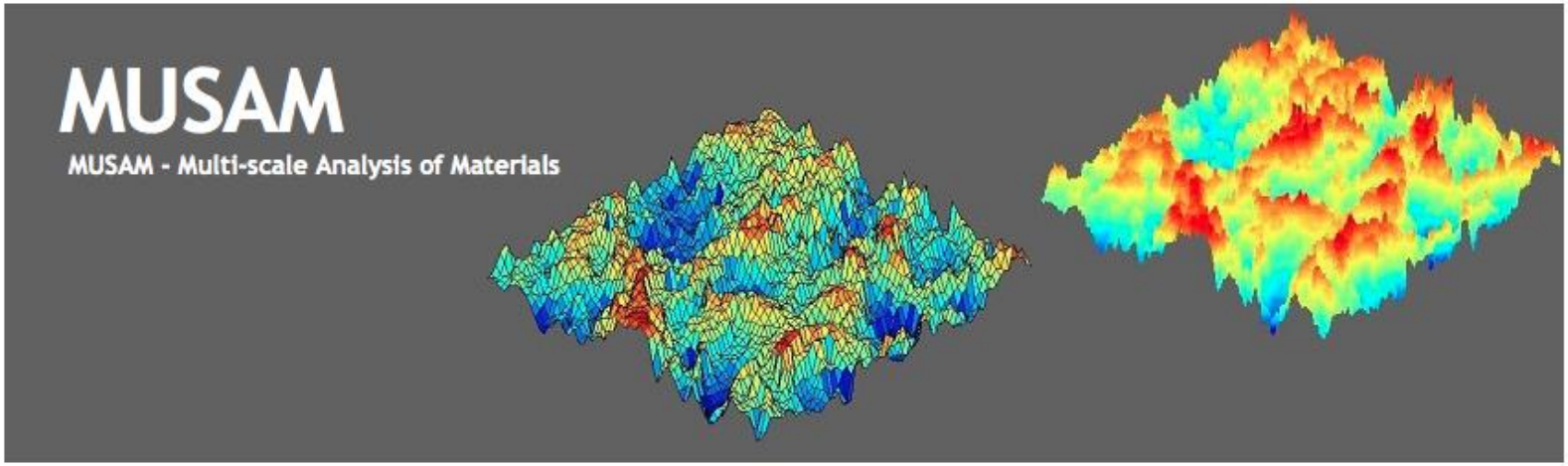
Institute for Solar Energy Research, Hamelin, Germany, June 3, 2014

Outline

- Overview of research facilities at IMT Lucca
- Introduction and motivations
- Experimental investigation
- Numerical modelling
- Conclusions and work in progress

MUSAM Research unit

http://musam.imtlucca.it



- Presentation
- People
- Research topics
- Mission/Objectives
- Expected results
- Research facilities
- Projects and funding
- Collaborations/Partnerships
- Events
- ERC StG CA2PVM
- FIRB - MIUR

Presentation

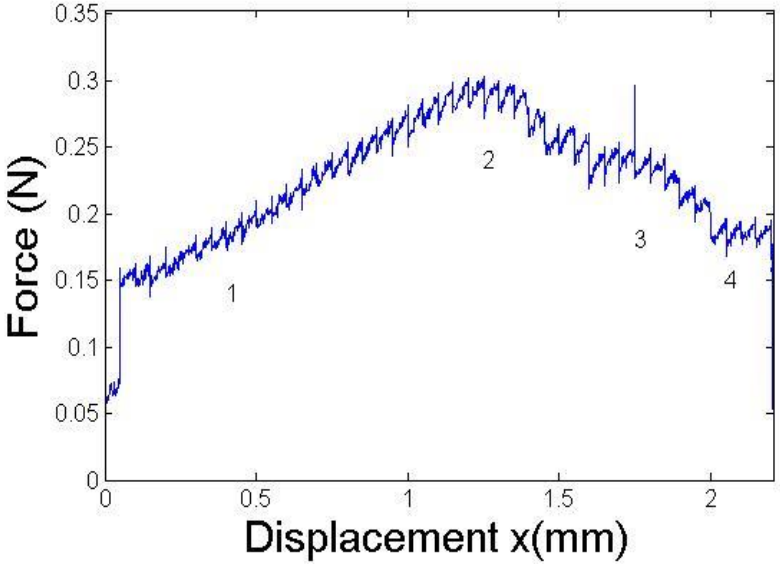
MUSAM is a research unit of engineers, physicists and applied mathematicians researching the multi-scale and multi-physics characterization of materials. Topics of investigation regard the deformation, fracture, fatigue, contact and structural integrity of heterogeneous materials and structures, coatings, material microstructures and devices. In addition to computational tools developed in-house (finite element method, boundary element method, molecular dynamics), the experimental facilities available in the laboratory include mechanical testing machines, a scanning electron microscope, a confocal and interferometric profilometer, a digital image correlation system and a high resolution thermocamera. This research is applied to areas of civil, mechanical, aerospace and electronic engineering, renewable energy systems and geophysics.

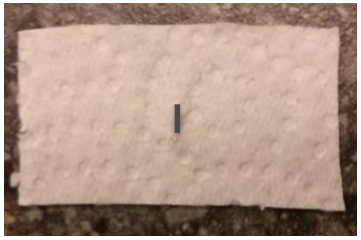
Composed of engineers, physicists and mathematicians, the unit aims at studying the deformation, fracture, fatigue, contact and the structural integrity of heterogeneous materials and structures with multi-scale and multi-physics computational and experimental methods.

Multi-scale Analysis of Materials Laboratory

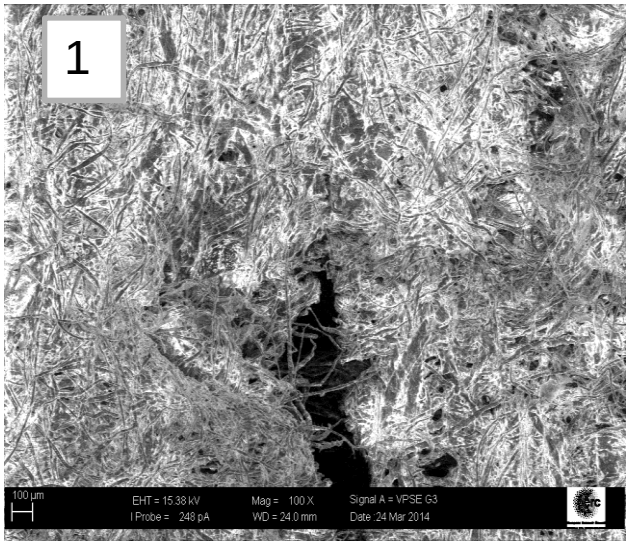
Ex-Officina Aromataria Convento San Francesco (XIII Century)

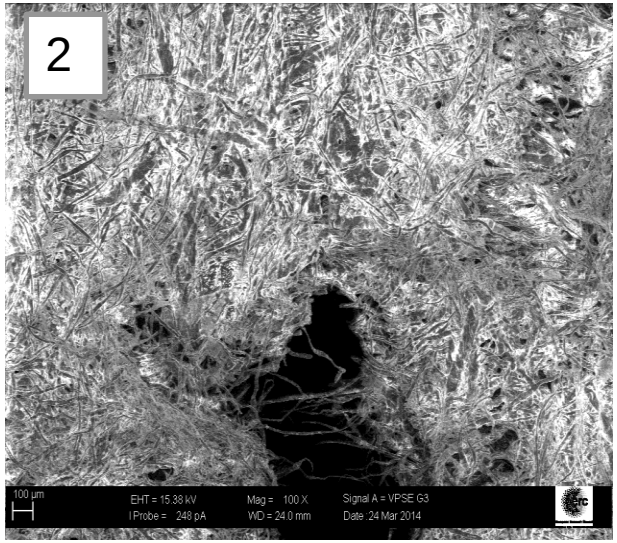
Testing of paper tissue

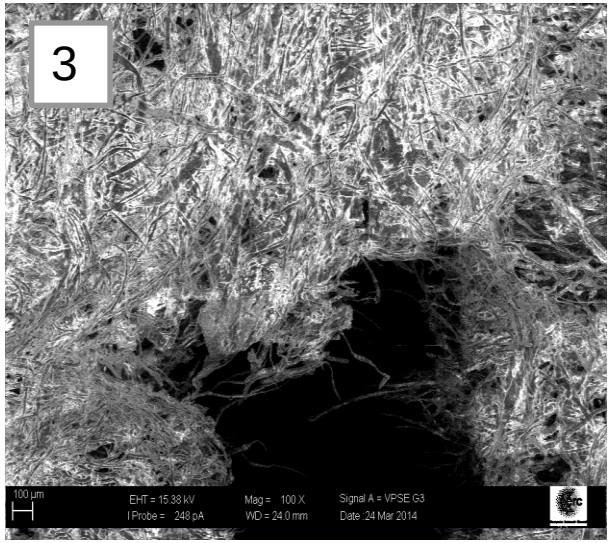


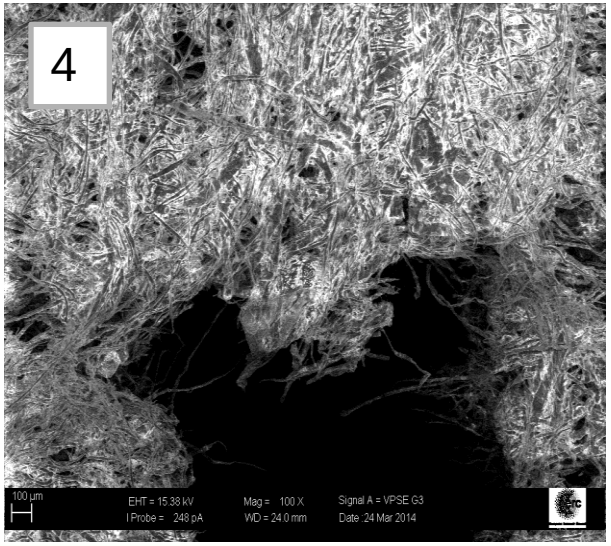


Crack 4 mm length

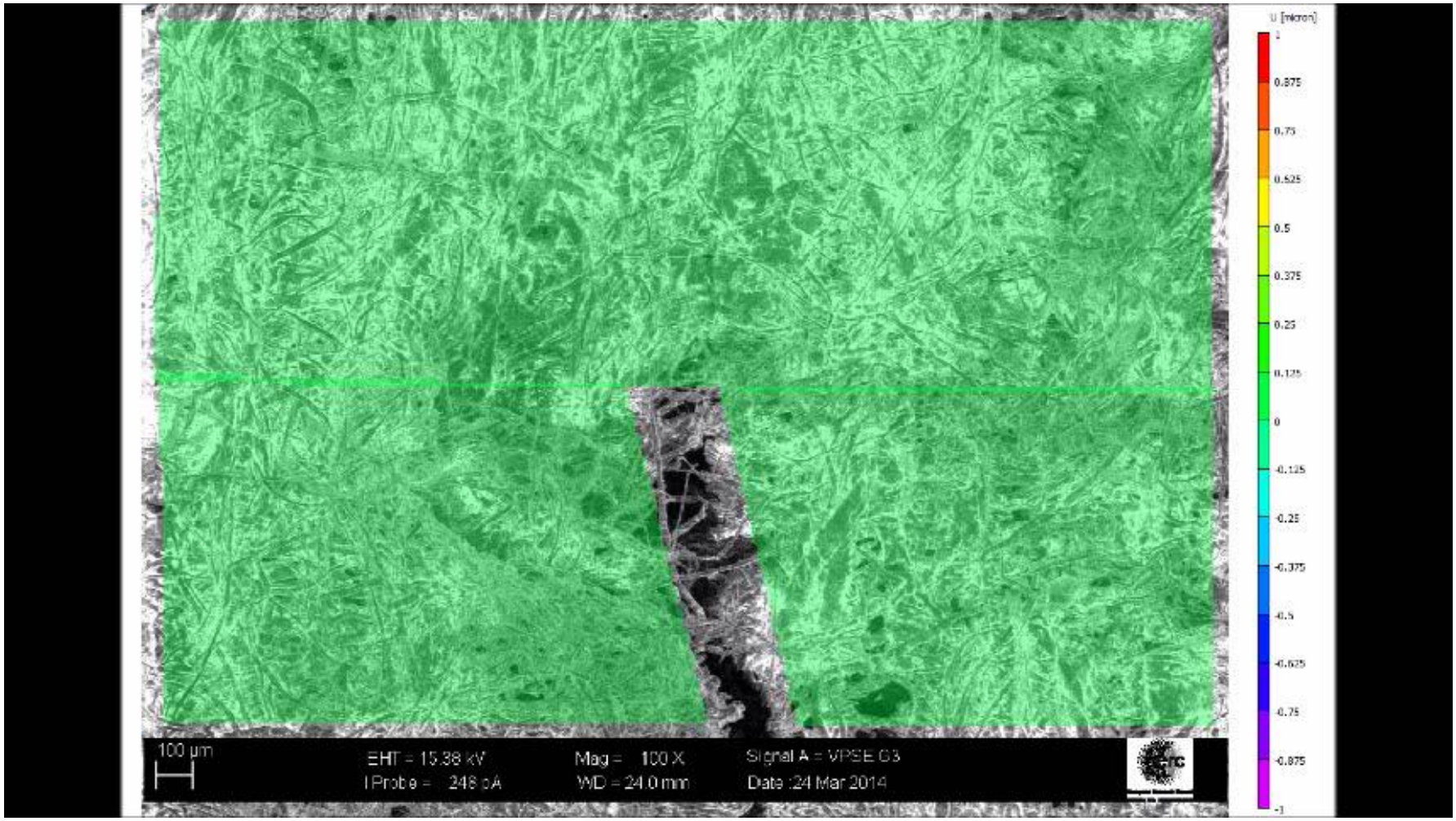




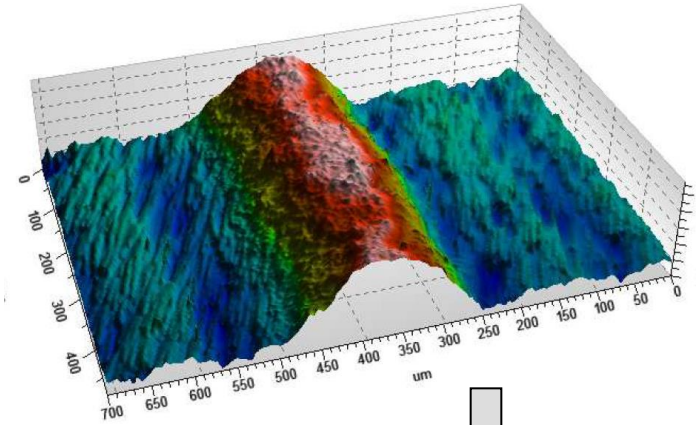


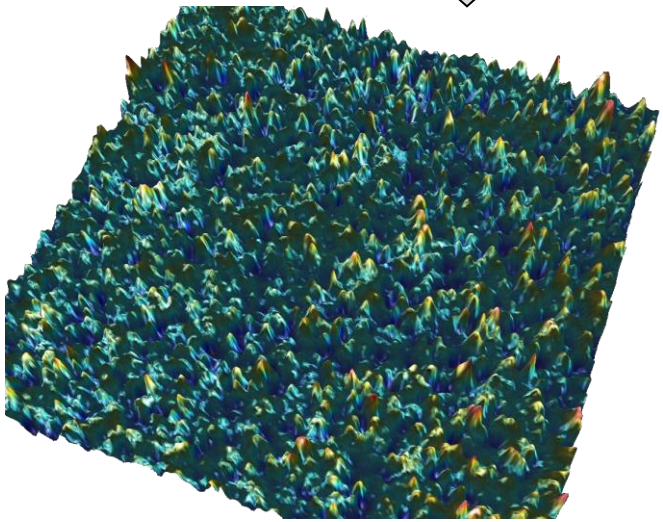


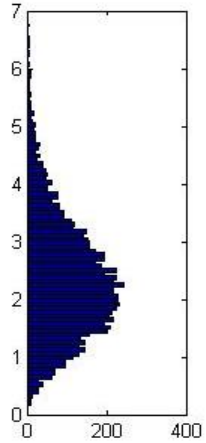
Digital image correlation

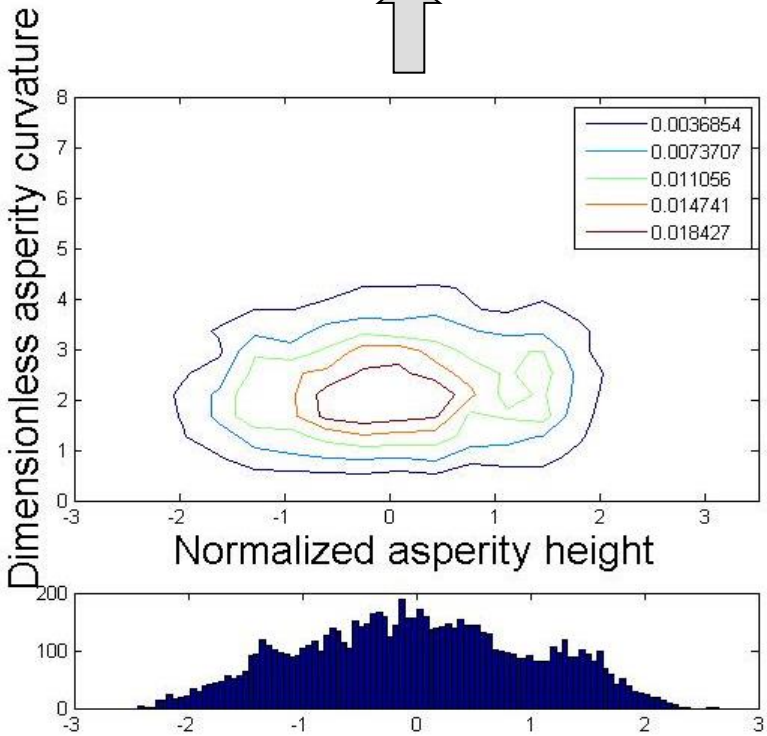


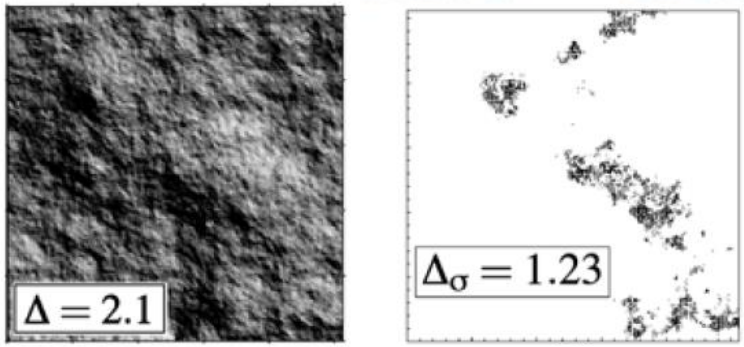
Contact mechanics





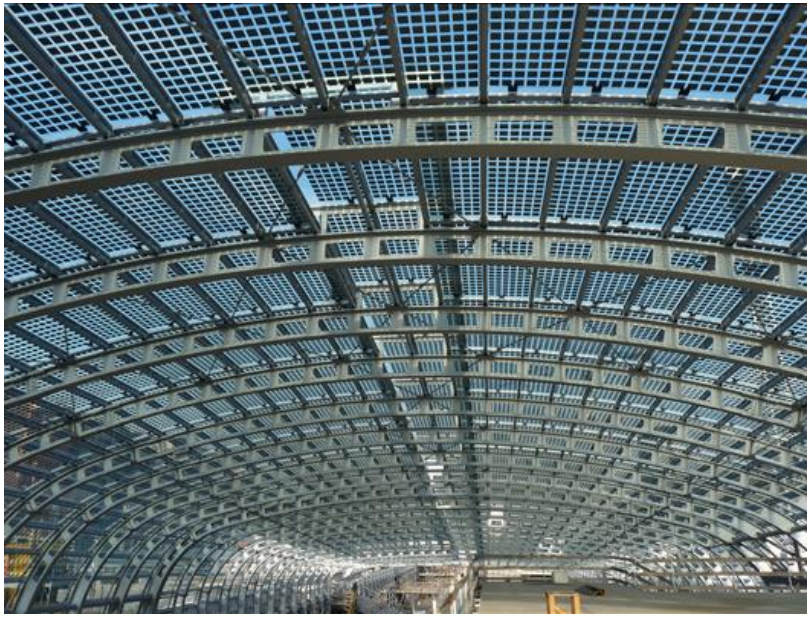




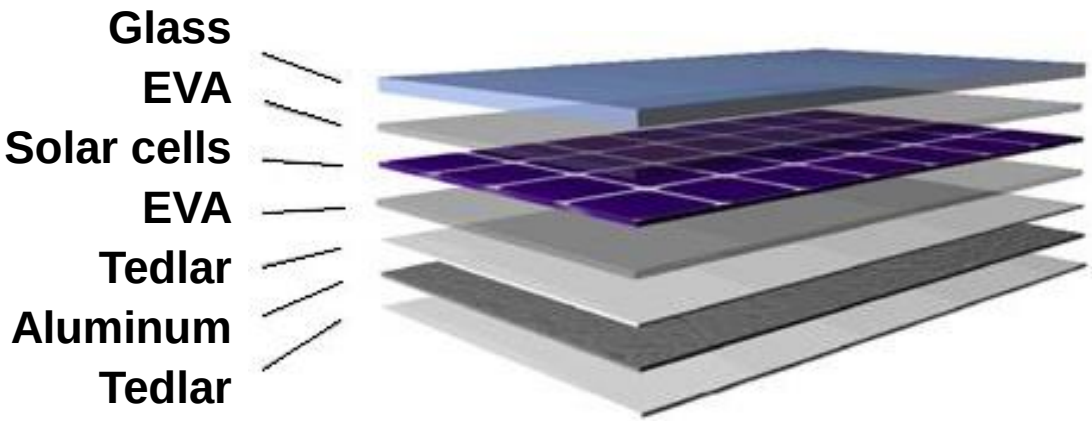


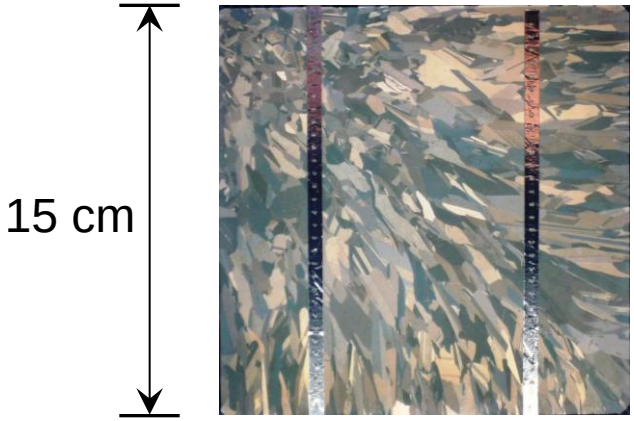
Introduction and motivations

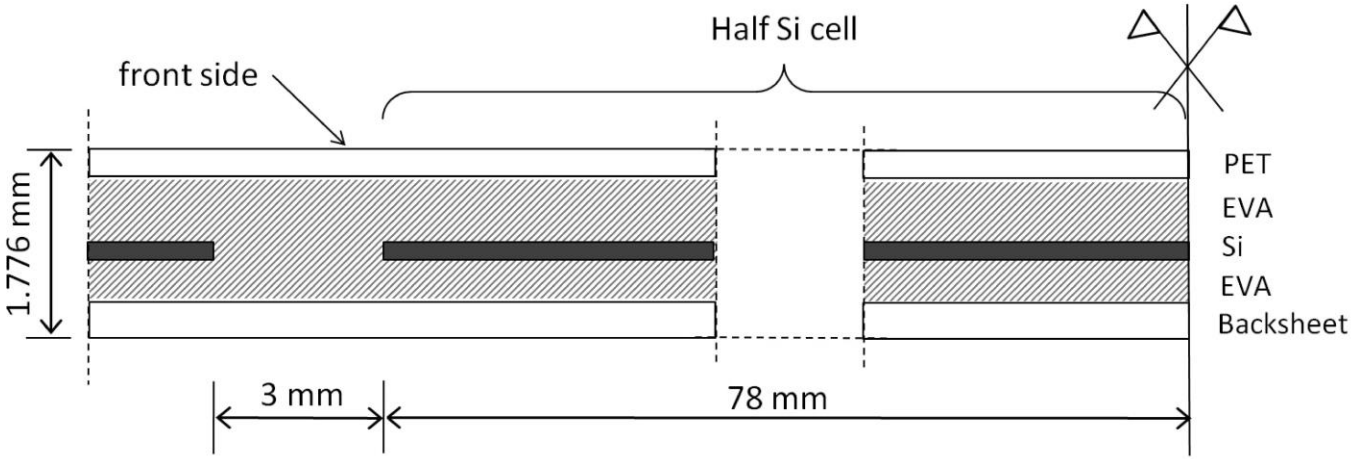
PV modules



PV modules

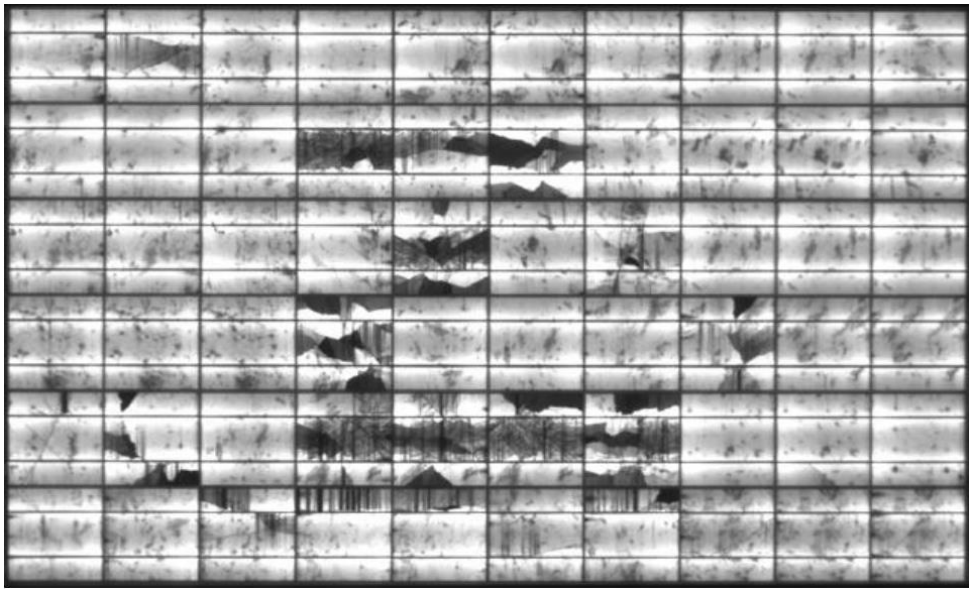




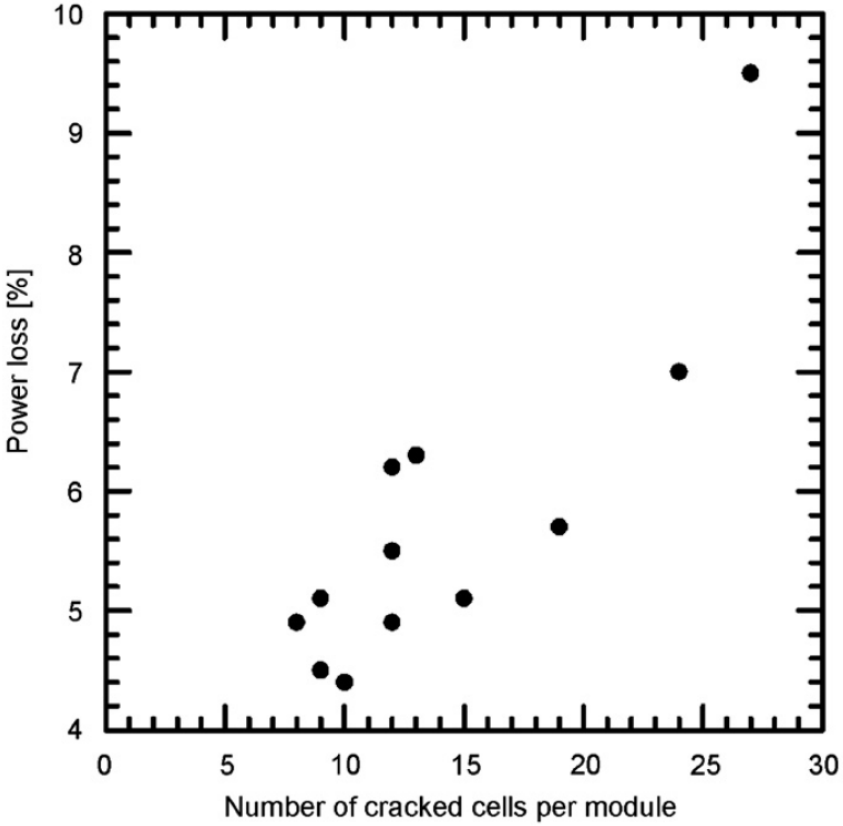


M. Paggi, S. Kajari-Schröder, U. Eitner (2011) J. Strain Analysis for Engng. Design, 46:772–782.

Durability: state-of-the-art

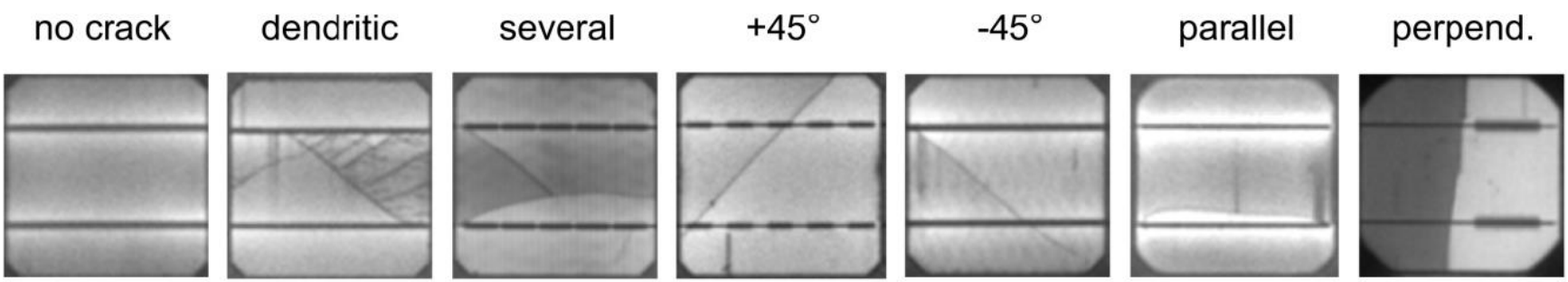


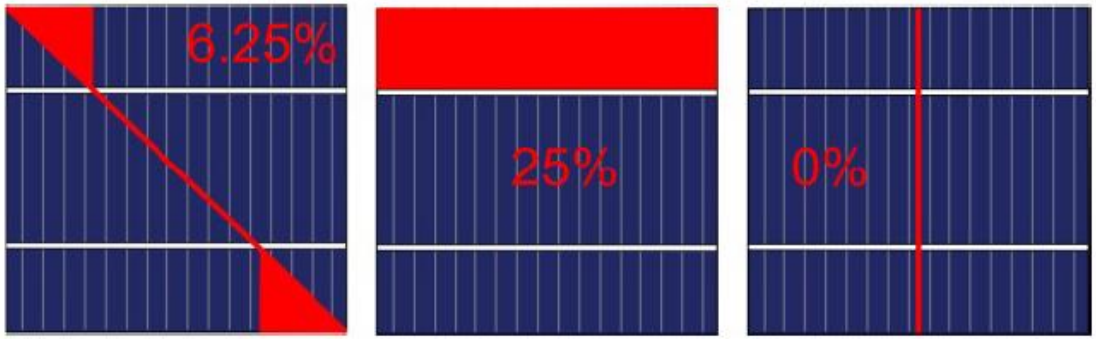
Electroluminescence image of cracking



Köntges M, Kunze I, Kajari-Schröder S, Breitenmoser X, Bjørneklett B (2011) Solar Energy Materials & Solar Cells 95:1131–1137

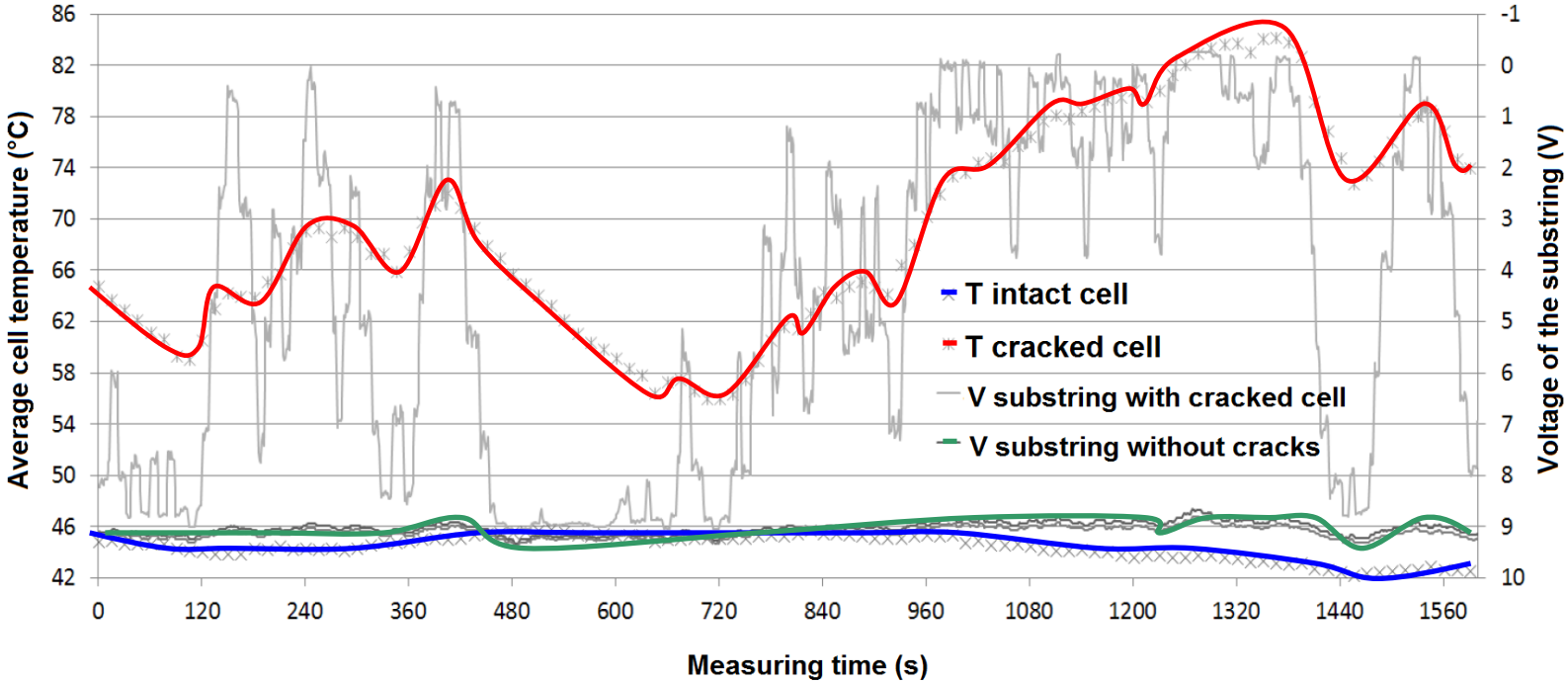
Durability: state-of-the-art

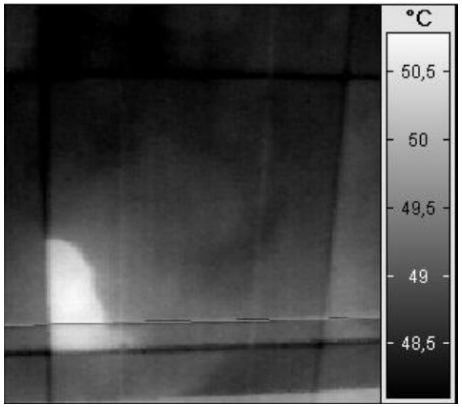




M. Köntges, I. Kunze, S. Kajari-Schröder, X. Breitenmoser, B. Bjørneklett (2011) Solar Energy Materials & Solar Cells 95:1131–1137

Thermo-electric coupling



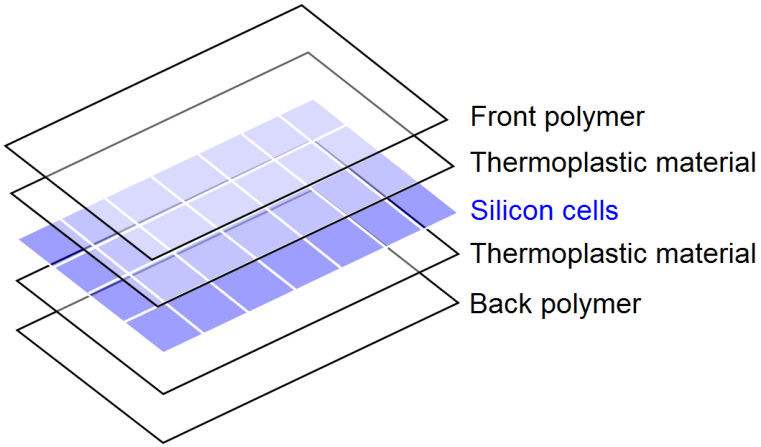


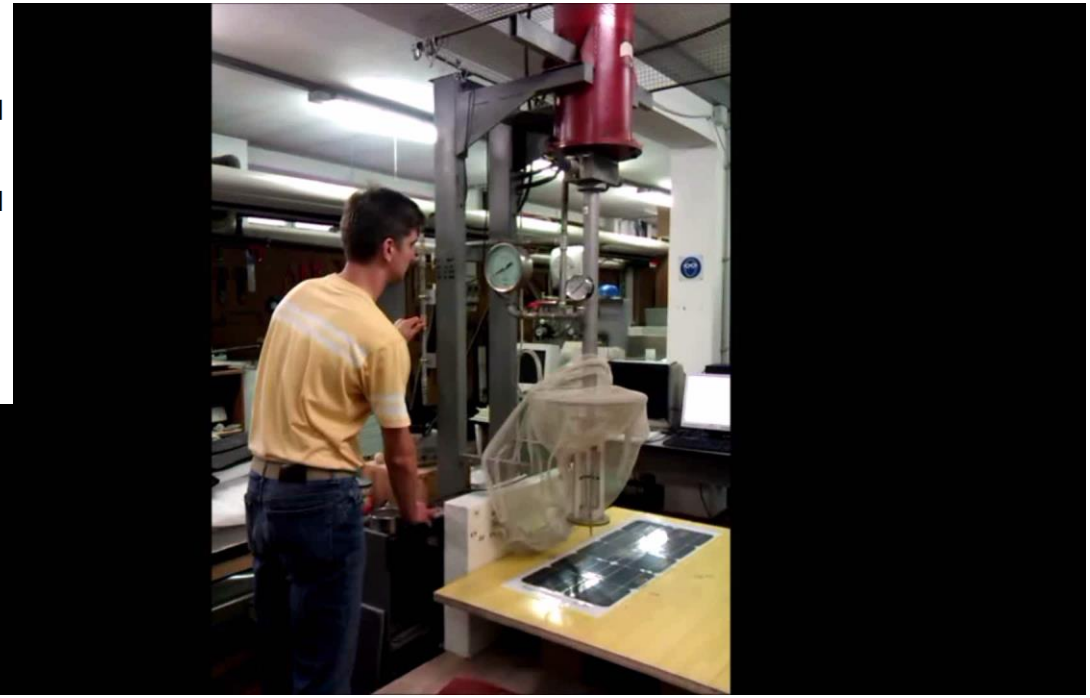
- Strong coupling between thermal and electric fields
- Electric recovery due to thermoelastic deformation

Weinreich et al., 2011

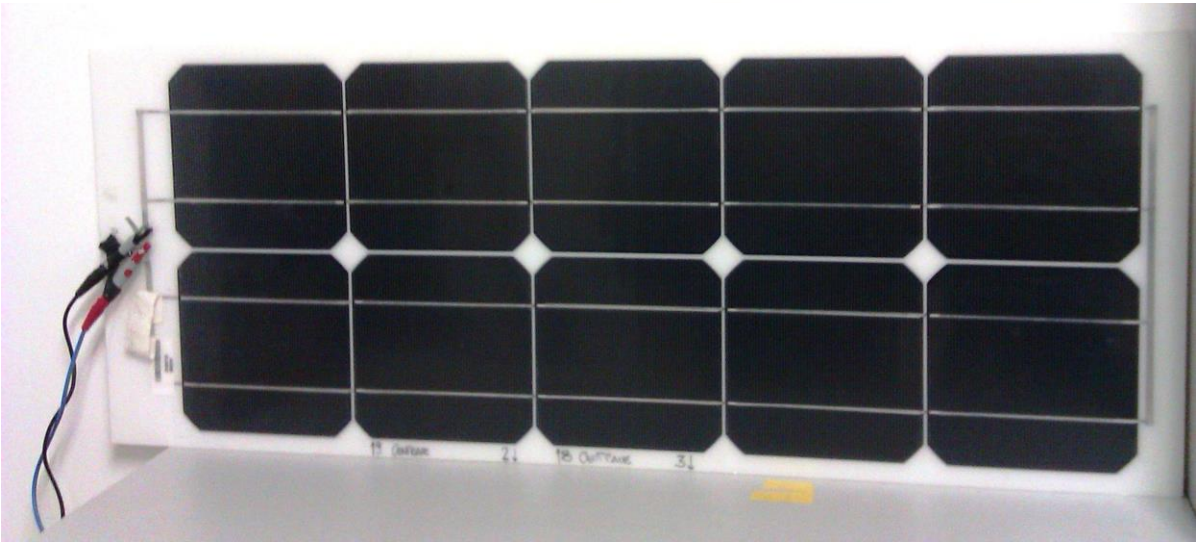
Experimental investigation

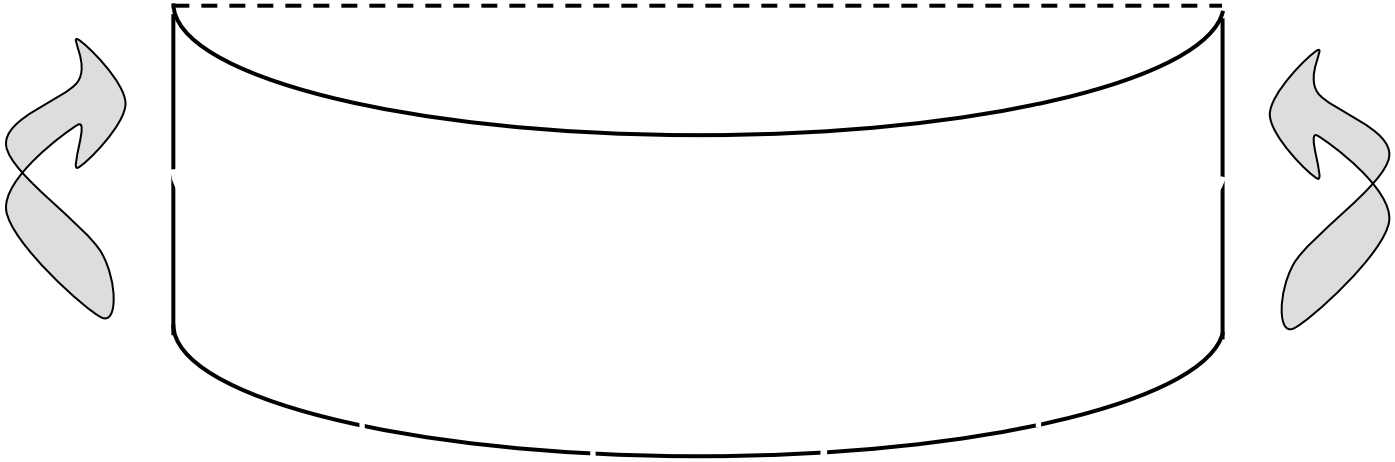
Electro-elastic coupling

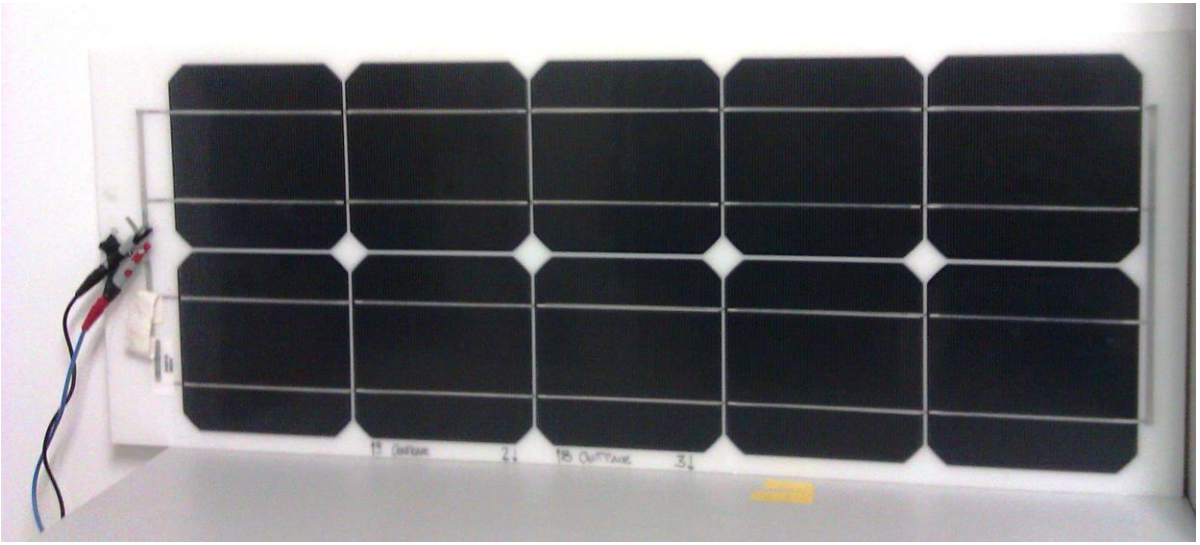


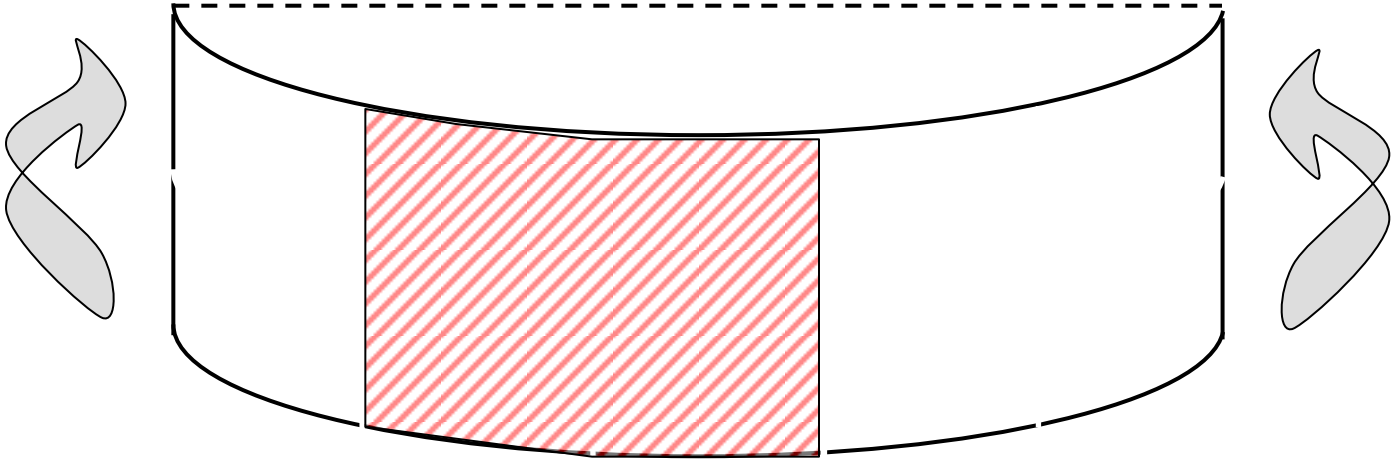


Paggi, Berardone, Infuso, Corrado (2014) Fatigue degradation and electric recovery in Silicon solar cells embedded in photovoltaic modules. **Sci. Rep.** 4:4506.

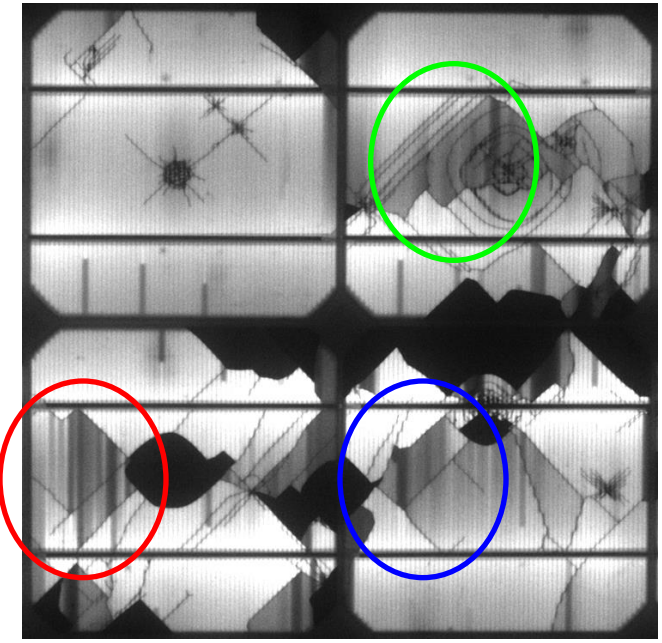




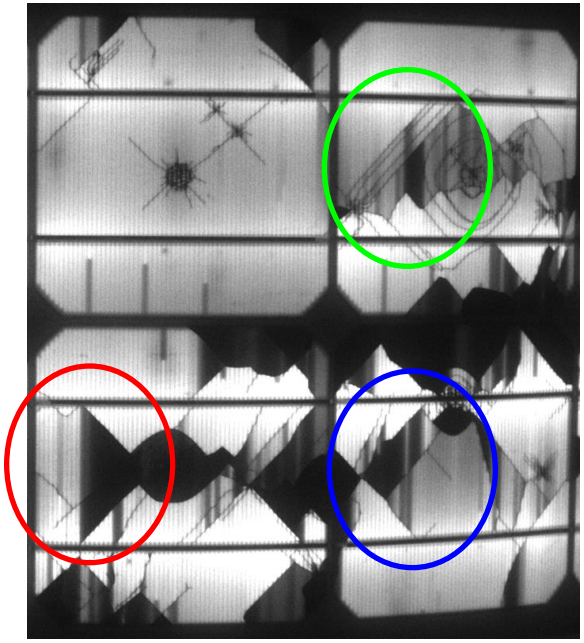




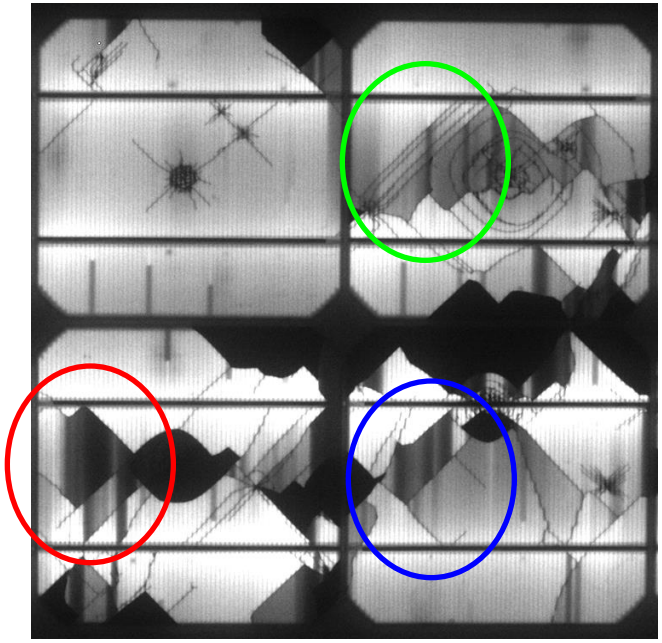
Results (1 cycle)



Initial flat configuration



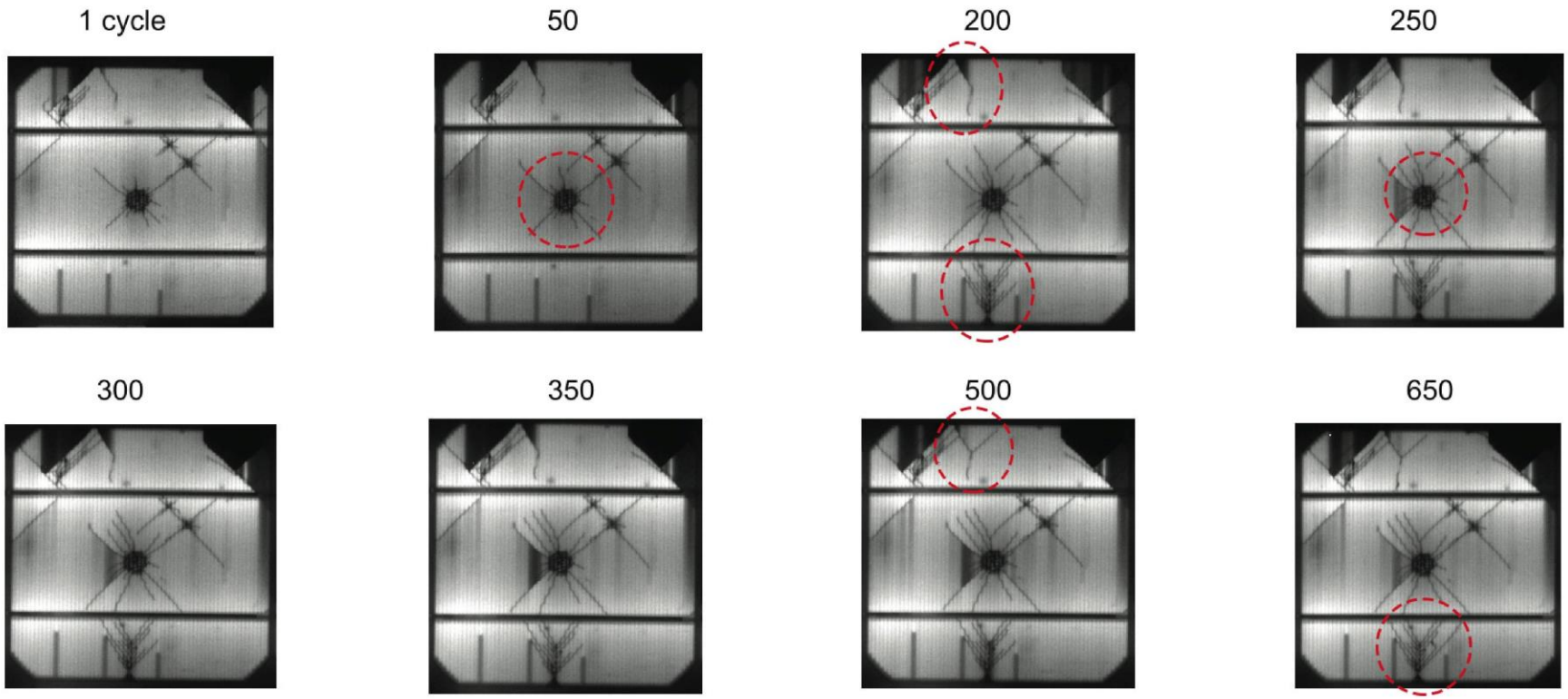
Max deflection



Final flat configuration

- **Some electrically inactive areas conduct again after unloading (crack closure & contact)**
- **The amount of electrically inactive areas increases after the loading cycle (fatigue effects)**

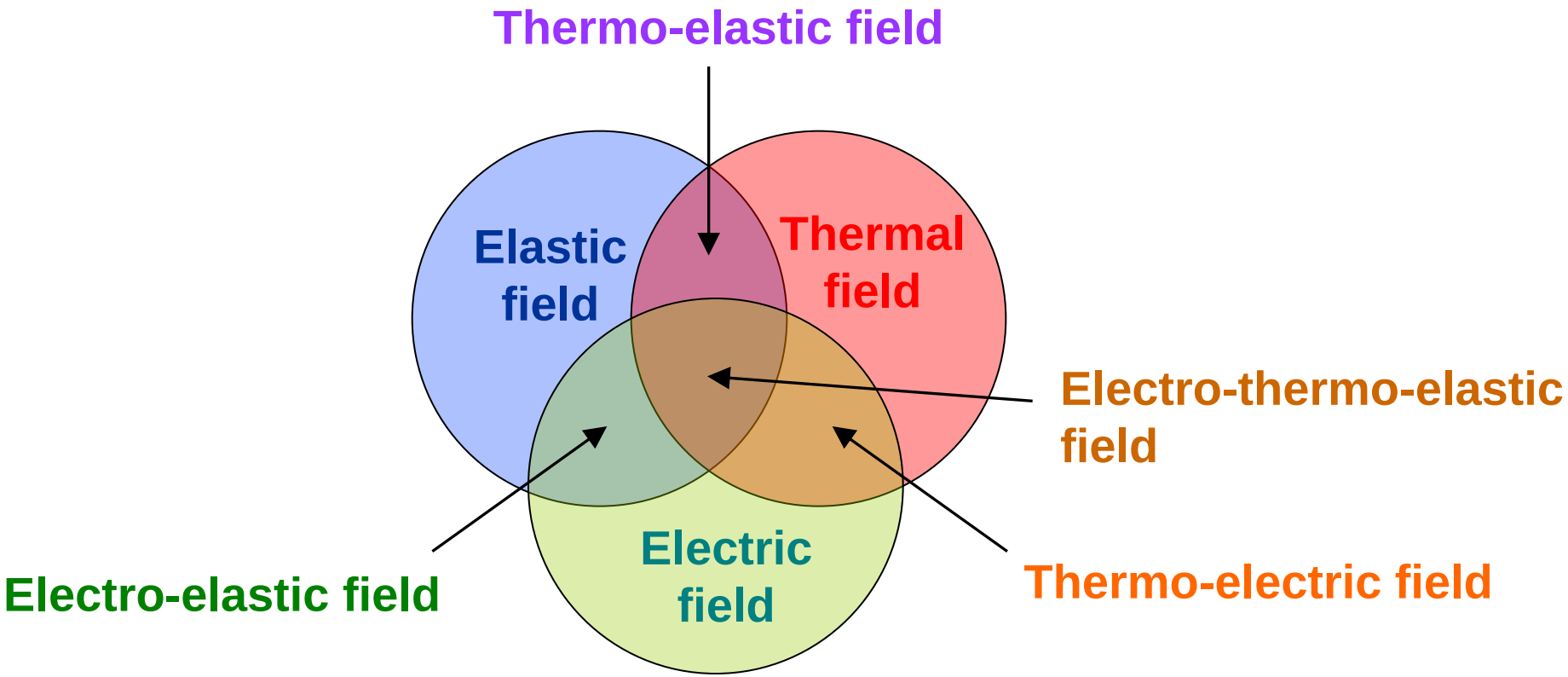
Fatigue



- **Crack propagation cycle after cycle**
- **Crack branching**
- **Strain localization near newly propagated cracks**

Computational modelling

Multi-physics



Paggi M., Corrado M., Rodriguez MA (2013) A multi-physics and multi-scale numerical approach to microcracking and power-loss in photovoltaic modules. Compos. Struct. 95, 630–638.

Multi-scale

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

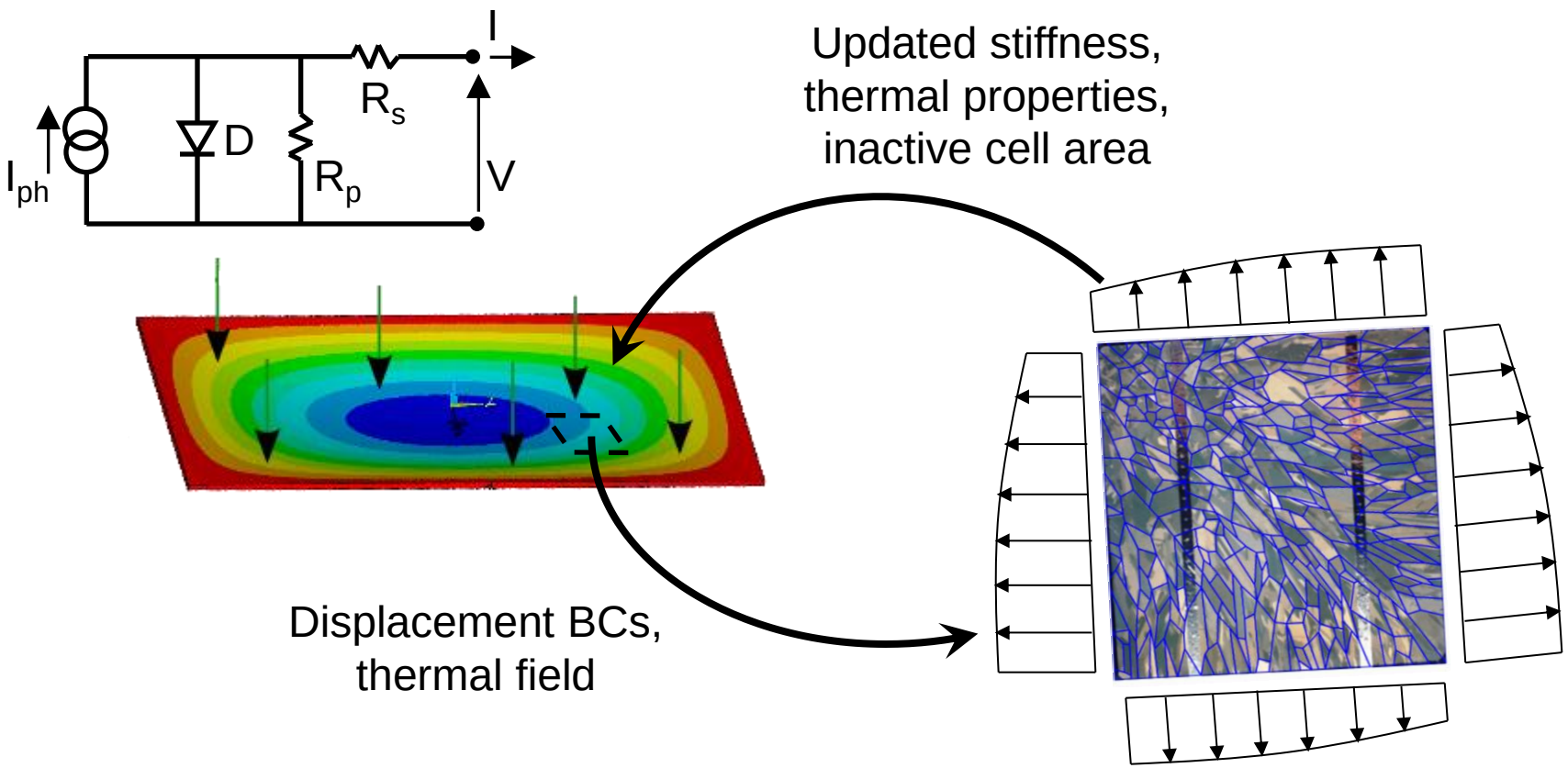
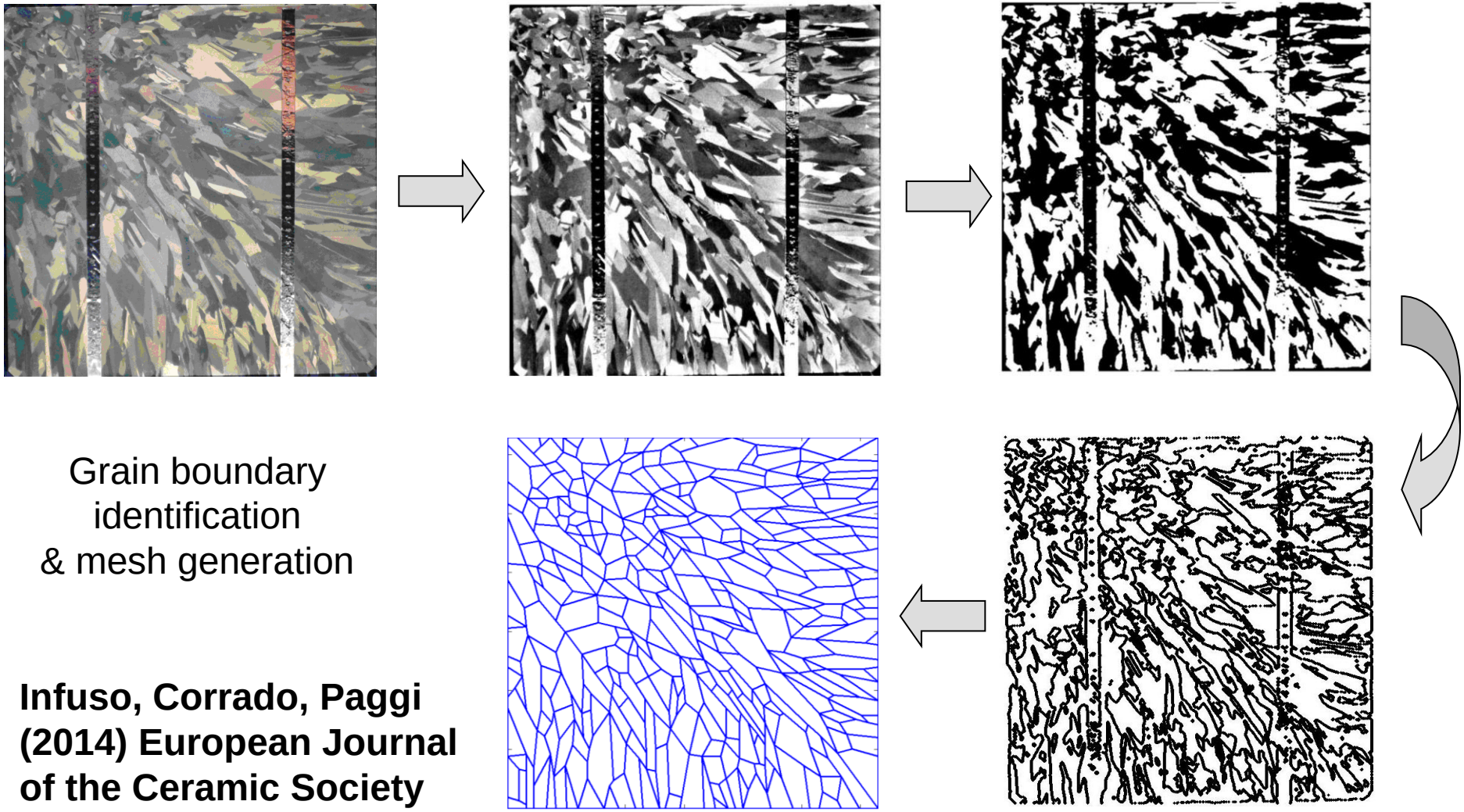


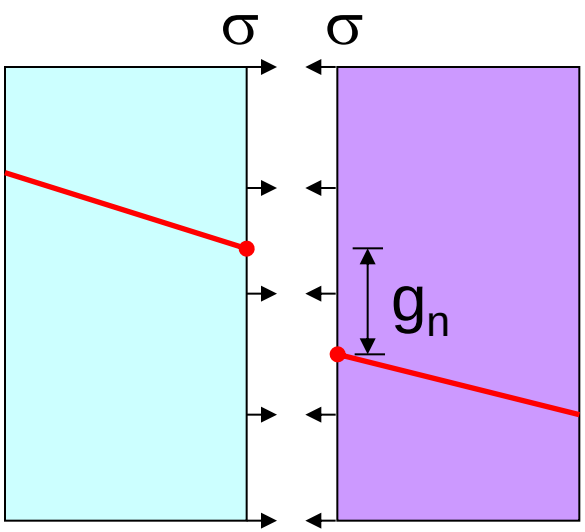
Image analysis



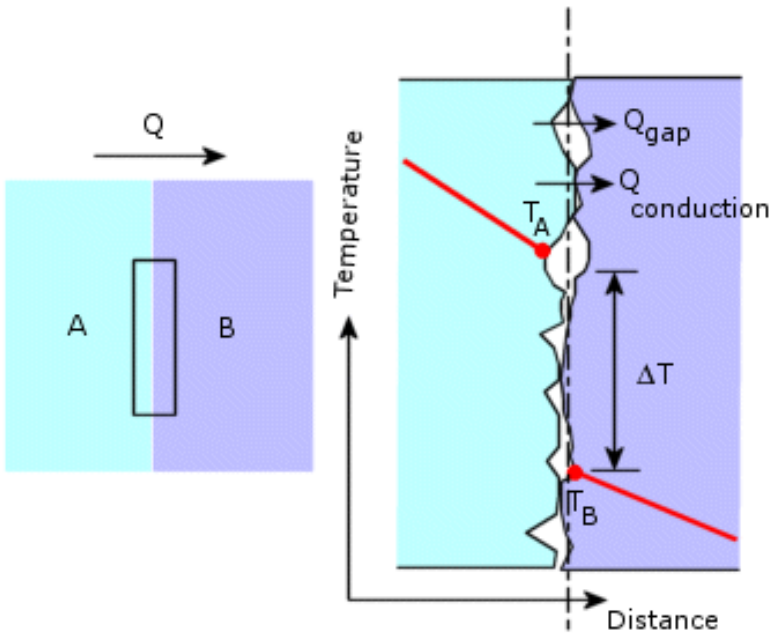
Grain boundary identification & mesh generation

Infuso, Corrado, Paggi (2014) European Journal of the Ceramic Society

Modelling of cracking



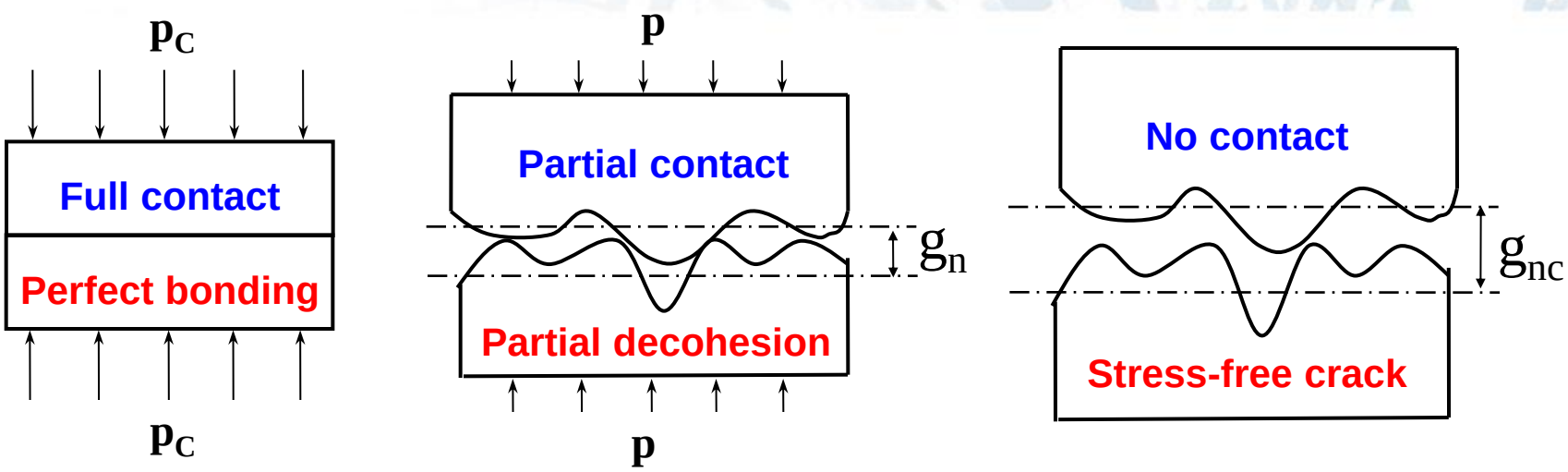
$\sigma=\sigma(g_n)$



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

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

Sapora and Paggi (2014) Computational Mechanics

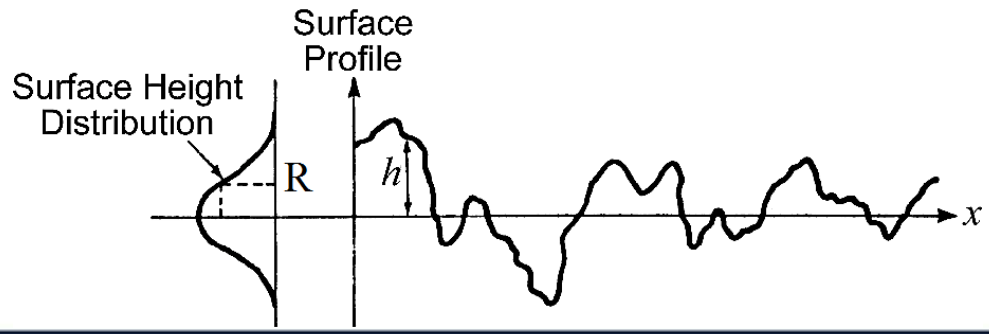


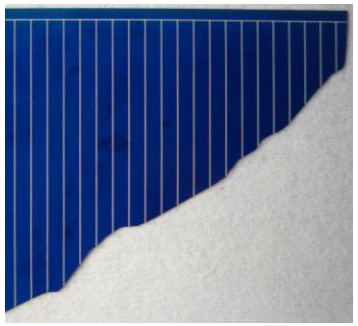
CONTACT

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

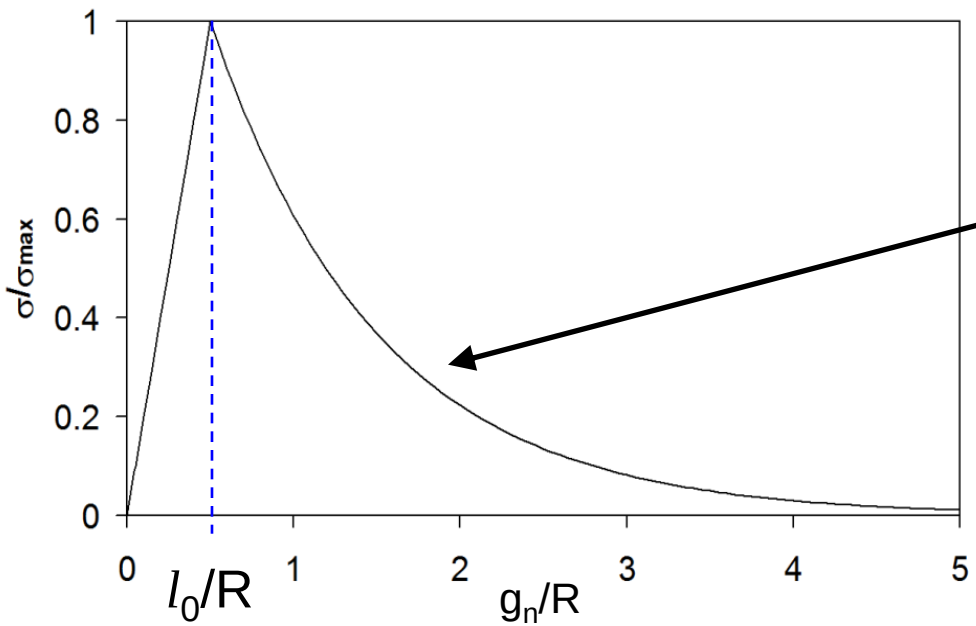
FRACTURE

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



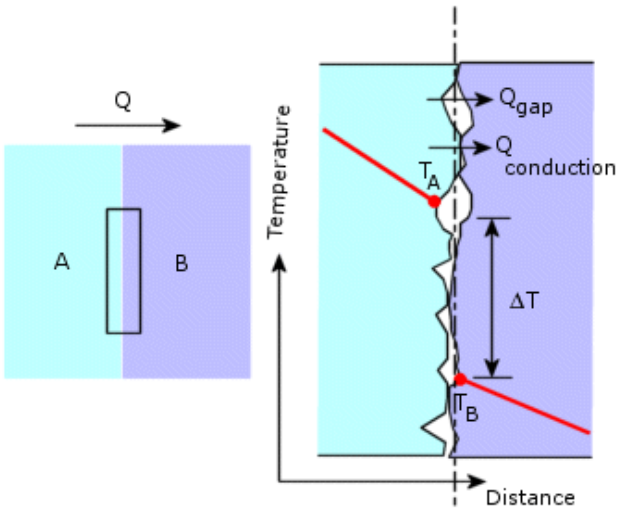


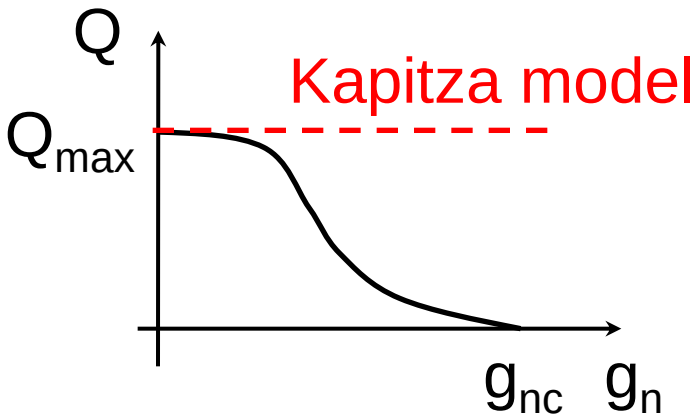
$$\sigma = \begin{cases} \sigma_{\max} \exp\left(\dfrac{-l_0 - |g_t|}{R}\right) \dfrac{g_n}{l_0}, & \text{if} \quad 0 \le \dfrac{g_n}{R} < \dfrac{l_0}{R} \\ \sigma_{\max} \exp\left(\dfrac{-g_n - |g_t|}{R}\right), & \text{if} \quad \dfrac{l_0}{R} \le \dfrac{g_n}{R} < \dfrac{g_{nc}}{R} \\ 0, & \text{if}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



Exponential decay inspired by micromechanical contact models:

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





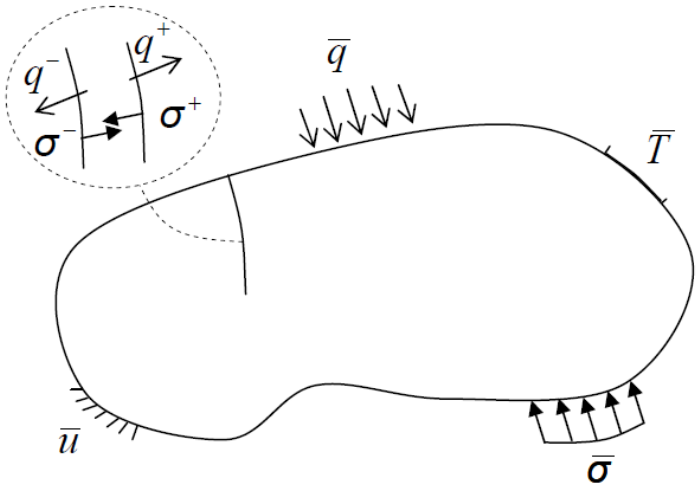
Thermal conductance proportional to the normal stiffness:

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

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

Paggi and Barber (2011) Int. J. Heat Mass Transfer

FE implementation



V: volume

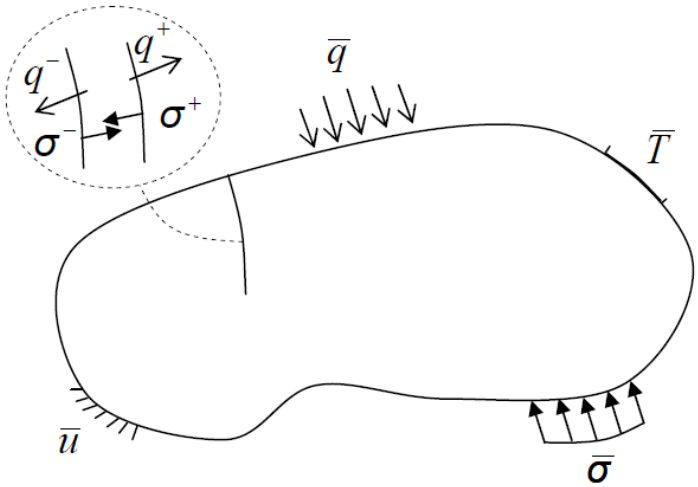
S: surface

S: Cauchy stress tensor
f: body force vector
w: displacement vector

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

Weak form:

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



V: volume

S: surface

$\mathbf{q}$: heat flux vector

Q: heat generation

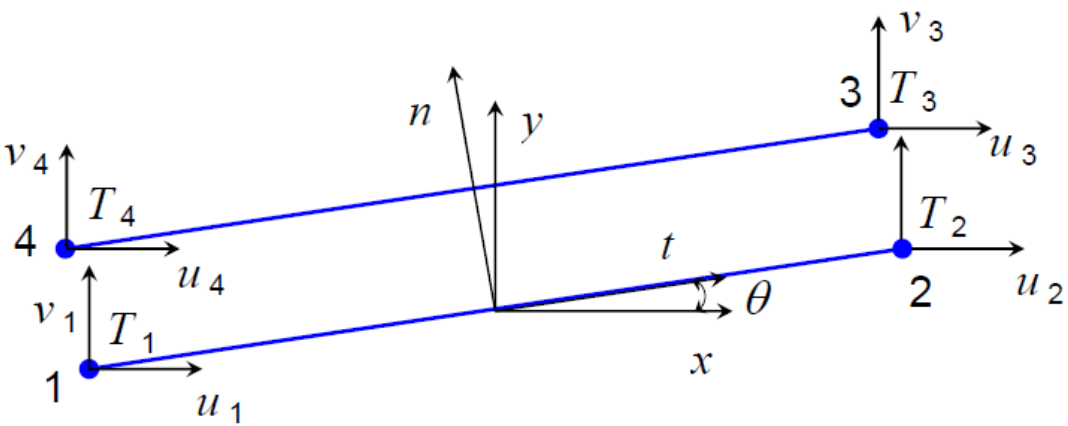
T: temperature

Strong form:

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

Weak form (energy balance):

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



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):

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

$$\mathbf{C} = \begin{bmatrix} \dfrac{\partial \tau}{\partial g_t} & \dfrac{\partial \tau}{\partial g_n} & 0 \\ \dfrac{\partial \sigma}{\partial g_t} & \dfrac{\partial \sigma}{\partial g_n} & 0 \\ \dfrac{\partial q}{\partial g_t} & \dfrac{\partial q}{\partial g_n} & \dfrac{\partial q}{\partial g_{\mathrm{T}}} \end{bmatrix}$$

Mechanical part

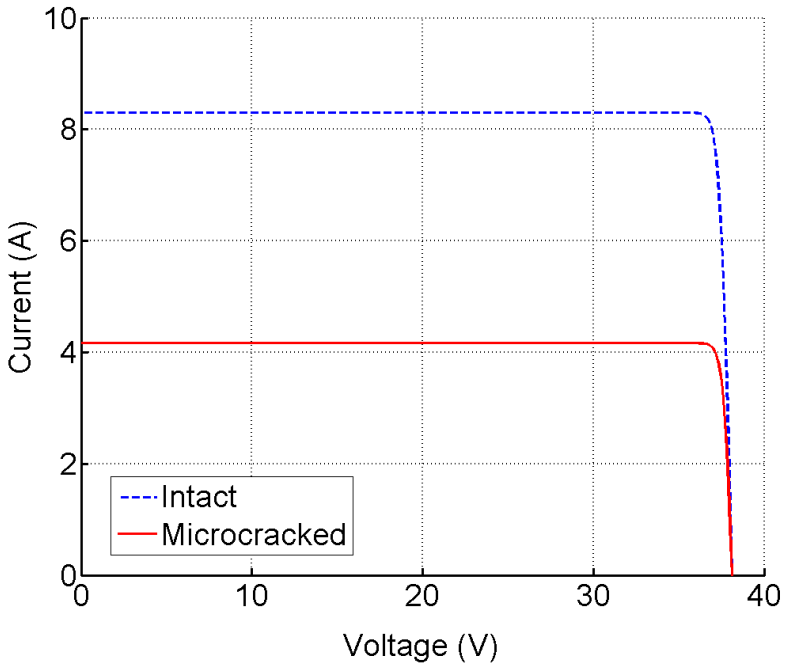
Thermoelastic part with coupling

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

Tangent stiffness matrix of the interface element:

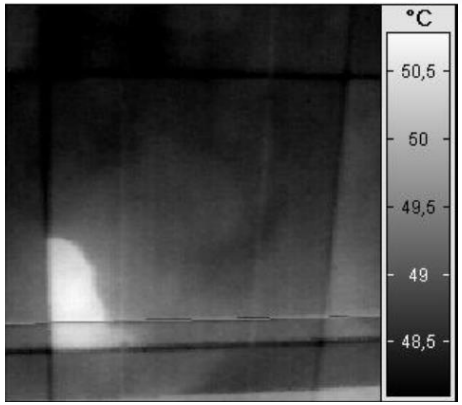
$$\mathrm{K} = \mathrm{R}^T \int_{S_{int}} \mathrm{B}^T \mathrm{C} \mathrm{B} dS \mathrm{R}$$

Example (1)

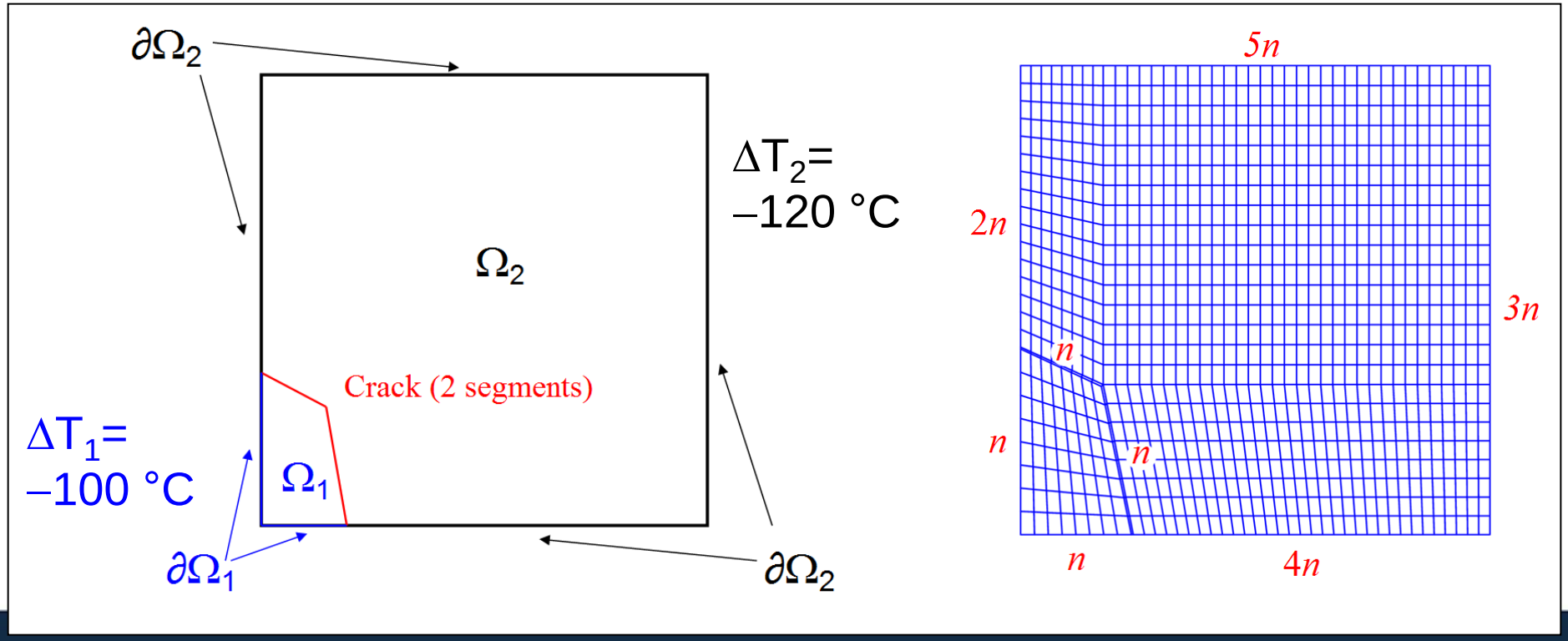


Paggi, Corrado, Rodriguez
Composite Structures, 2013

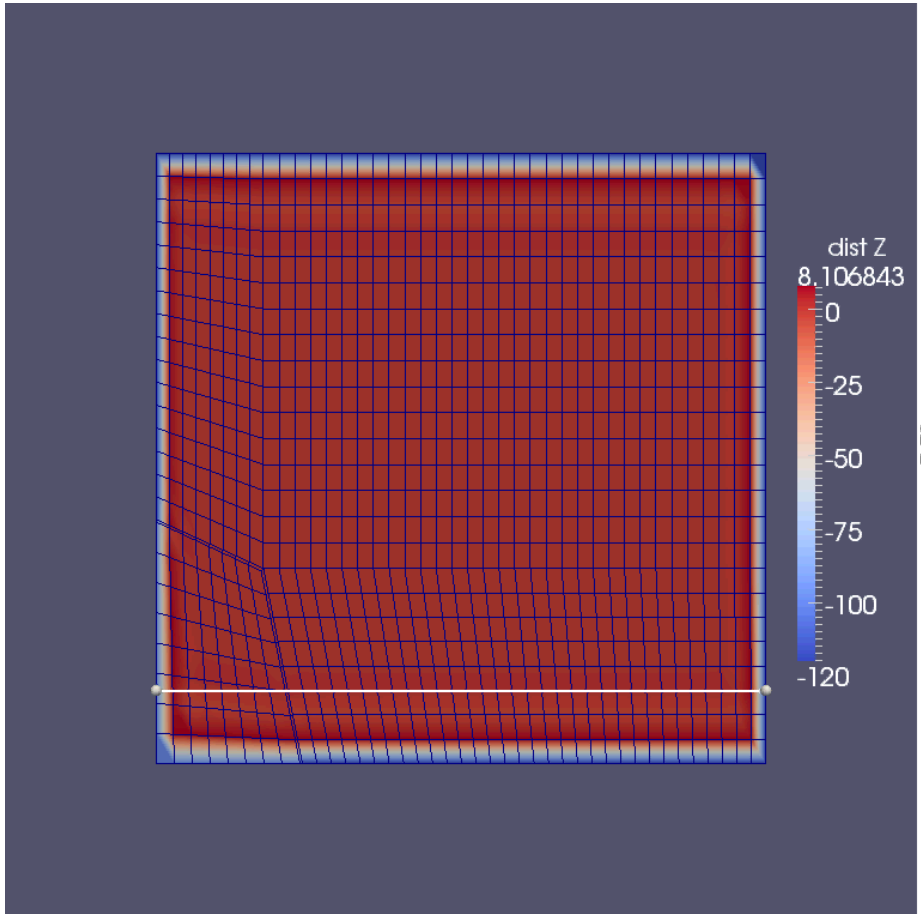
Example (2)

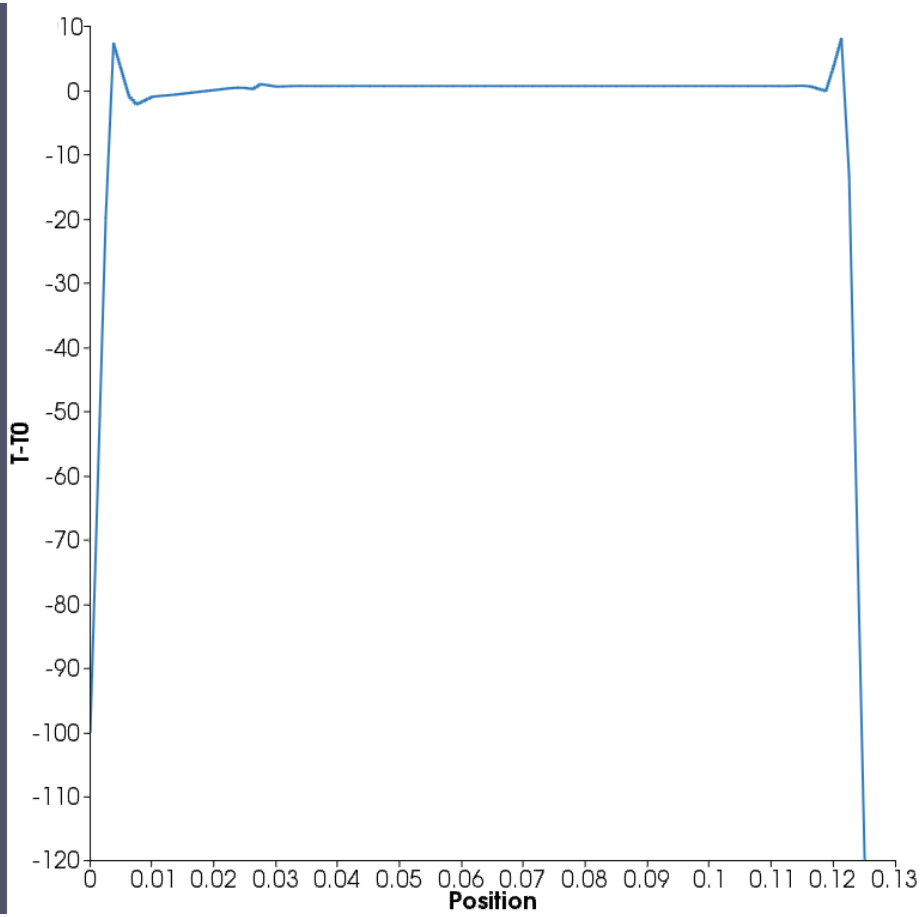


Stress-free temperature coincident with the lamination temperature (T_0=150°C)

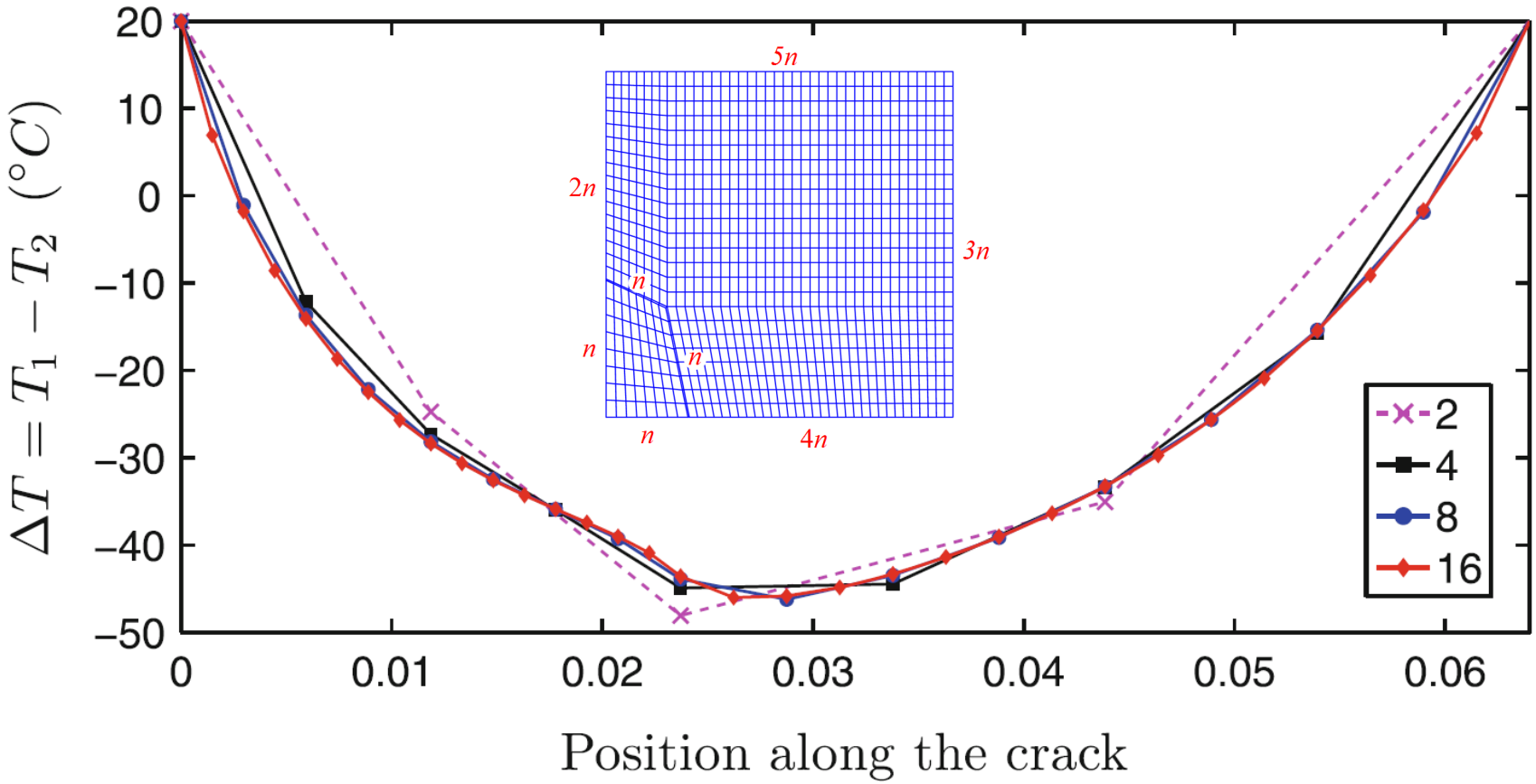


Example (2)

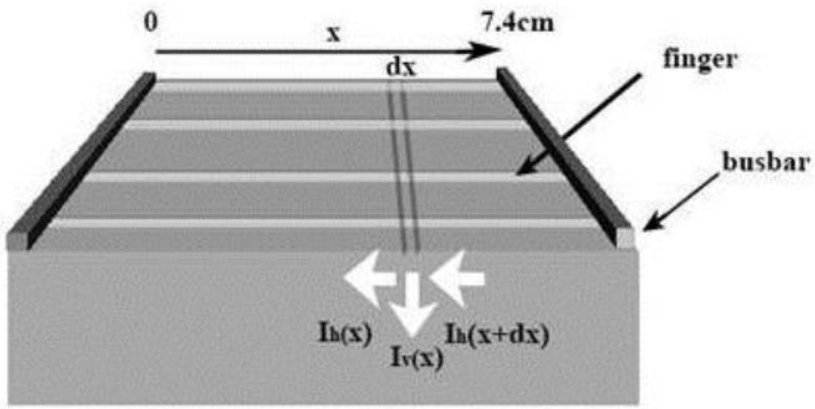

dist Z
8.106843
0
-25
-50
-75
-100
-120


T-T0
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
Position

Example (2)


20
10
0
−10
−20
−30
−40
−50
0
0.01
0.02
0.03
0.04
0.05
0.06
$\Delta T = T_1 - T_2$ (°C)
Position along the crack
5n
2n
3n
n
n
n
n
4n
2
4
8
16

Electric model



Berardone, Corrado, Paggi (2014)
Energy Procedia

Governing equations:

$$V(x+dx)=V(x)+V'(x)dx+\frac{V''(x)}{2}dx^2$$

$$V'(x+dx)=V'(x)+V''(x)dx$$

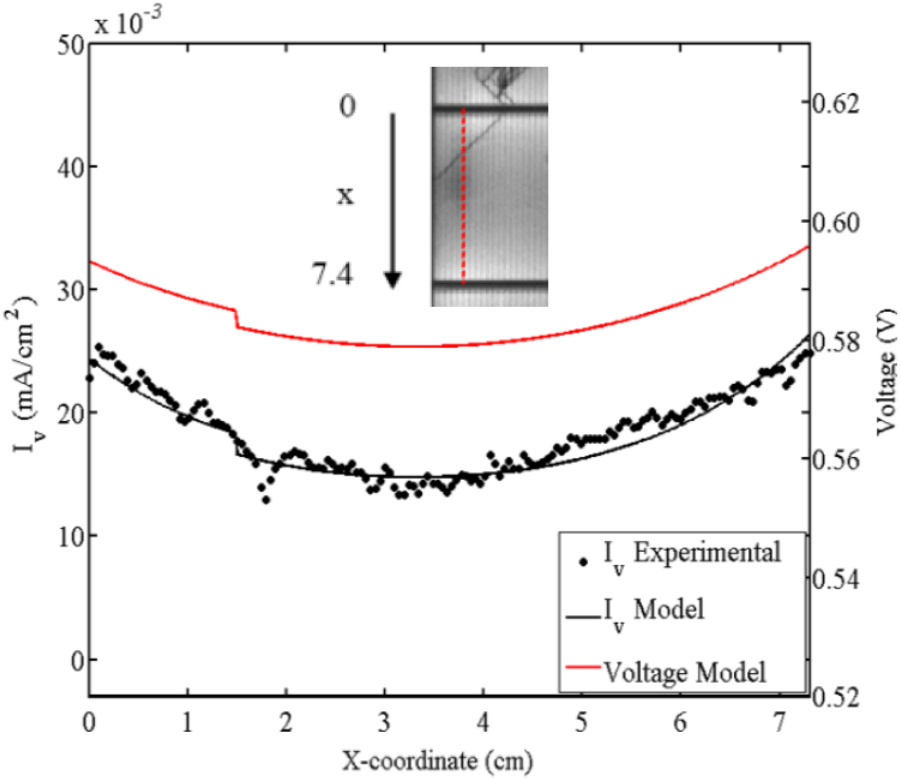
$$I_h(x+dx)=I_h(x)+I_v(x)dx$$

$$V(x_{cr}^{+})=V(x_{cr}^{-})+R_{cr}I_h(x_{cr})$$

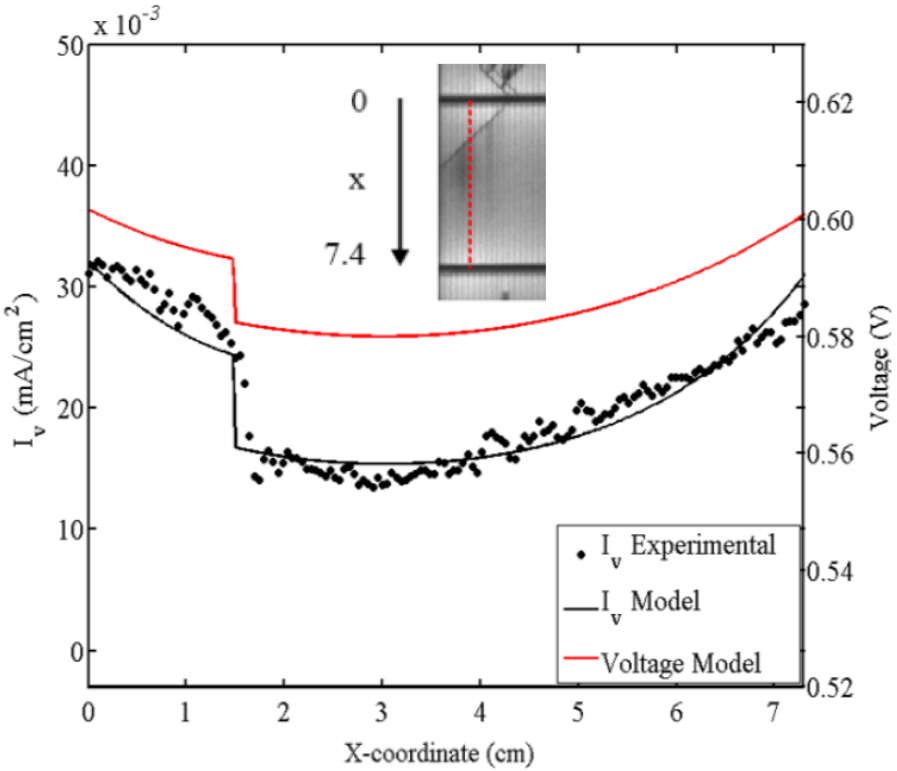
Boundary conditions:

$$V(x_0)=V_0;\ \ V'(x_0)=0$$

Example (1)

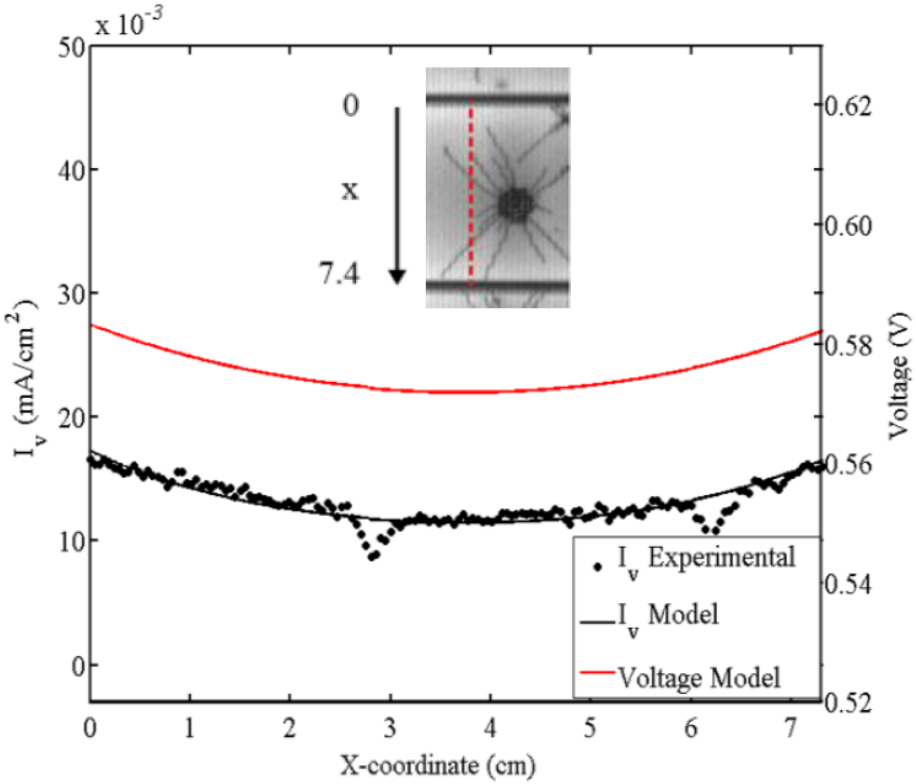


(a) Unloaded condition.
(x_0=3.33 cm, V_0=0.579 V, R_{cr}=0.096 Ωcm2)

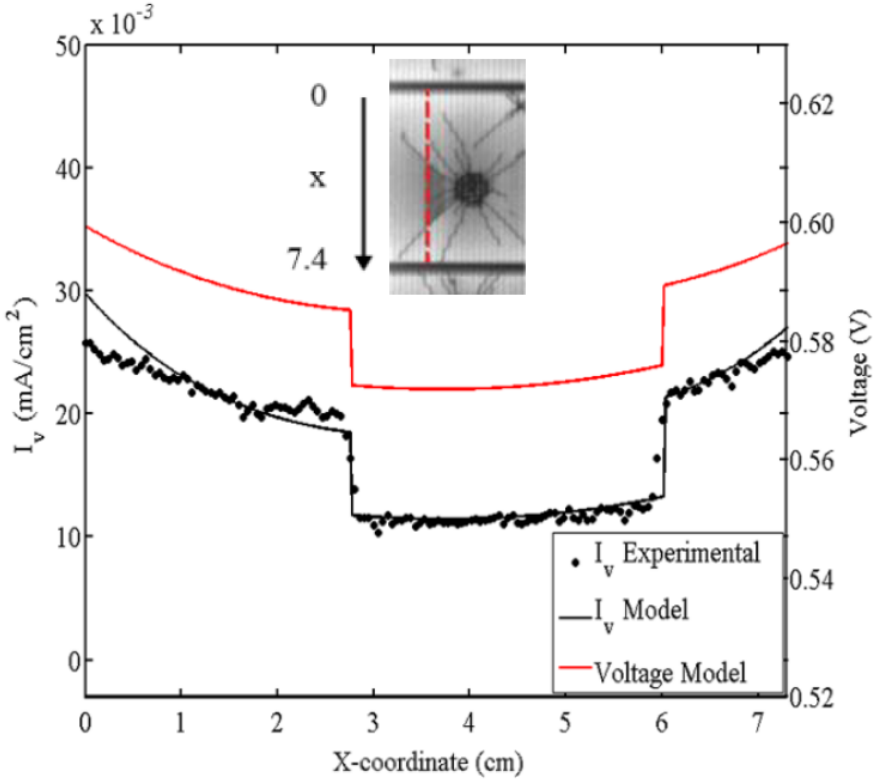


(b) Loaded condition.
(x_0=3.03 cm, V_0=0.580 V, R_{cr}=0.22 Ωcm2)

Example (2)



(a) Unloaded condition.
(x_0=3.73 cm, V_0=0.572 V, R_{cr1}=R_{cr2}=0.0 Ωcm^2)



(b) Loaded condition. (x_0=3.72 cm,
V_0=0.572 V, R_{cr1}=1.13 Ωcm^2, R_{cr2}=0.48 Ωcm^2)

Conclusions

Conclusions:

Understanding of coupled (multi-physics) effects in PV modules is important to assess the actual power-loss, in addition to worst case scenarios

Work in progress:

Realization of a single computational tool integrating thermo-elastic finite element simulations, fracture mechanics and electric models

Simulation of thermo-mechanically-driven spalling, in collaboration with ISFH

Modelling of Graphene-based solar cells

Outreach activities on energy in sustainable infrastructures in cooperation with Columbia University, Virginia Tech, Northwestern University and the Hong Kong University of Science and Technology

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FIRB Future in Research 2010

"Structural mechanics models for renewable energy applications"

ERC Starting Grant IDEAS 2012

"Multi-field and Multi-scale Computational Approach to Design and Durability of PhotoVoltaic Modules" – **CA2PVM**