IMT INSTITUTE FOR ADVANCED STUDIES LUCCA

European Research Council
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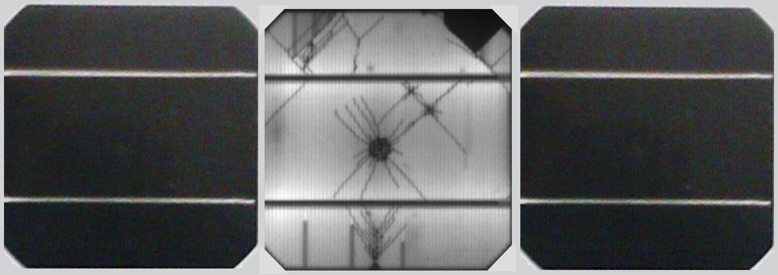
IDEAS

Durability of photovoltaics modules: modeling, simulation and experiments



Marco Paggi

IMT School for Advanced Studies Lucca

Dipartimento di Ingegneria dell'Informazione

Università di Pisa

October 26, 2016

MUSAM Research unit

- **M. Paggi**, Associate Professor
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- **M. Gagliardi**, Post-doc
- **F. Fantoni**, Post-doc
- **I. Berardone**, Post-doc
- **O.S. Ojo**, Post-doc
- **P. Lenarda**, Post-doc
- **V. Carollo**, PhD student (30th cycle)
- **P. Cinat**, PhD student (30th cycle)
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- **R. Del Toro**, PhD student (31st cycle)
- **N. Dardano**, PhD student (32nd cycle)
- **T. Guillen Hernandez**, PhD student (32nd cycle)

Visiting professors

- **D. Bigoni**, Full Professor, University of Trento, ERC AdG, Italy
- **J. Reinoso**, Assistant Professor, University of Seville, Spain
- **M. Corrado**, Assistant Professor, PoliTO & Marie Curie Fellow at EPFL
- **A. Gizzi**, Assistant Professor, Università Campus Bio-Medico of Rome

Introduction, motivation, aims

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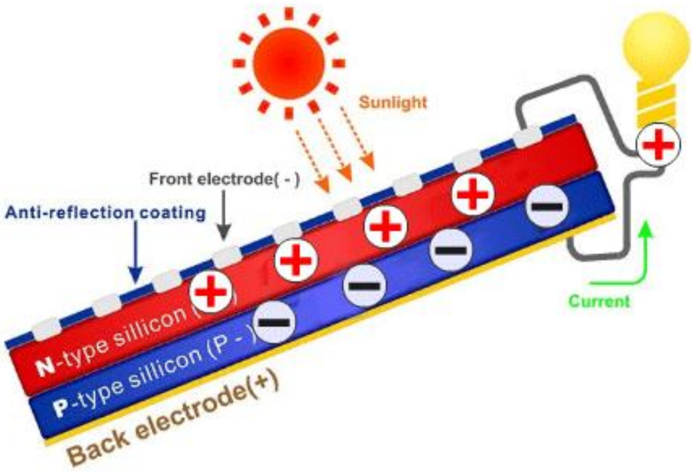
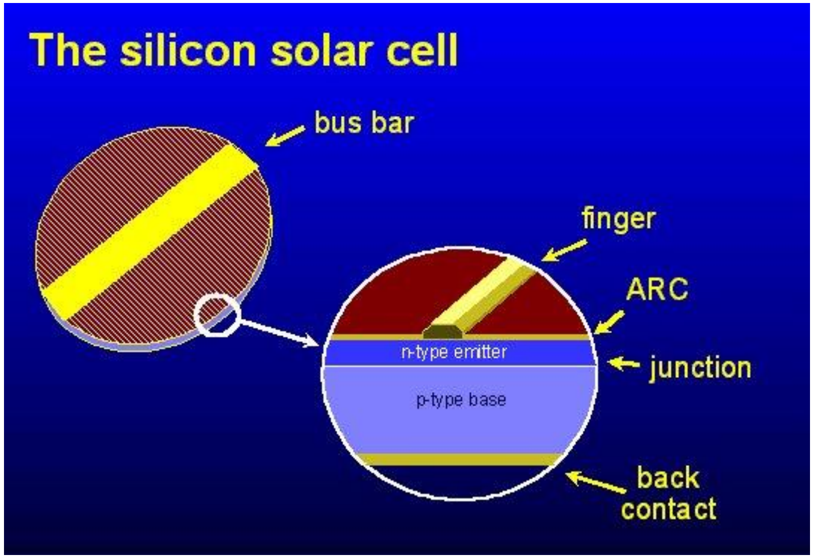
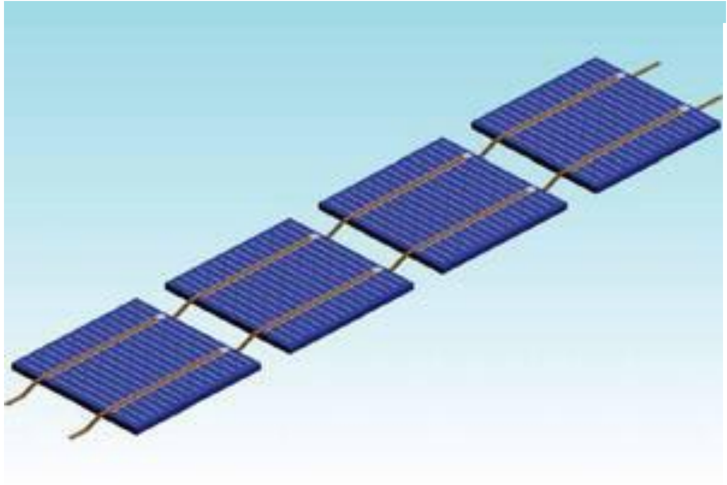
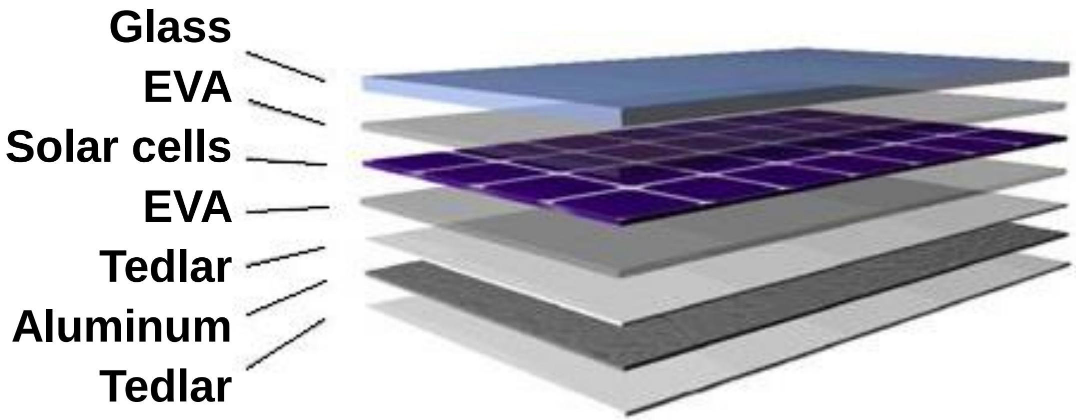
Photovoltaics (PV)









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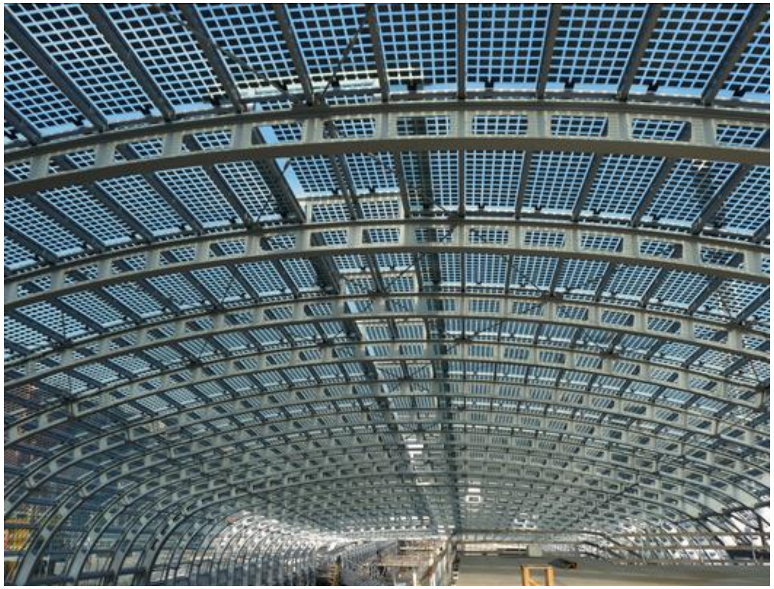
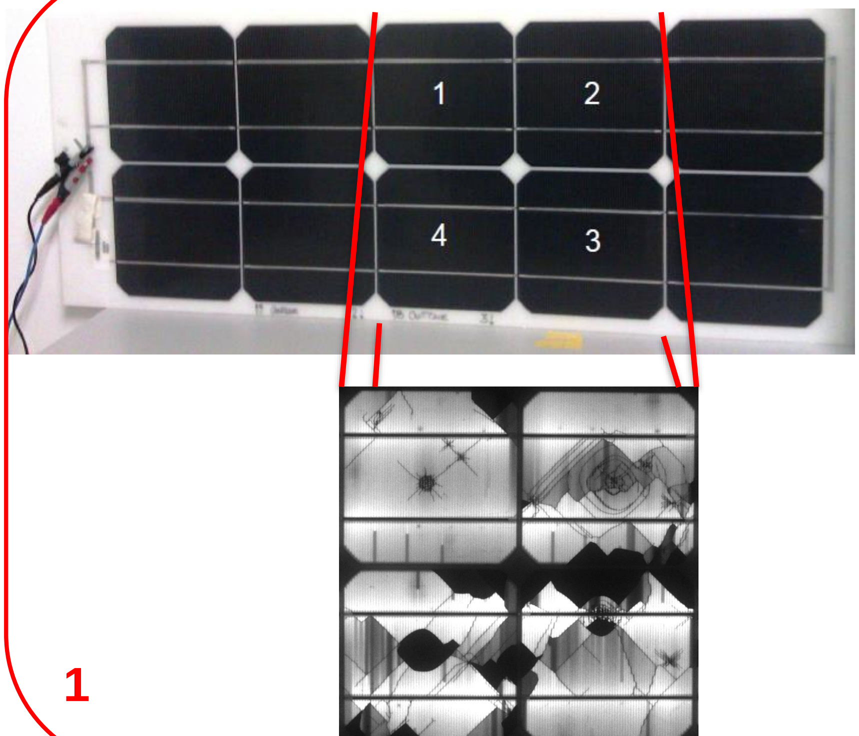
Applications: from PV parks to BIPV



Durability

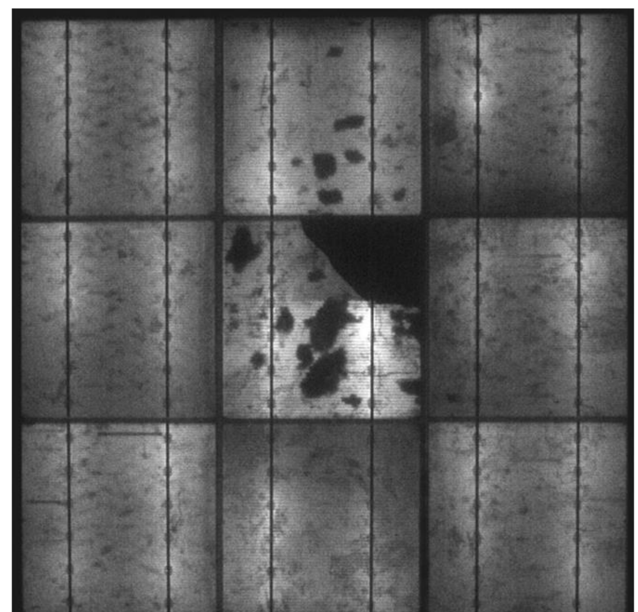
Some failure modes of PV modules:

1. **Cracks**
2. **Decohesion of the encapsulant**
3. **Moisture-induced degradation**



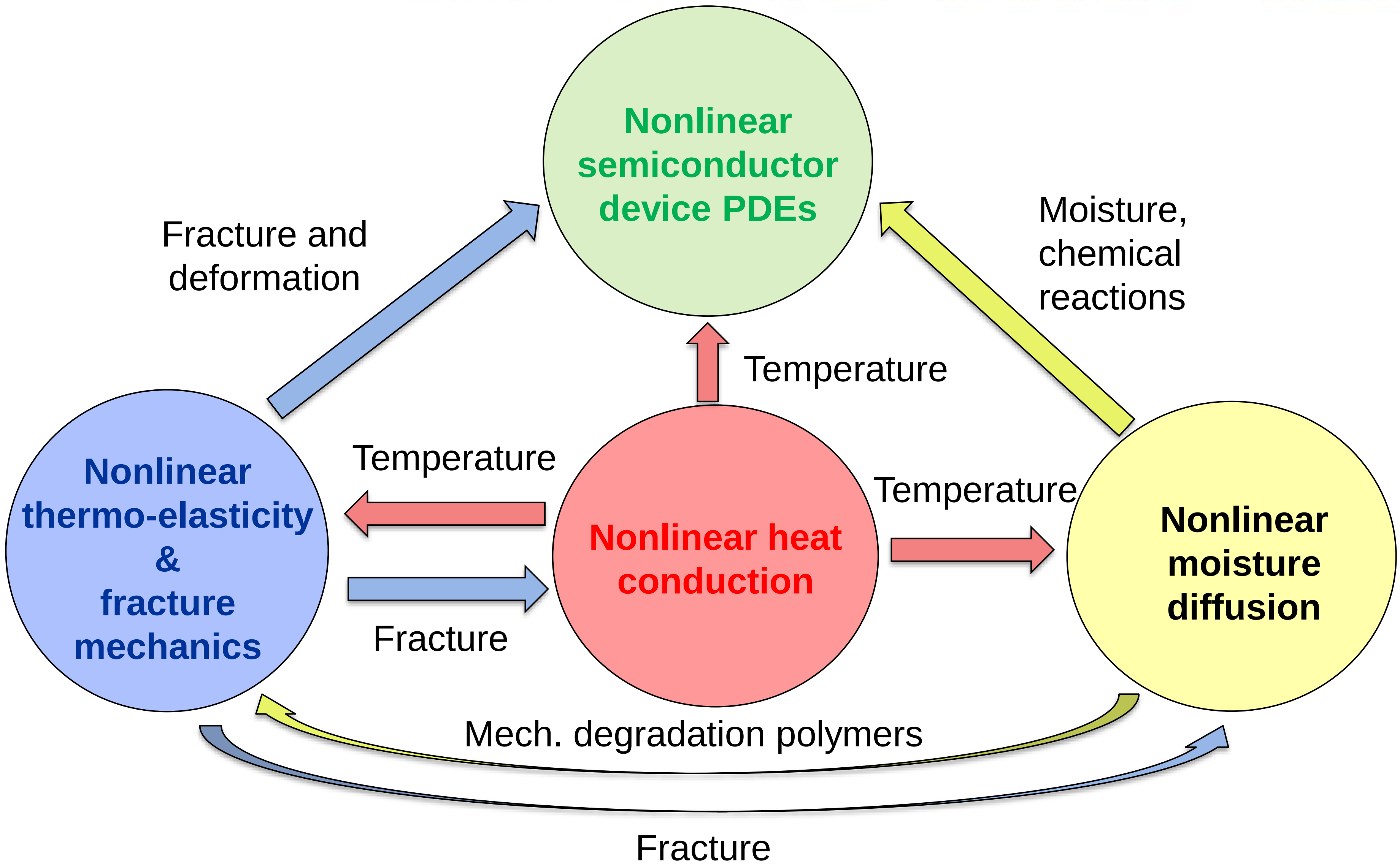
1

2



3

Multi-physics modelling & simulation



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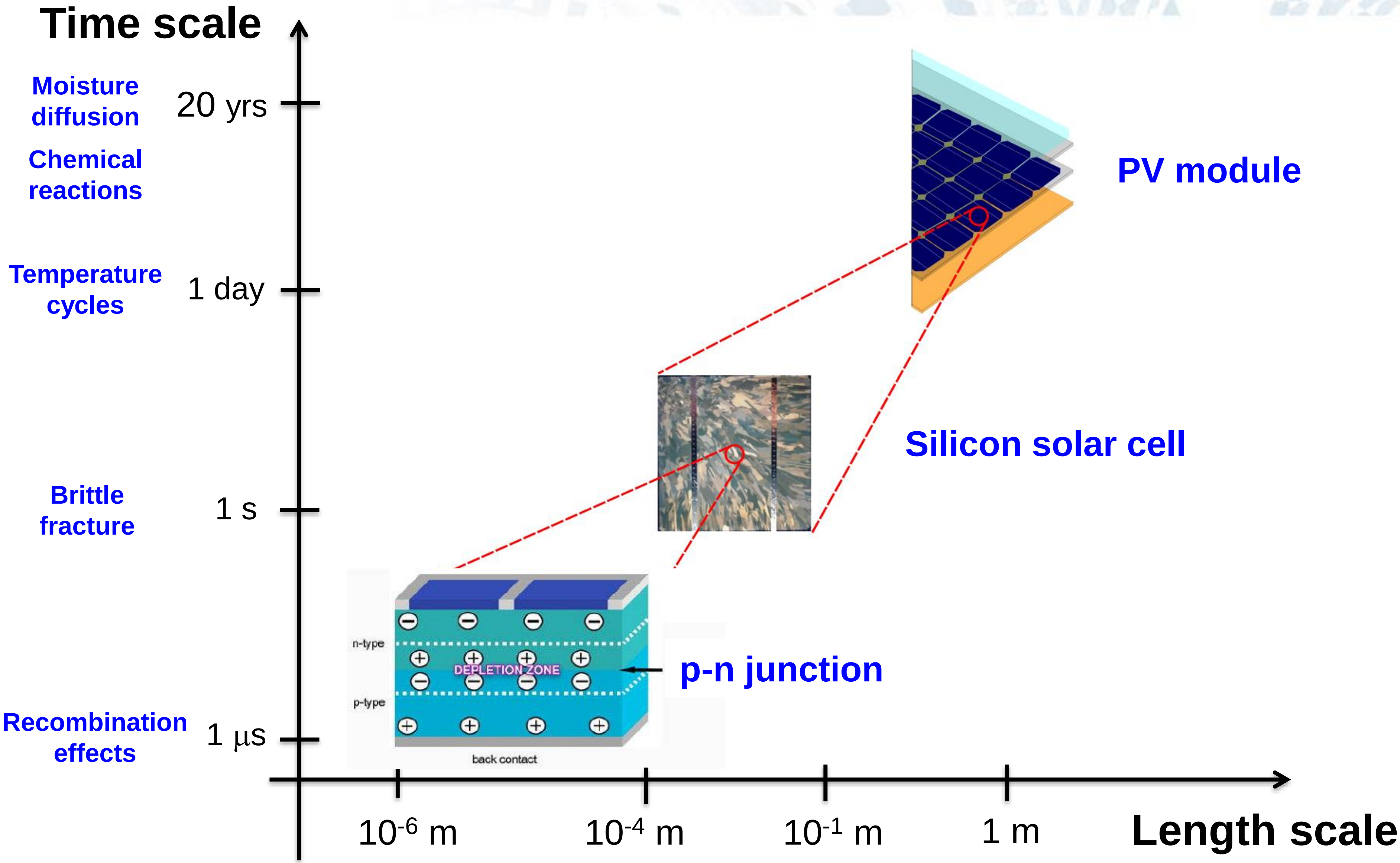
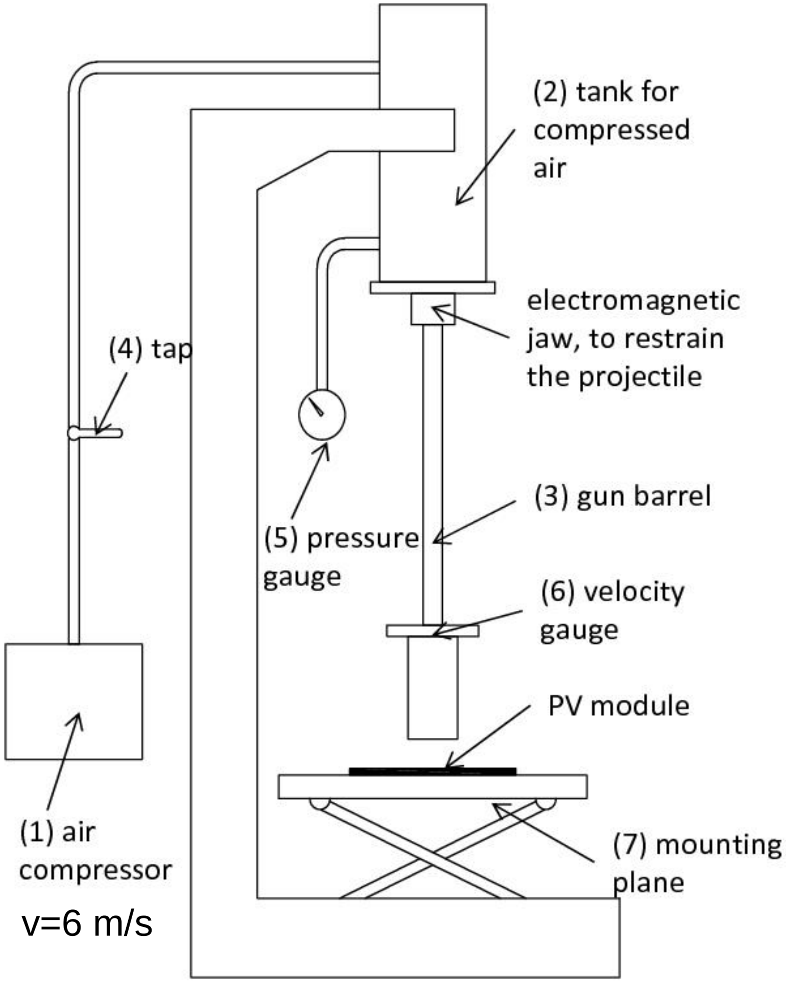
Length and time scales



Experimental tests

Simulated hail impact tests on flexible PV modules



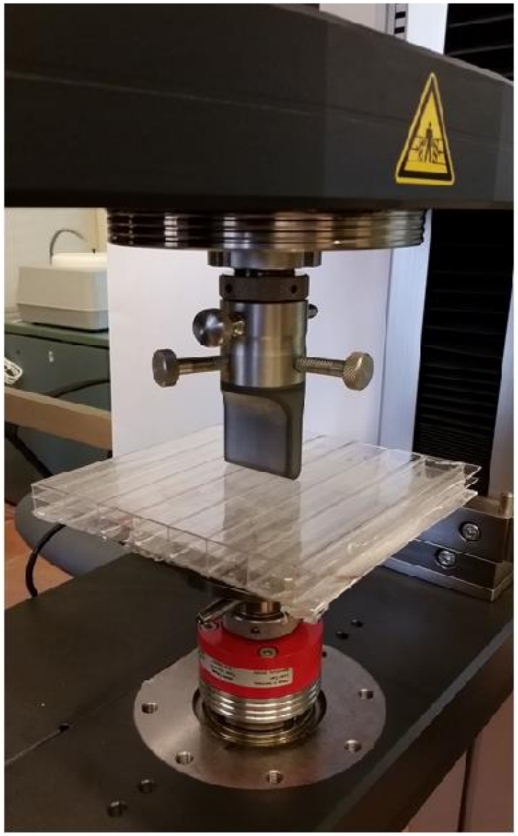
v=6 m/s

Corrado, Infuso, Paggi (2016) Simulated hail impact tests on photovoltaic laminates, Meccanica.

Substrate stiffness

(a)

Hard



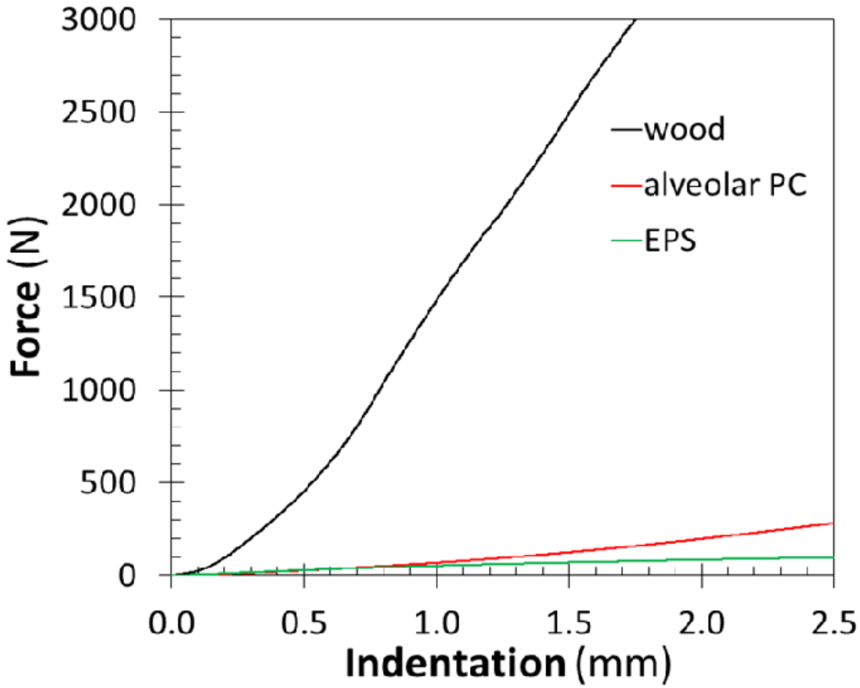
(b)

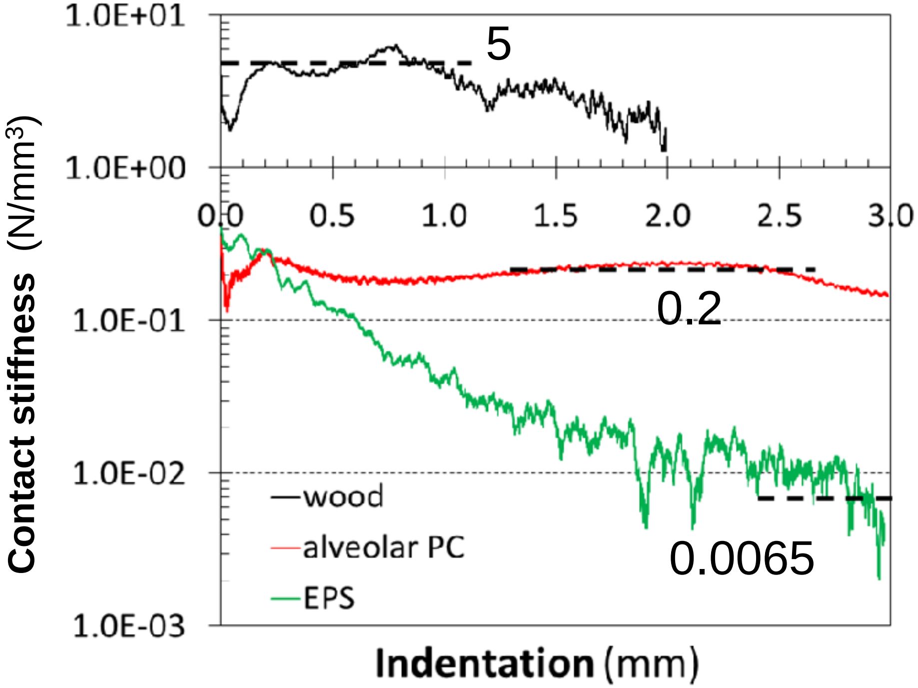
Medium

(c)

Soft

Substrate stiffness

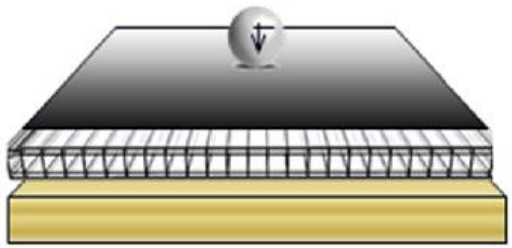




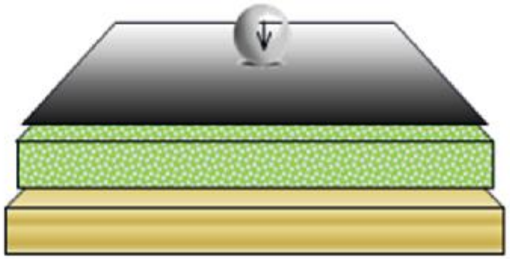
(1 : 30 : 770)

Crack patterns

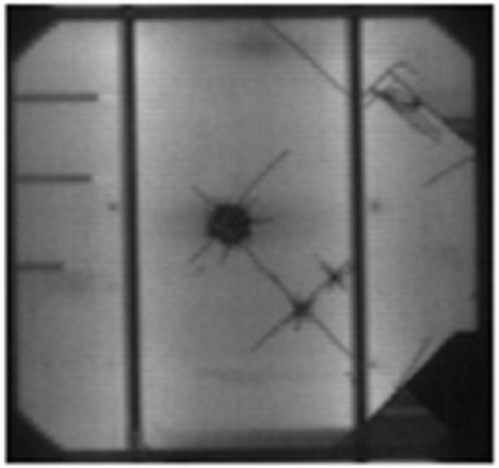
Wooden board



Alveolar PC +
Wooden board

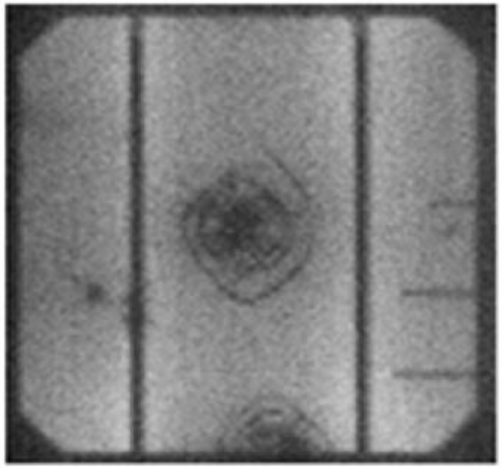


Polystirene +
Wooden board



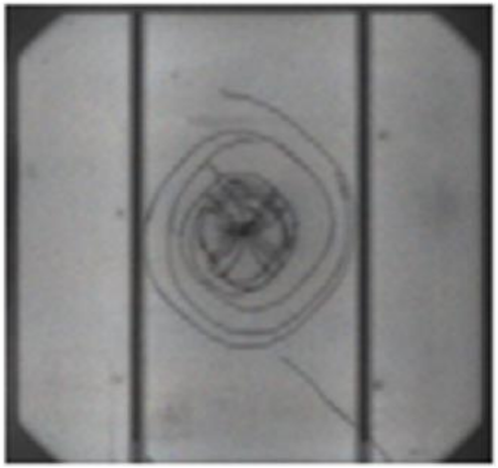
Case A: Hard substrate

r*=7.5 mm



CaseB: Medium substrate

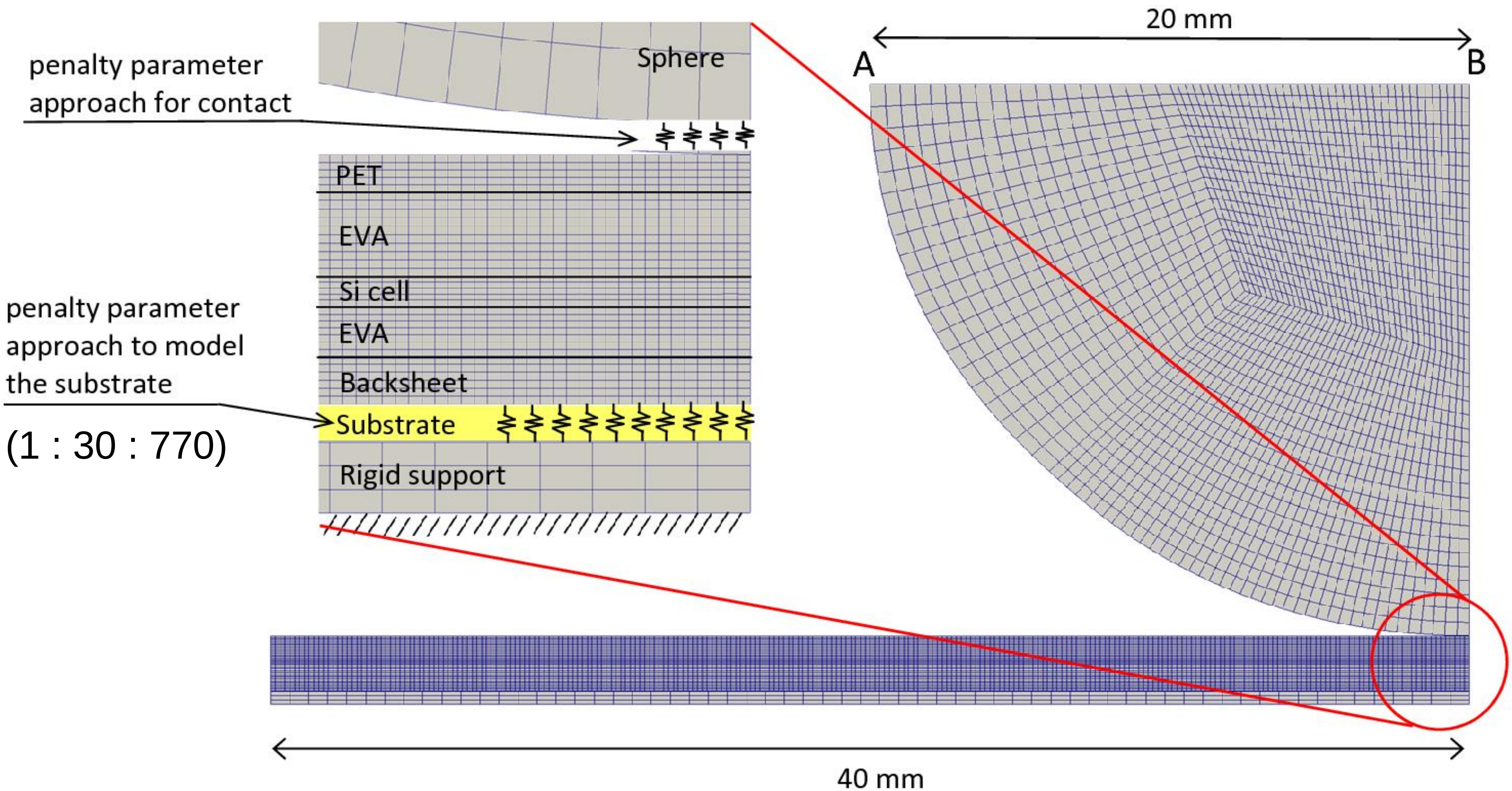
r*=15.8 mm



Case C: Soft substrate

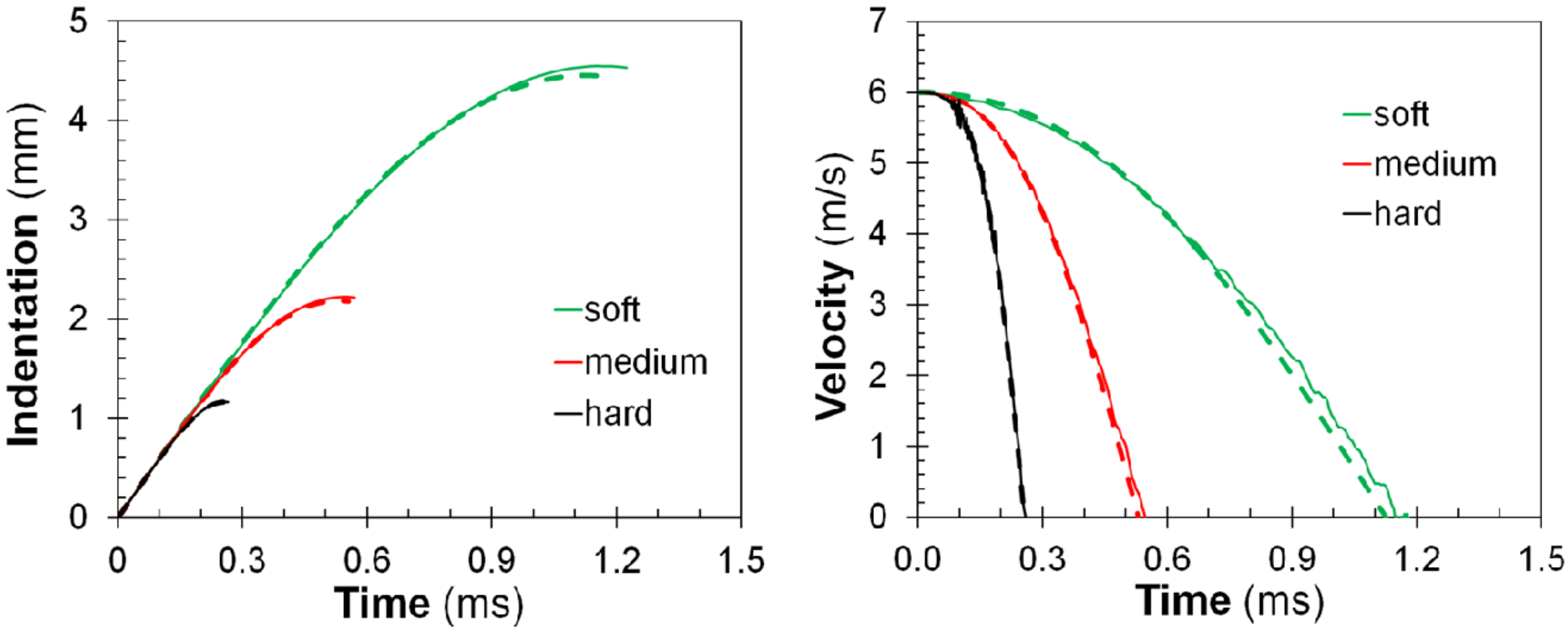
r*=31.0 mm

Finite element models



- **Approach 1 (simplified)**: quasi-static FE contact simulation & SDOF model
- **Approach 2 (the most accurate)**: dynamic fully implicit FE contact simulation

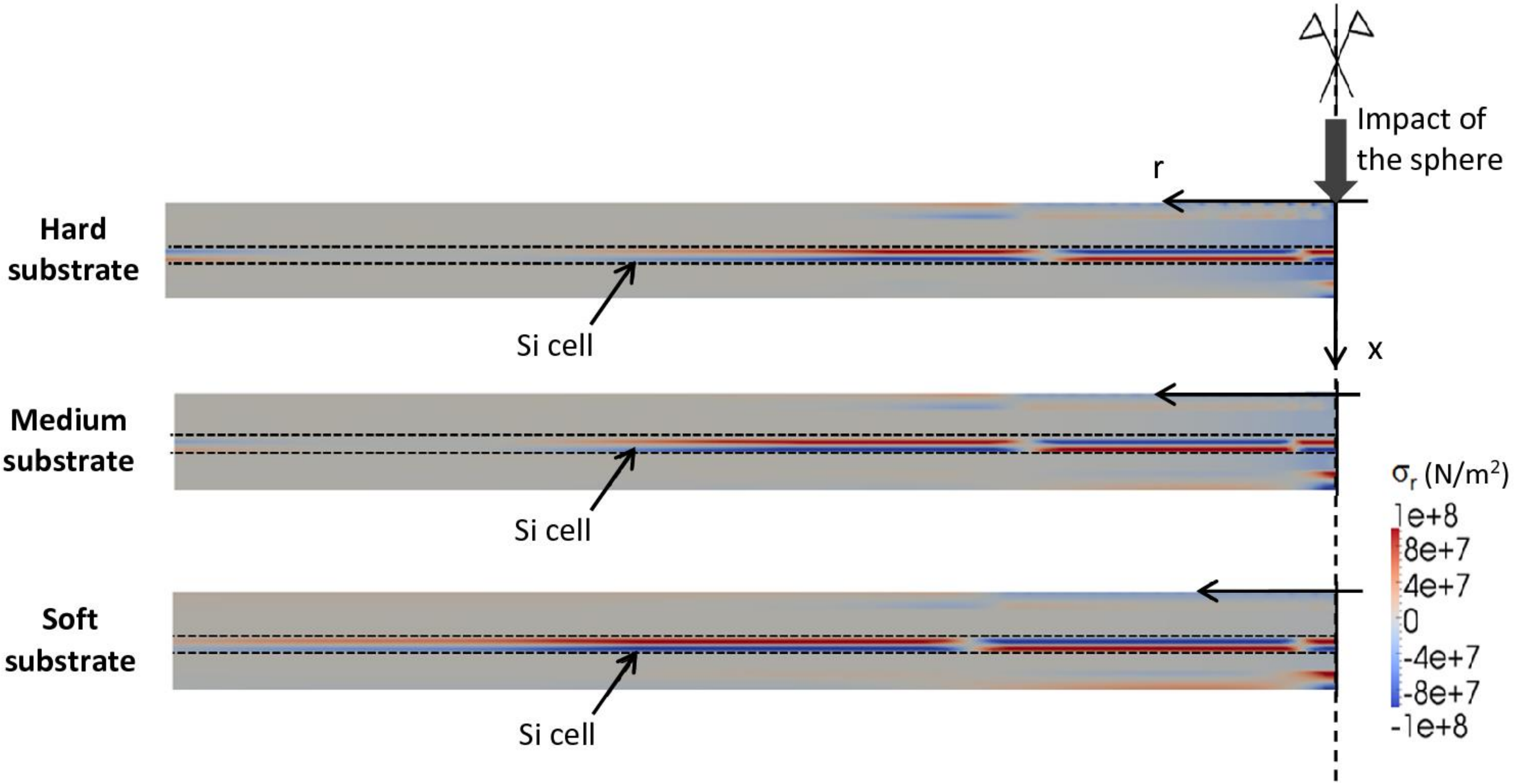
Dynamic response



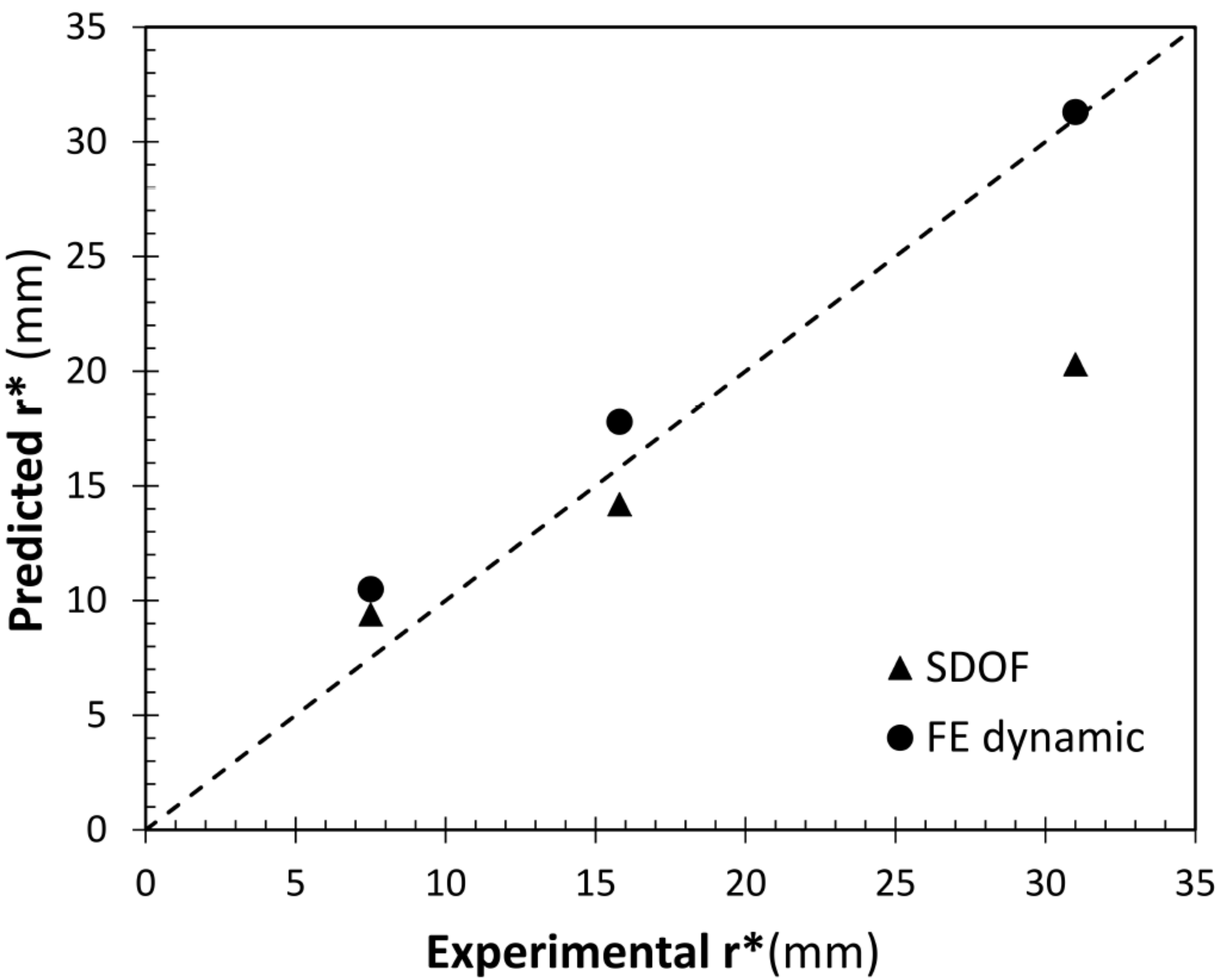
Approach 1 (simplified)

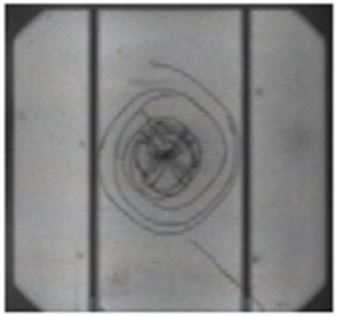
Approach 2 (the most accurate)

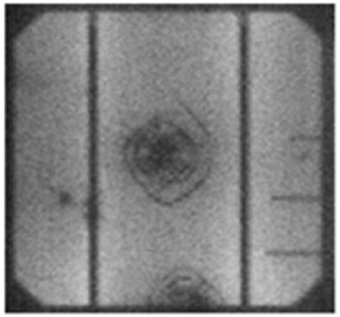
Radial stresses

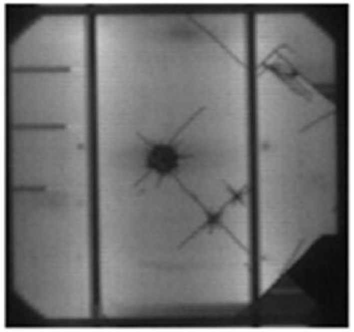


Size of the crack pattern

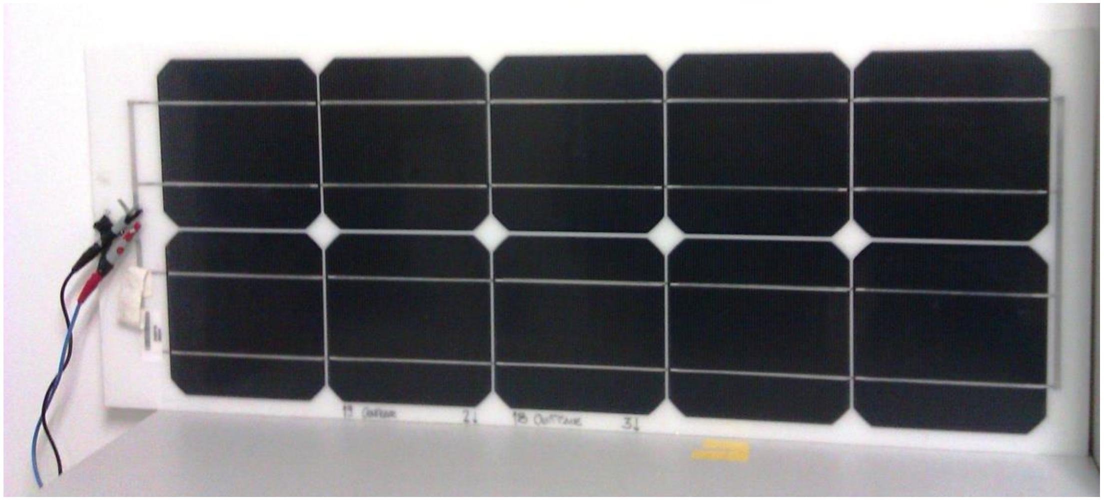


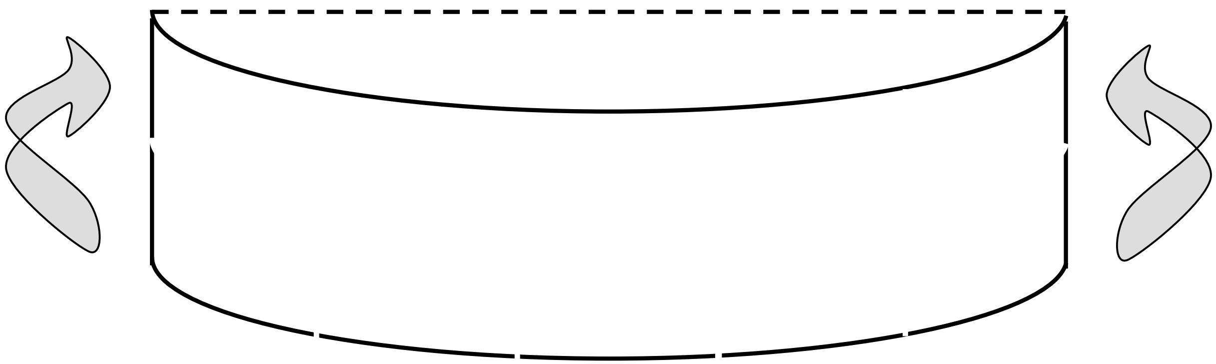




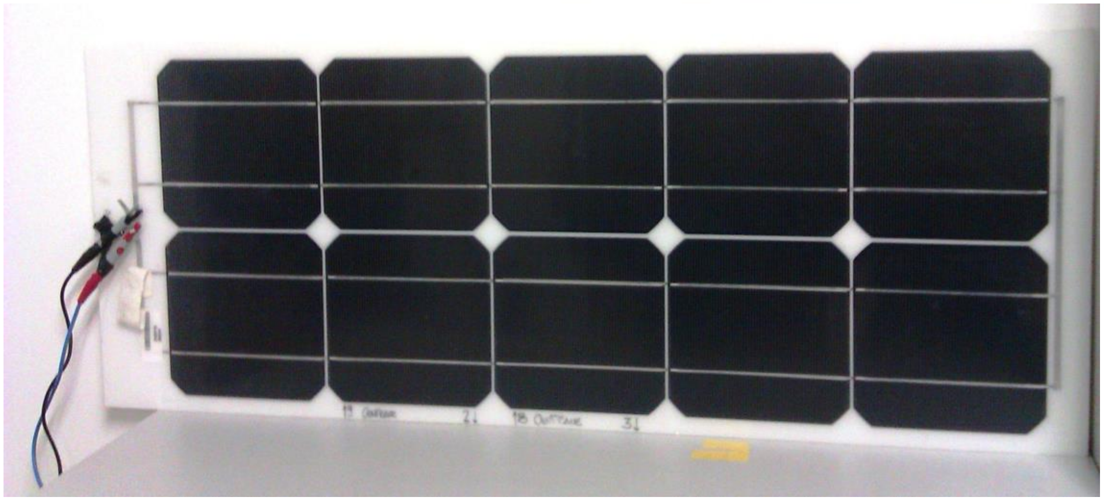


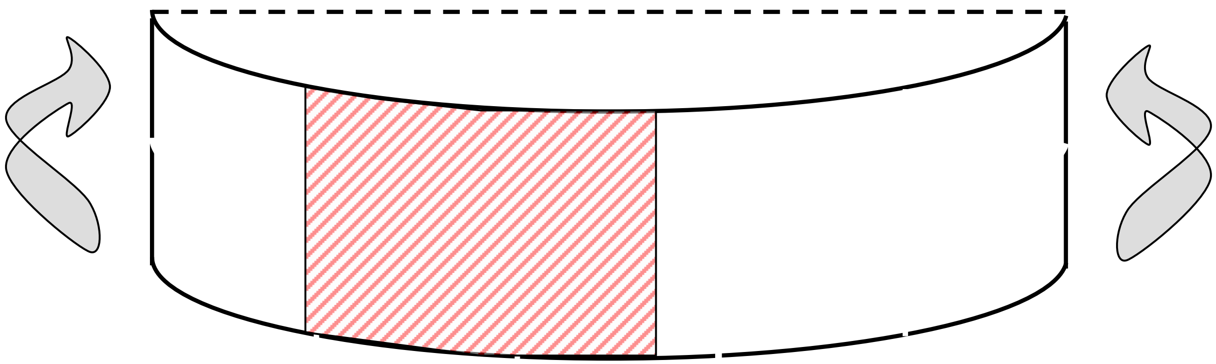
Influence of cracks and deformation on the electric field





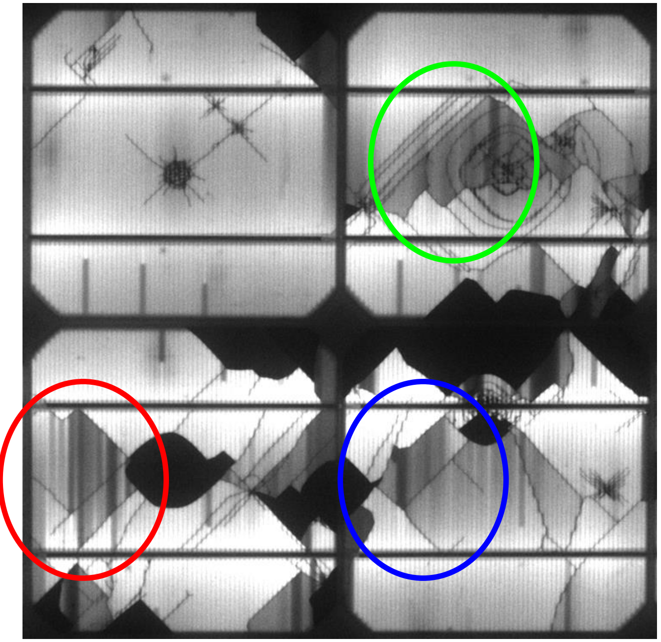
Paggi M, Berardone I, Infuso A, Corrado M (2014) Fatigue degradation and electric recovery in Silicon solar cells embedded in photovoltaic modules. **Sci. Rep.,** 4:4506.



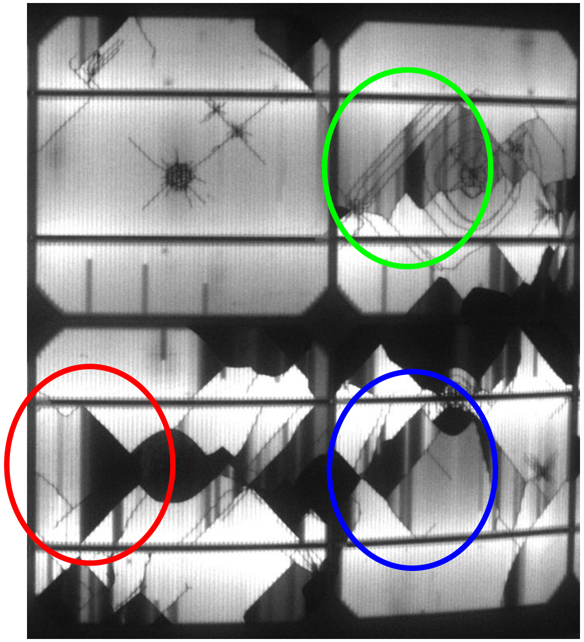


Paggi M, Berardone I, Infuso A, Corrado M (2014) Fatigue degradation and electric recovery in Silicon solar cells embedded in photovoltaic modules. Sci Rep 4:4506.

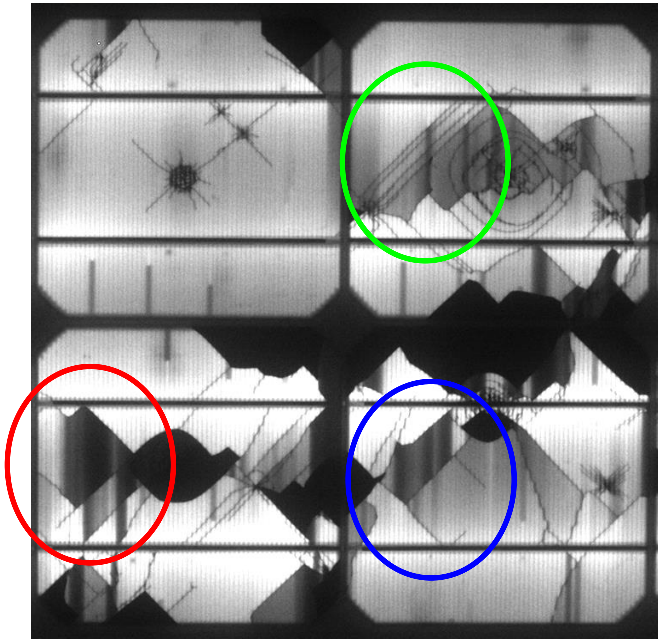
Results



Initial flat configuration



Max deflection

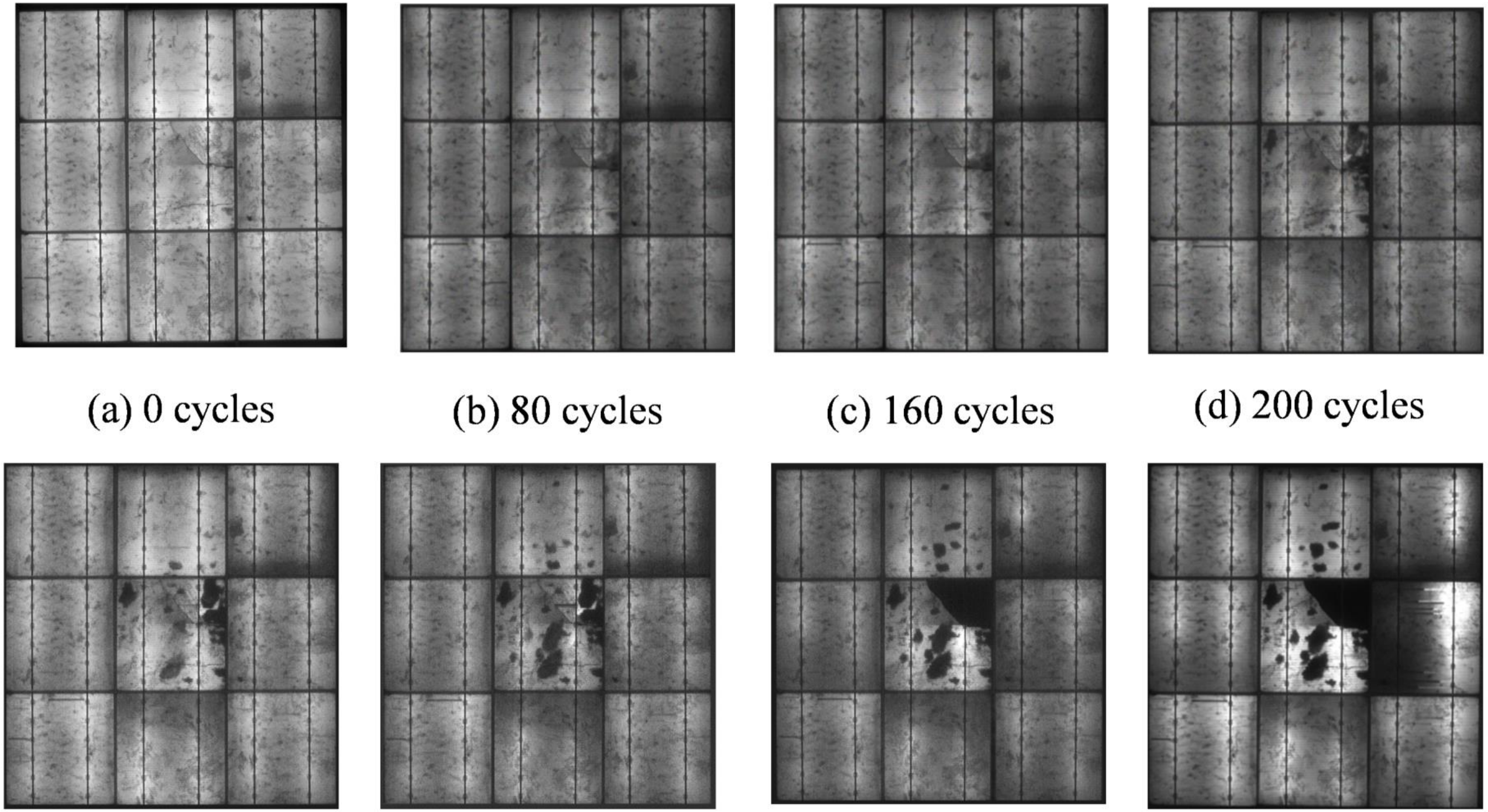


Final flat configuration

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

Aging of PV modules containing cracked solar cells

Accelerated degradation: damp-heat test

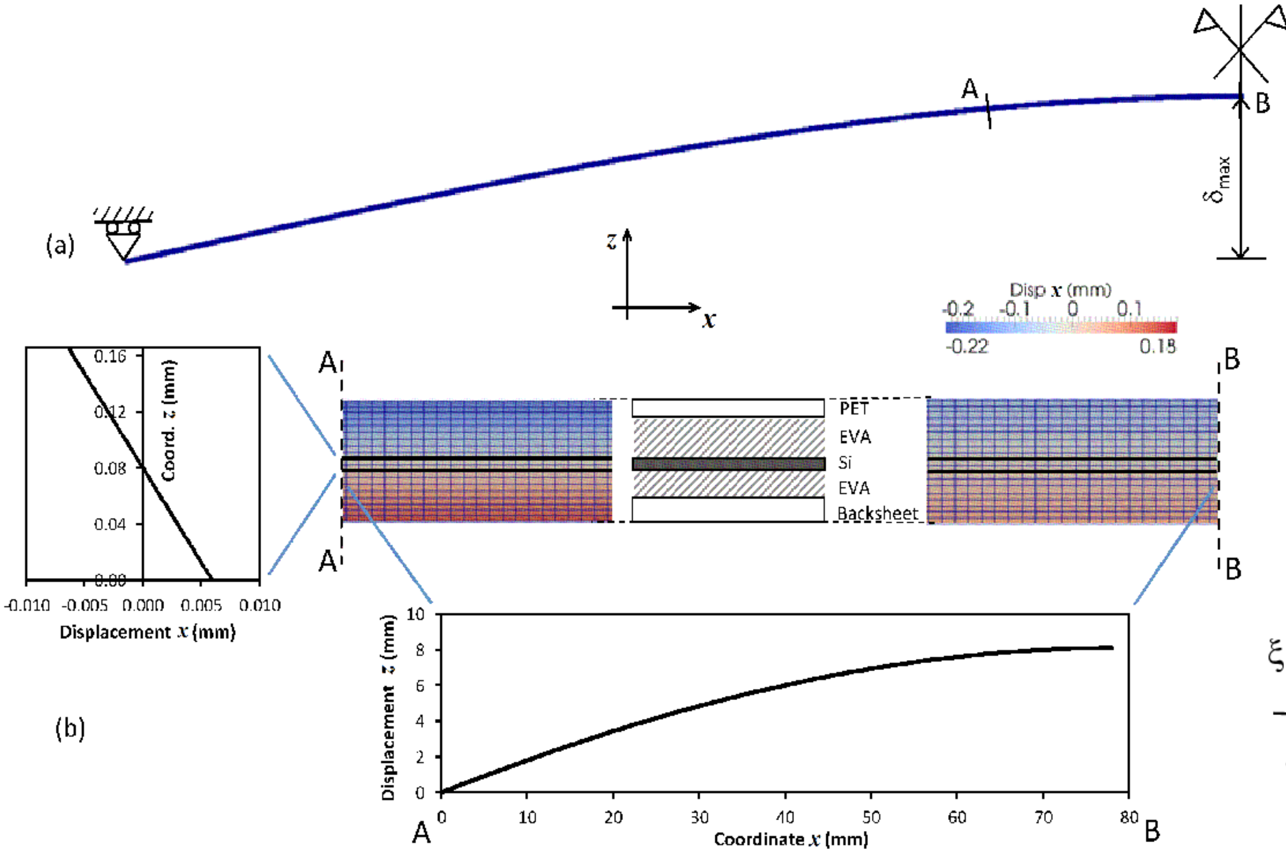


(a) 0 cycles (b) 80 cycles (c) 160 cycles (d) 200 cycles

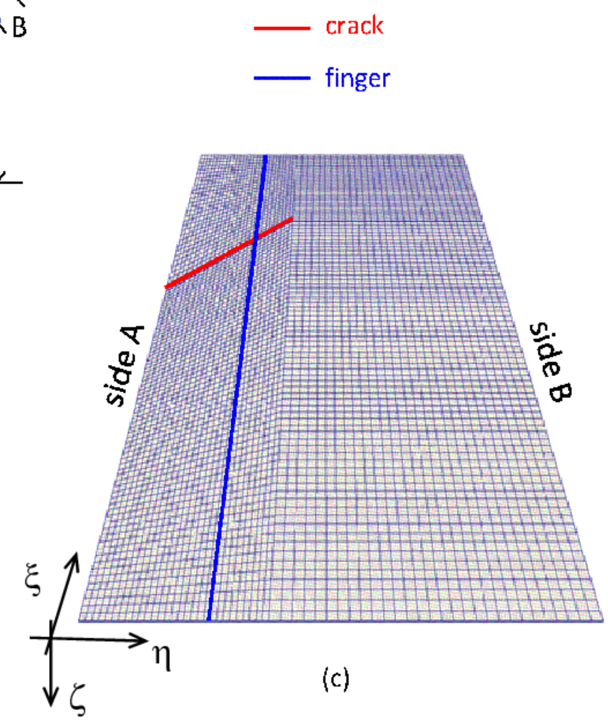
(e) 240 cycles (f) 320 cycles (g) 400 cycles (h) 500 cycles

Computational models

Global/local FE approach



Global (coarse scale) FE model

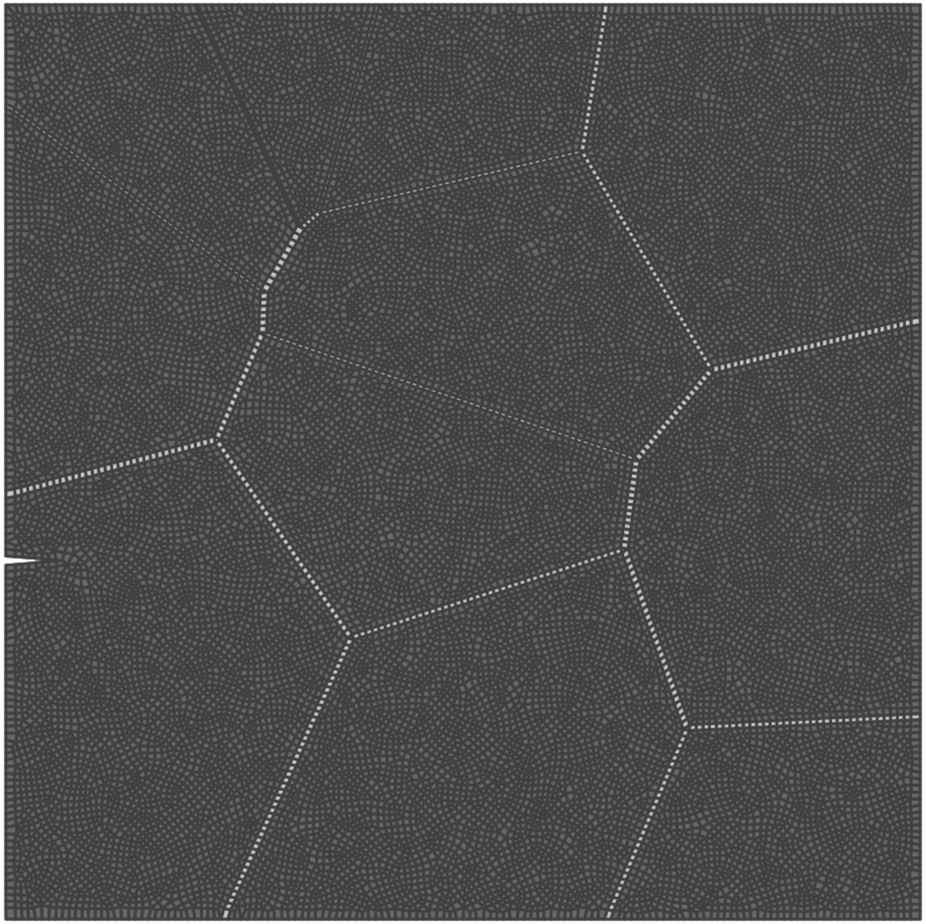


Local (fine scale) nonlinear FE model of each solar cells with cohesive cracks

Paggi M, Berardone I, Corrado M (2016) A global/local approach for the prediction of the electric response of cracked solar cells in photovoltaic modules under the action of mechanical loads. **EFM**, doi:10.1016/j.engfracmech.2016.01.018

Intergranular vs. transgranular fracture

Imposed vertical displacements



Initial defect

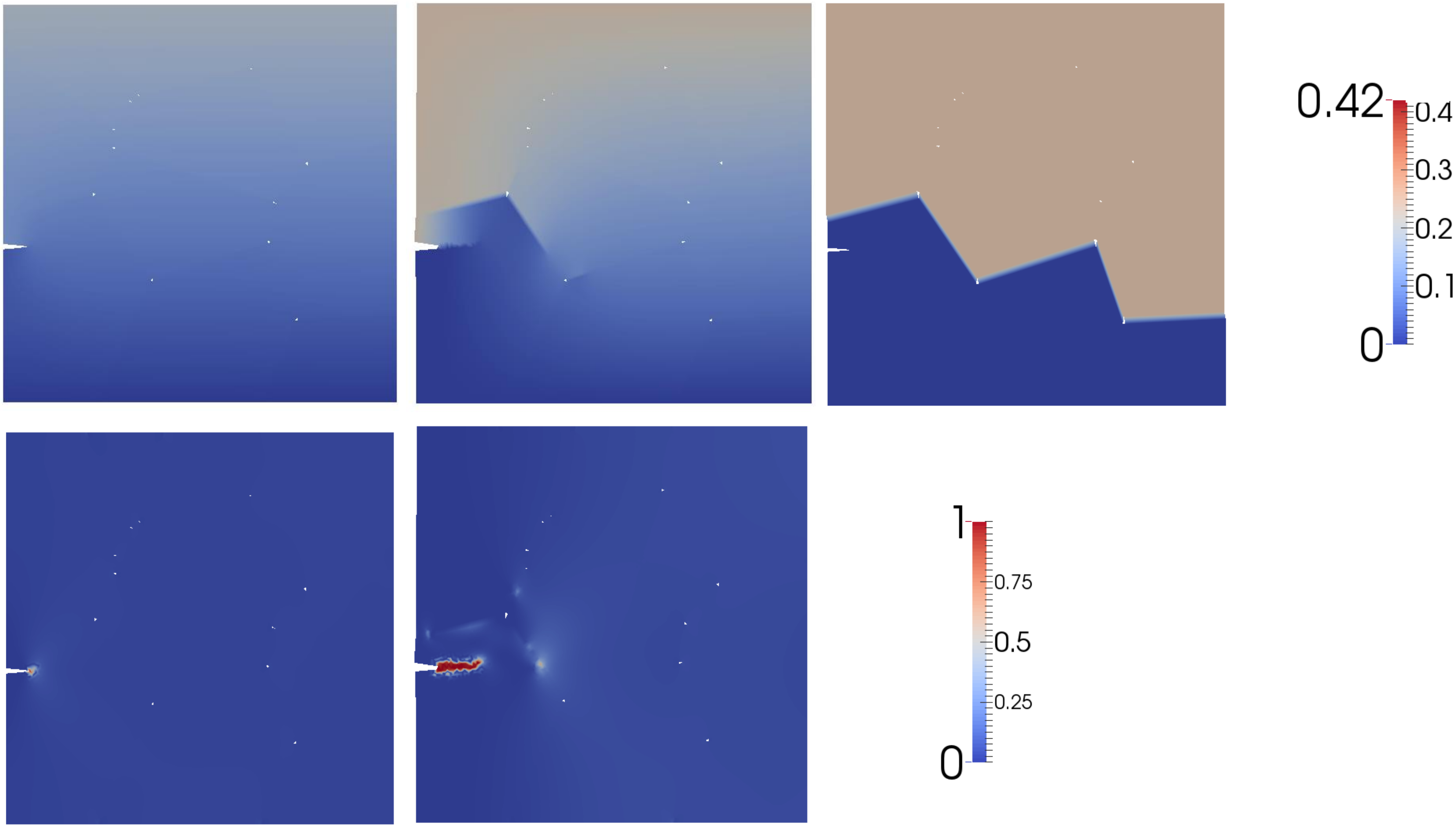
Clamped edge

Phase field approach for brittle fracture in the bulk

Cohesive zone model for the grain boundaries

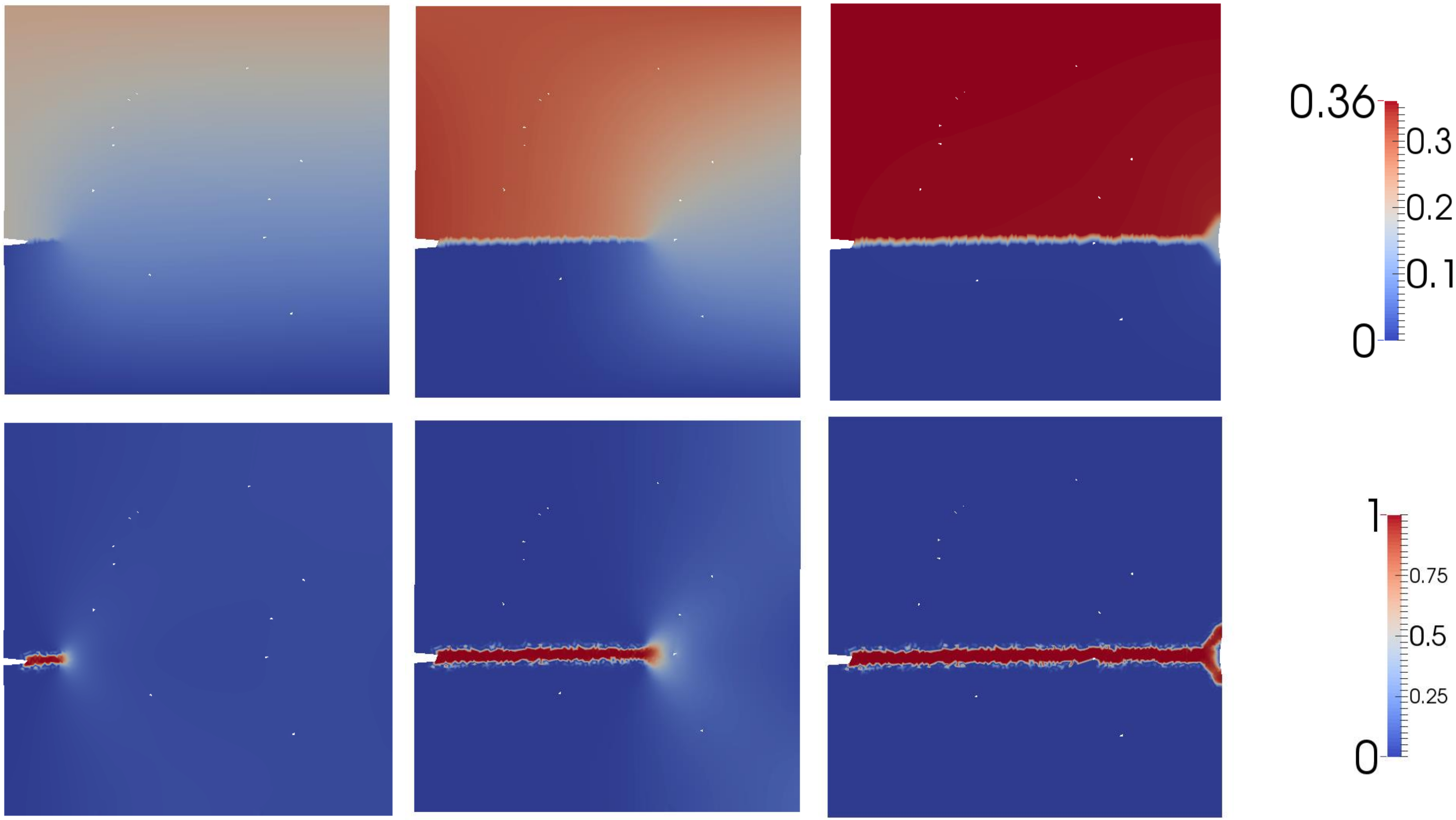
Paggi M, Reinoso J, Corrado M (2016) Intergranular vs. transgranular fracture based on a unified phase field-cohesive zone modeling framework, in preparation.

Intergranular vs. transgranular fracture



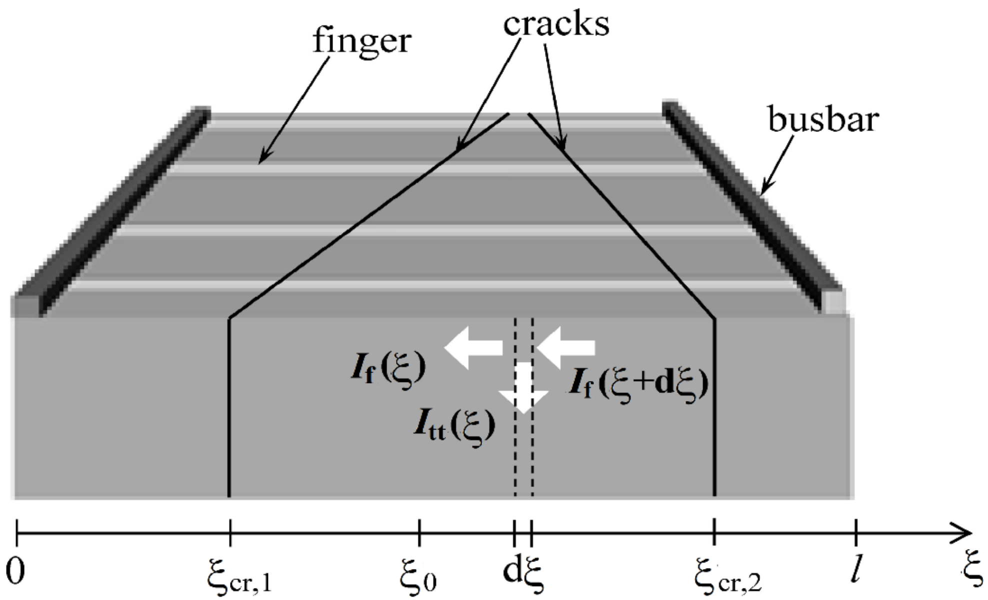
Paggi M, Reinoso J, Corrado M (2016) Intergranular vs. transgranular fracture based on a unified phase field-cohesive zone modeling framework, in preparation.

Intergranular vs. transgranular fracture



Paggi M, Reinoso J, Corrado M (2016) Intergranular vs. transgranular fracture based on a unified phase field-cohesive zone modeling framework, in preparation.

Electric model



$$\frac{dV(\xi)}{d\xi} = -\rho_S I_f(\xi)$$

$$\frac{dI_f(\xi)}{d\xi} = -I_{tt}(\xi)$$

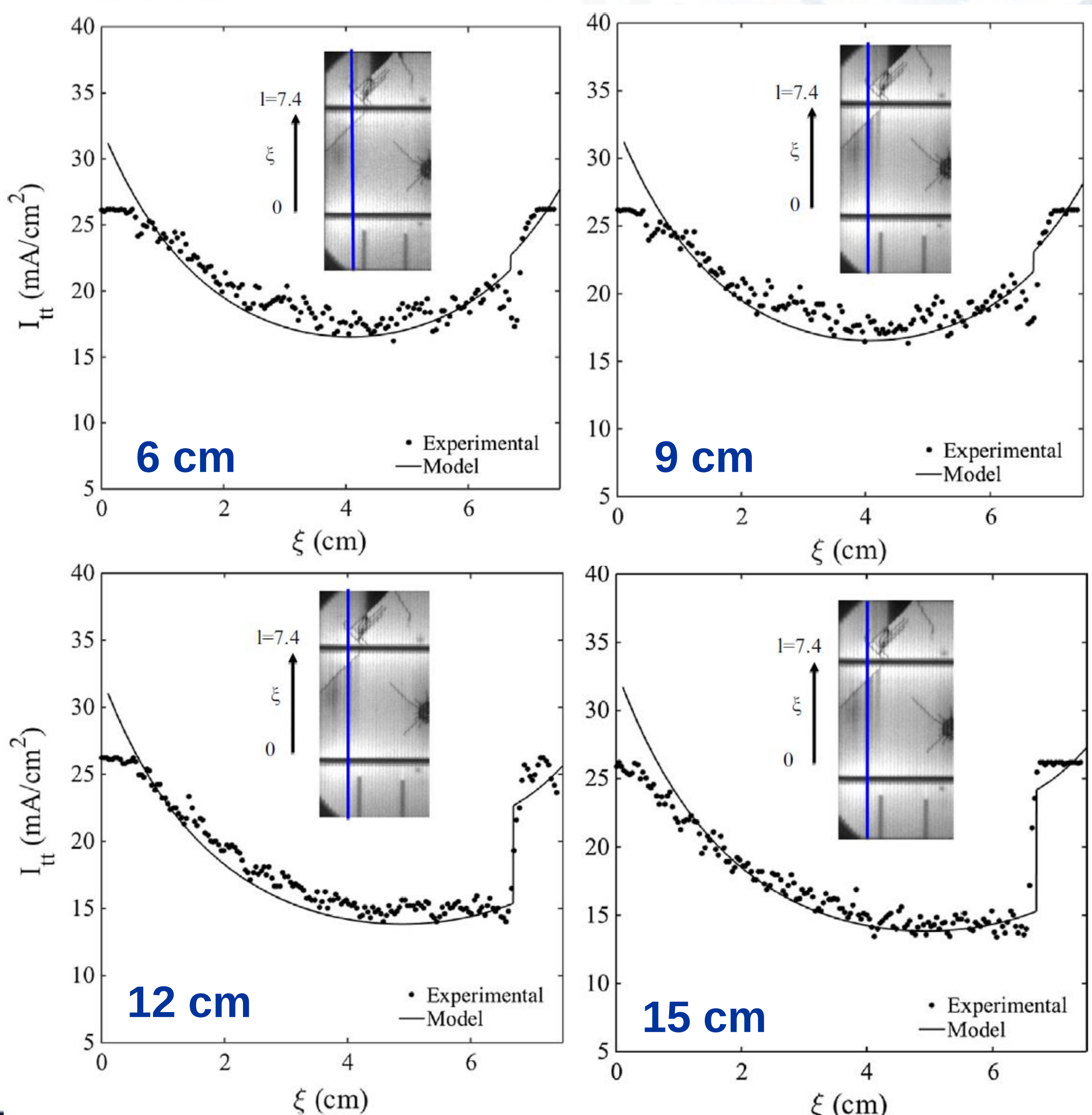
$$I_{tt}(\xi) = I_{01} \exp\left(\frac{V(\xi) - R_{hom} I_{tt}(x)}{n_1 V_T}\right)$$

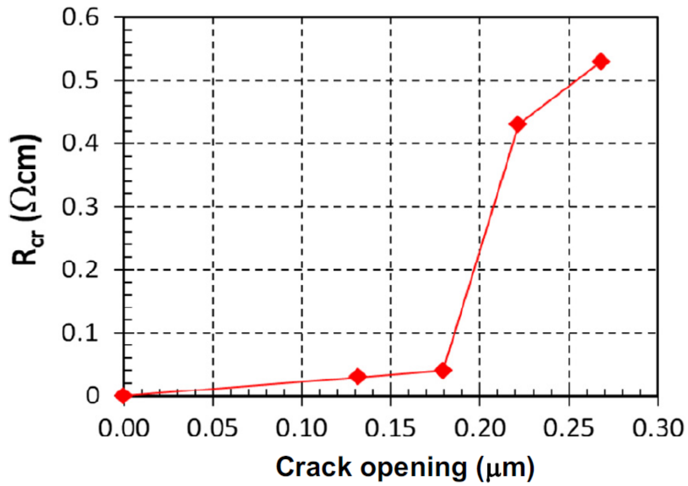
$$V(\xi_{cr,1}^-) = V(\xi_{cr,1}^+) + R_{cr,1} I_f(\xi_{cr,1})$$

Berardone I, Corrado M, Paggi M (2014) A generalized electric model for mono and polycrystalline silicon in the presence of cracks and random defects. **Energy Procedia** 55:22-29.

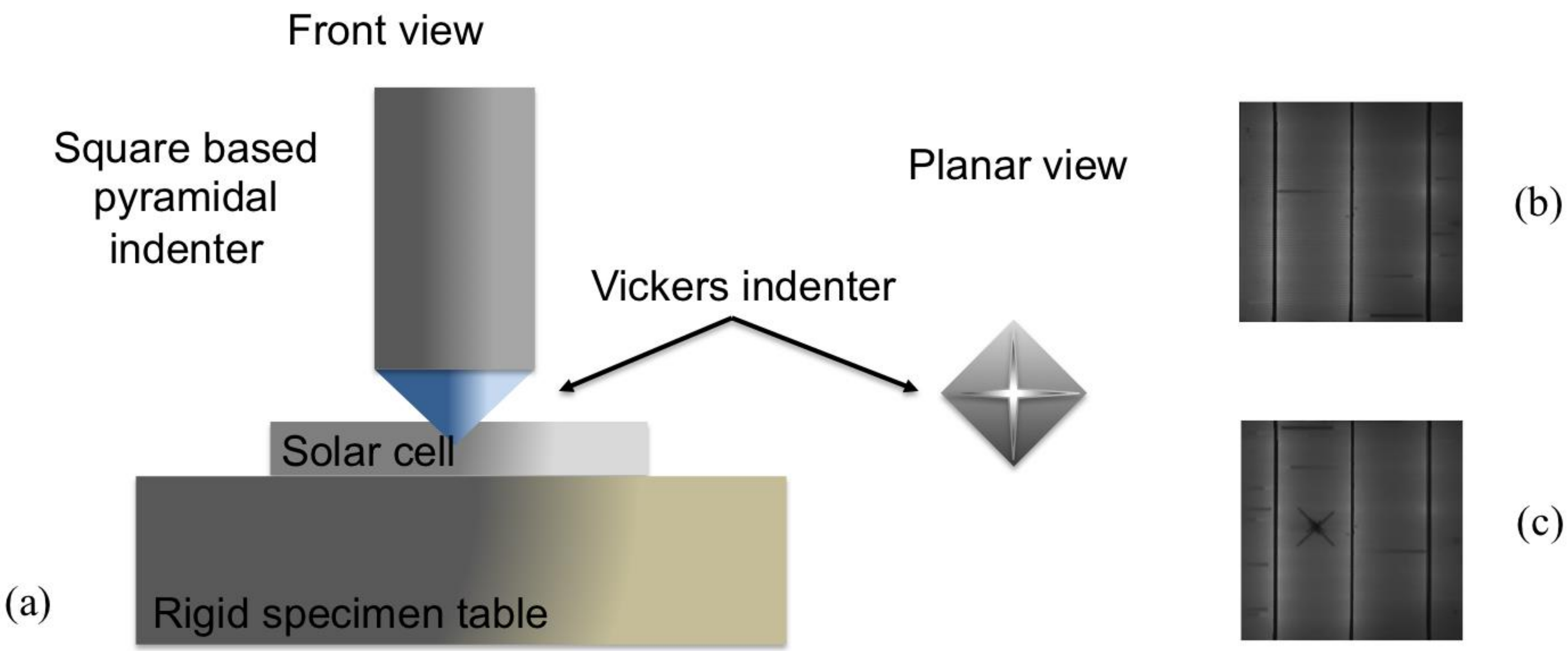
Paggi M, Berardone I, Corrado M (2016) A global/local approach for the prediction of the electric response of cracked solar cells in photovoltaic modules under the action of mechanical loads. **Engineering Fracture Mechanics**, doi:10.1016/j.engfracmech.2016.01.018

Electric model



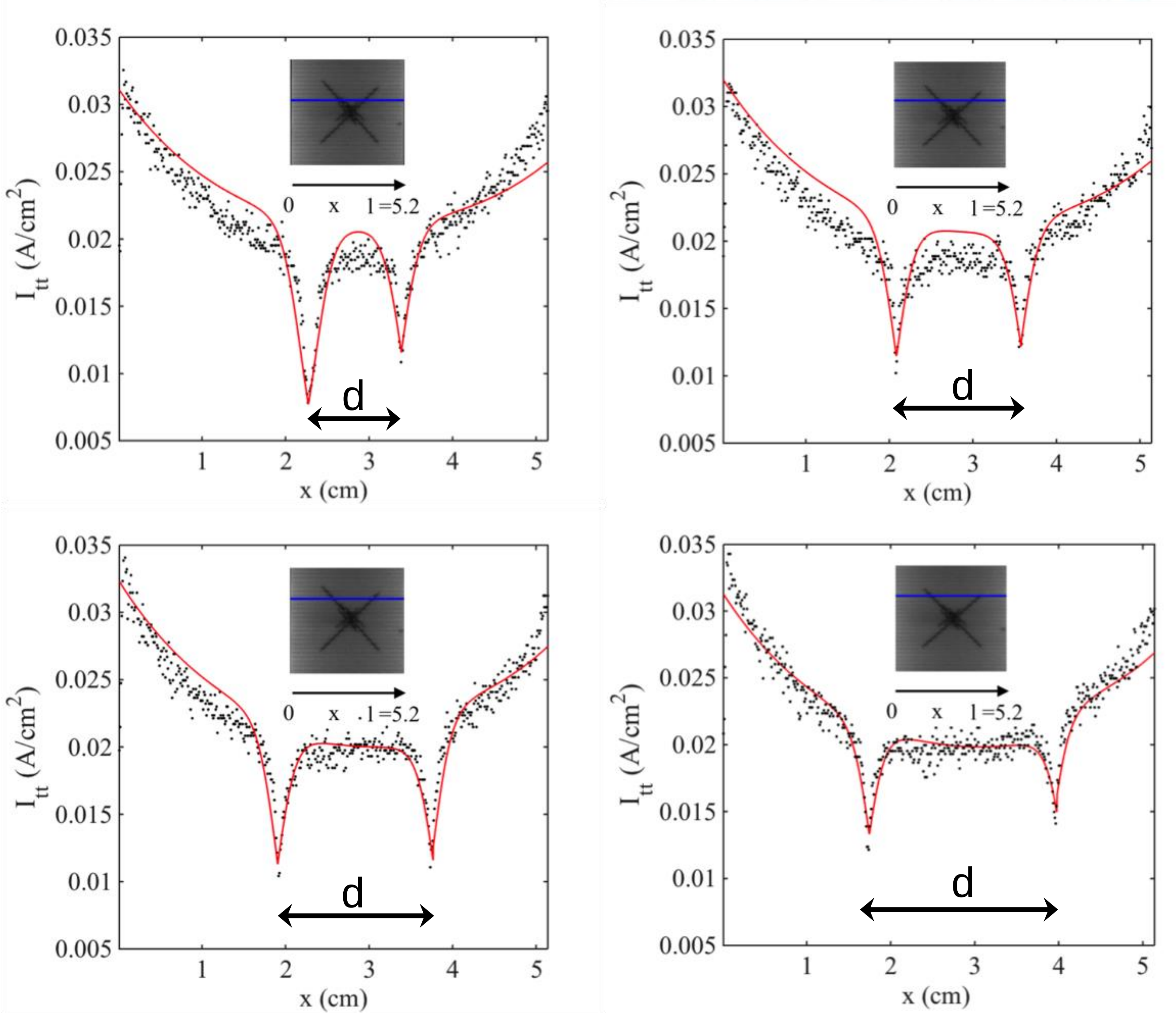


Indentation tests



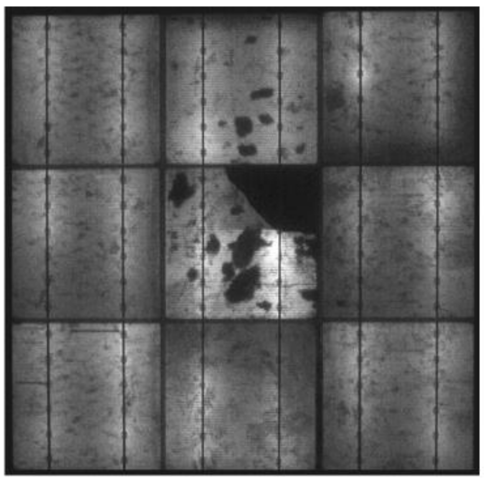
In collaboration with M. Martire, Applied Materials Srl
(Olmi di S. Biagio di Callalta, Italy)

Indentation tests

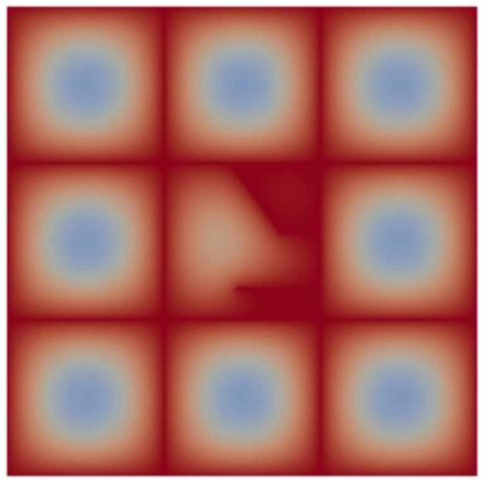


Environmental vs. accelerated aging

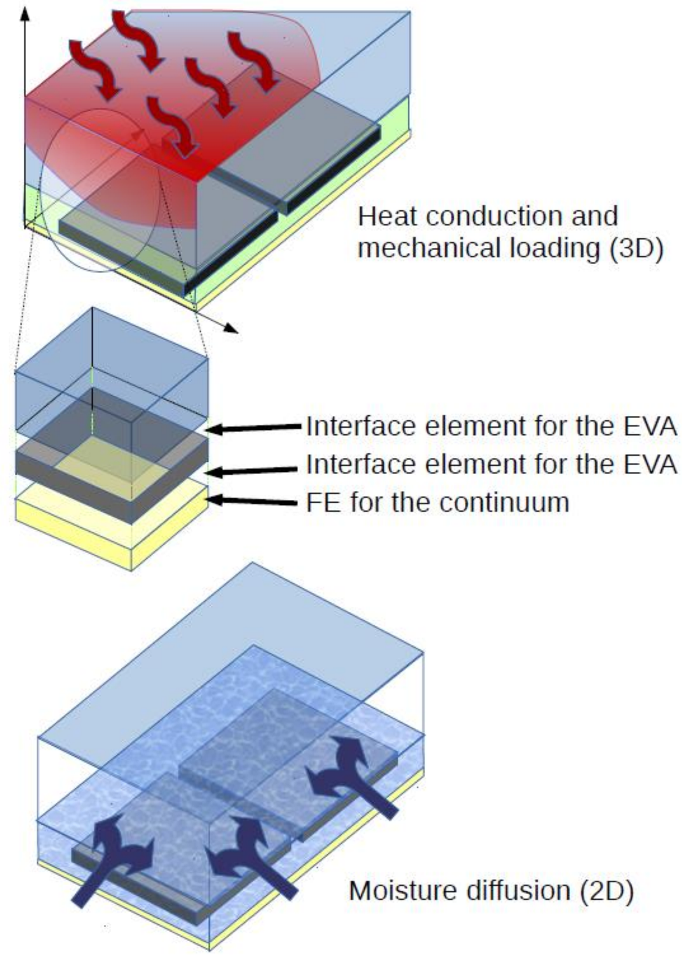
Moisture diffusion and chemical reactions take place inside the EVA layers



EL image



Predicted moisture concentration



P. Lenarda, M. Paggi (2016) A geometrical multi-scale numerical method for coupled hygro-thermo-mechanical problems in photovoltaic laminates. **Computational Mechanics**.

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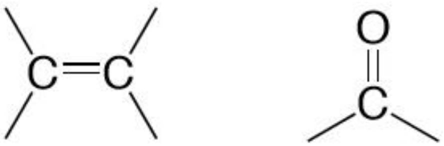
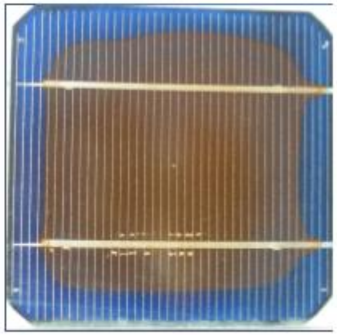
The role of chemistry

Yellowing and browning



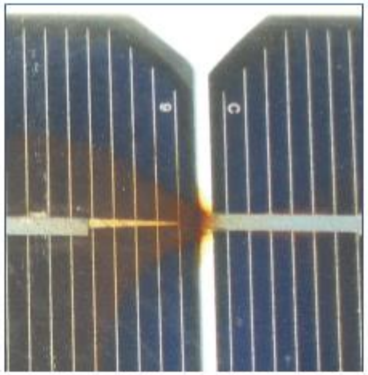
Chromophores



$$A(\lambda) = -\log_{10}(T_R(\lambda))$$

$$T_R(\lambda) = \frac{\Phi_T}{\Phi_I} = e^{-\int_0^s \mu(z,\lambda)dz}$$

Acetic acid (CH_3COOH)



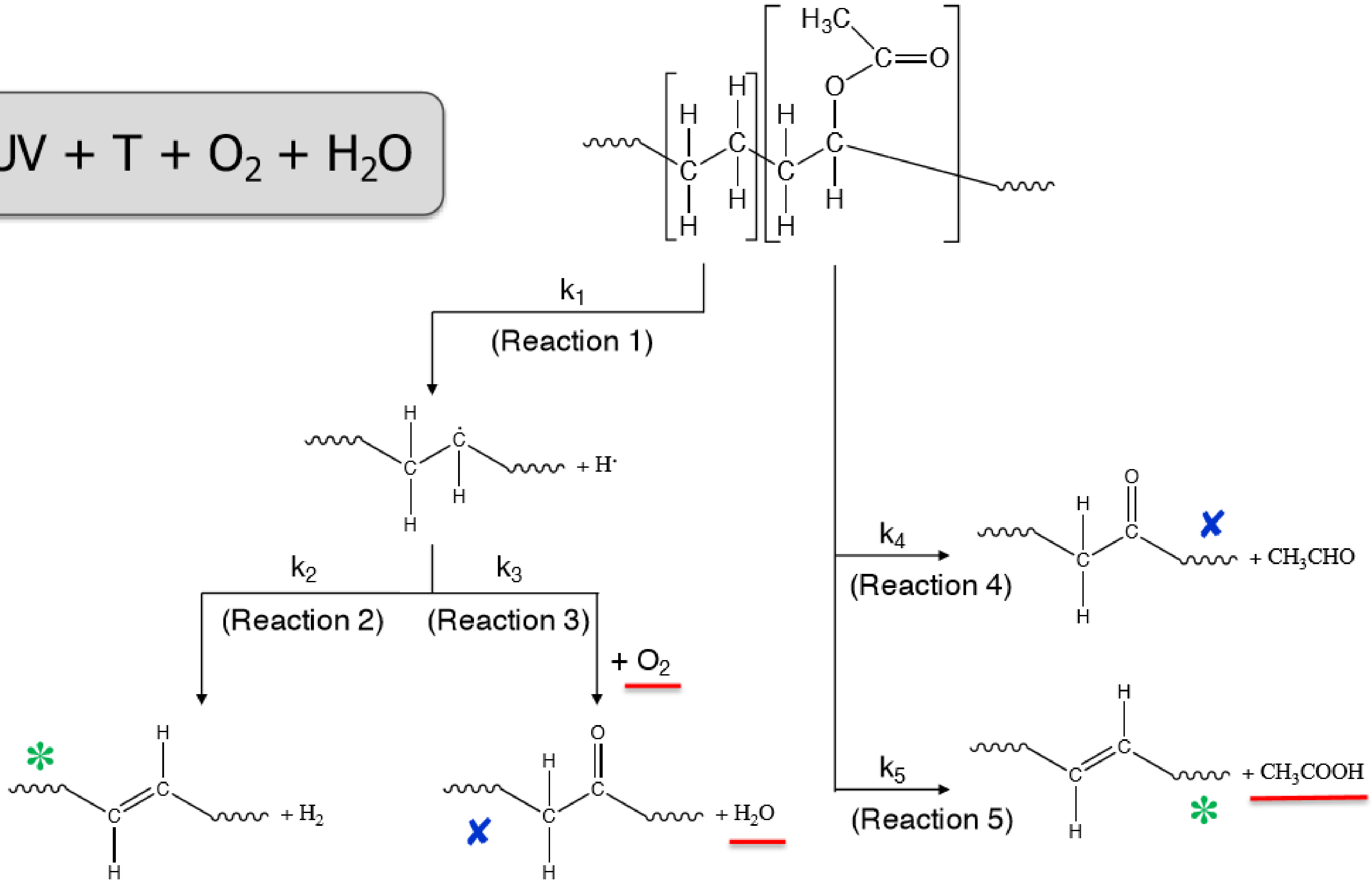
Ag corrosion

Snail trails

Moisture sorption + gas formation + overheating

Environmental vs. accelerated aging

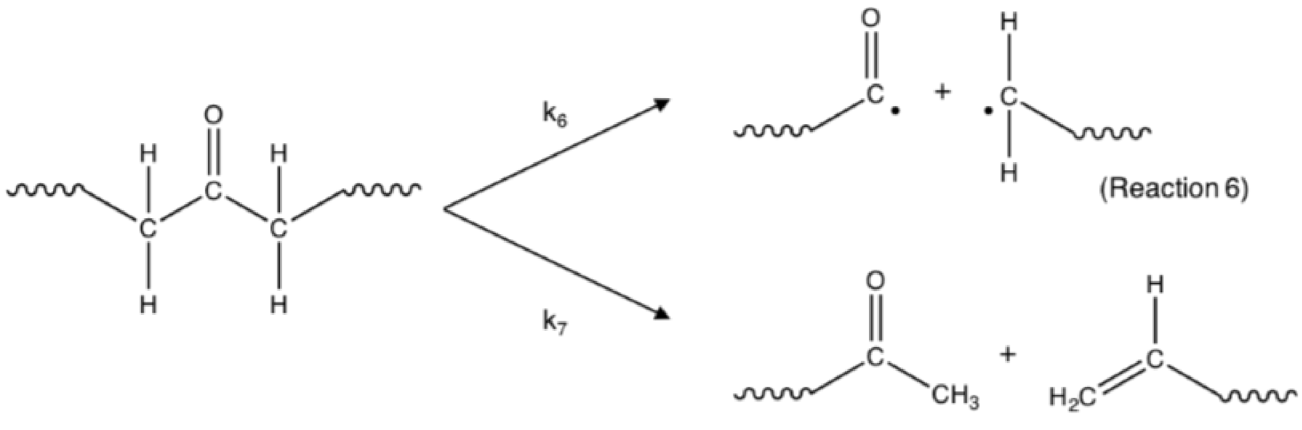
UV + T + O_2 + H_2O



Primary reactions: deprotonation, oxidation, deacetylation

Environmental vs. accelerated aging

Secondary following reactions: polymer chain cleavage

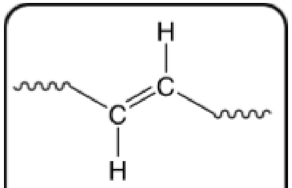


(Reaction 6)

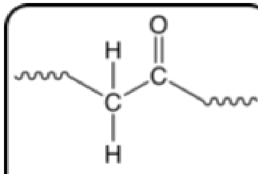
(Reaction 7)

Degradation products:

- Polymeric (unsaturations, carbonyl bonds)
  - Small molecules (water, acetic acid)



Unsaturation



Carbonyl bonds

Environmental vs. accelerated aging

Reaction-diffusion PDEs

$$\frac{\mathrm{d}[\mathrm{H}^\bullet]}{\mathrm{d}t} - \Delta(D_{H^\bullet}[\mathrm{H}^\bullet]) = k_1[\mathrm{ET}]$$

$$\frac{\mathrm{d}[\mathrm{H}_2]}{\mathrm{d}t} - \Delta(D_{H_2}[\mathrm{H}_2]) = k_2[\mathrm{R}^\bullet]$$

$$\frac{\mathrm{d}[\mathrm{O}_2]}{\mathrm{d}t} - \Delta(D_{O_2}[\mathrm{O}_2]) = -k_3[\mathrm{R}^\bullet][\mathrm{O}_2]$$

$$\frac{\mathrm{d}[\mathrm{H}_2\mathrm{O}]}{\mathrm{d}t} - \Delta(D_{H_2O}[\mathrm{H}_2\mathrm{O}]) = k_3[\mathrm{R}^\bullet][\mathrm{O}_2]$$

$$\frac{\mathrm{d}[\mathrm{CH}_3\mathrm{CHO}]}{\mathrm{d}t} - \Delta(D_{CH_3CHO}[\mathrm{CH}_3\mathrm{CHO}]) = k_4[\mathrm{VAc}]$$

$$\frac{\mathrm{d}[\mathrm{CH}_3\mathrm{COOH}]}{\mathrm{d}t} - \Delta(D_{CH_3COOH}[\mathrm{CH}_3\mathrm{COOH}]) = k_5[\mathrm{VAc}]$$

+ Fourier heat transfer PDE (for acelerated aging)

Reaction kinetics ODEs

$$\frac{\mathrm{d}[\mathrm{ET}]}{\mathrm{d}t} = -k_1[\mathrm{ET}]$$

$$\frac{\mathrm{d}[\mathrm{R}^\bullet]}{\mathrm{d}t} = k_1[\mathrm{ET}]$$

$$\frac{\mathrm{d}[\mathrm{U}]}{\mathrm{d}t} = k_2[\mathrm{R}^\bullet] + k_5[\mathrm{VAc}]$$

$$\frac{\mathrm{d}[\mathrm{C_b}]}{\mathrm{d}t} = k_3[\mathrm{R}^\bullet][\mathrm{O}_2] + k_4[\mathrm{VAc}] - (k_6 + k_7)[\mathrm{C_b}]$$

$$\frac{\mathrm{d}[\mathrm{VAc}]}{\mathrm{d}t} = -(k_4 + k_5)[\mathrm{VAc}]$$

$$\frac{\mathrm{d}[\mathrm{C_b}^\bullet]}{\mathrm{d}t} = k_6[\mathrm{C_b}]$$

$$\frac{\mathrm{d}[\mathrm{R_t}^\bullet]}{\mathrm{d}t} = k_6[\mathrm{C_b}]$$

$$\frac{\mathrm{d}[\mathrm{C_bt}]}{\mathrm{d}t} = k_7[\mathrm{C_b}]$$

$$\frac{\mathrm{d}[\mathrm{U_t}]}{\mathrm{d}t} = k_7[\mathrm{C_b}]$$

Environmental vs. accelerated aging

Reaction-diffusion PDEs

$$\frac{\mathrm{d}[\mathrm{H}^\bullet]}{\mathrm{d}t} - \Delta(D_{H^\bullet}[\mathrm{H}^\bullet]) = k_1[\mathrm{ET}]$$
$$\frac{\mathrm{d}[\mathrm{H}_2]}{\mathrm{d}t} - \Delta(D_{H_2}[\mathrm{H}_2]) = k_2[\mathrm{R}^\bullet]$$
$$\frac{\mathrm{d}[\mathrm{O}_2]}{\mathrm{d}t} - \Delta(D_{O_2}[\mathrm{O}_2]) = -k_3[\mathrm{R}^\bullet][\mathrm{O}_2]$$
$$\frac{\mathrm{d}[\mathrm{H}_2\mathrm{O}]}{\mathrm{d}t} - \Delta(D_{H_2O}[\mathrm{H}_2\mathrm{O}]) = k_3[\mathrm{R}^\bullet][\mathrm{O}_2]$$
$$\frac{\mathrm{d}[\mathrm{CH}_3\mathrm{CHO}]}{\mathrm{d}t} - \Delta(D_{CH_3CHO}[\mathrm{CH}_3\mathrm{CHO}]) = k_4[\mathrm{VAc}]$$
$$\frac{\mathrm{d}[\mathrm{CH}_3\mathrm{COOH}]}{\mathrm{d}t} - \Delta(D_{CH_3COOH}[\mathrm{CH}_3\mathrm{COOH}]) = k_5[\mathrm{VAc}]$$

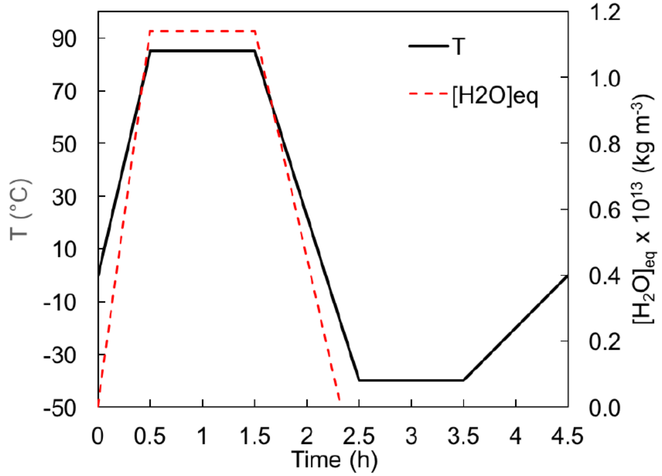
+ Fourier heat transfer PDE
  (for acelerated aging)

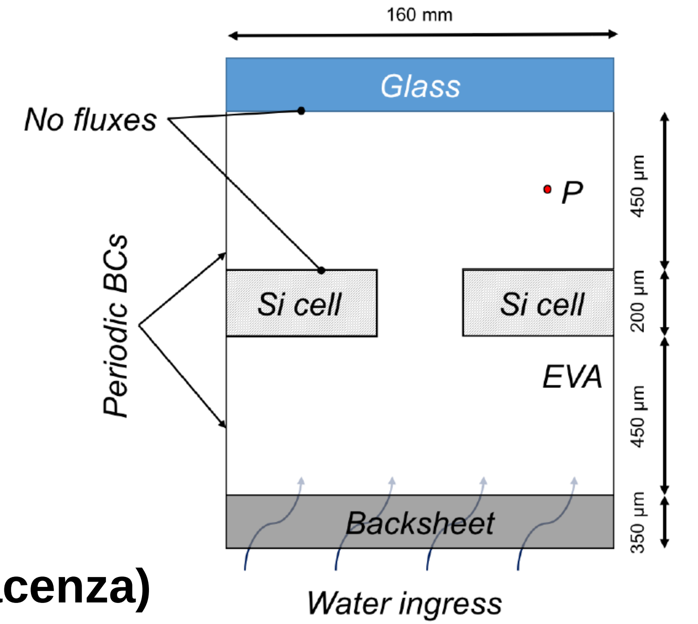
Reaction kinetics ODEs

$$\frac{\mathrm{d}[\mathrm{ET}]}{\mathrm{d}t} = -k_1[\mathrm{ET}]$$
$$\frac{\mathrm{d}[\mathrm{R}^\bullet]}{\mathrm{d}t} = k_1[\mathrm{ET}]$$
$$\frac{\mathrm{d}[\mathrm{U}]}{\mathrm{d}t} = k_2[\mathrm{R}^\bullet] + k_5[\mathrm{VAc}]$$
$$\frac{\mathrm{d}[\mathrm{C_b}]}{\mathrm{d}t} = k_3[\mathrm{R}^\bullet][\mathrm{O}_2] + k_4[\mathrm{VAc}] - (k_6 + k_7)[\mathrm{C_b}]$$
$$\frac{\mathrm{d}[\mathrm{VAc}]}{\mathrm{d}t} = -(k_4 + k_5)[\mathrm{VAc}]$$
$$\frac{\mathrm{d}[\mathrm{C_b}^\bullet]}{\mathrm{d}t} = k_6[\mathrm{C_b}]$$
$$\frac{\mathrm{d}[\mathrm{R_t}^\bullet]}{\mathrm{d}t} = k_6[\mathrm{C_b}]$$
$$\frac{\mathrm{d}[\mathrm{C_b t}]}{\mathrm{d}t} = k_7[\mathrm{C_b}]$$
$$\frac{\mathrm{d}[\mathrm{U_t}]}{\mathrm{d}t} = k_7[\mathrm{C_b}]$$

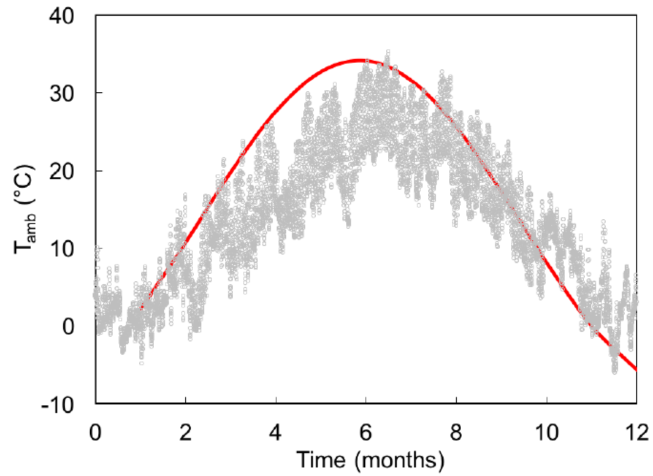
Environmental vs. accelerated aging

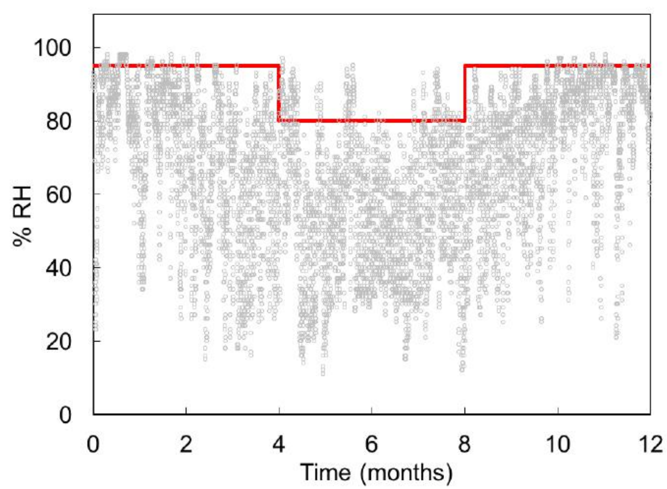
Accelerated aging (damp-heat test)



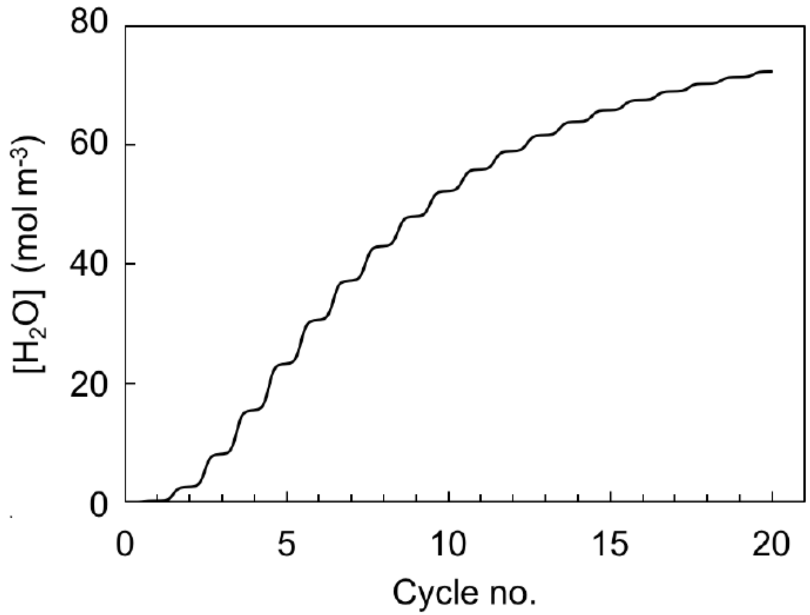


Environmental degradation (climatic data from Piacenza)

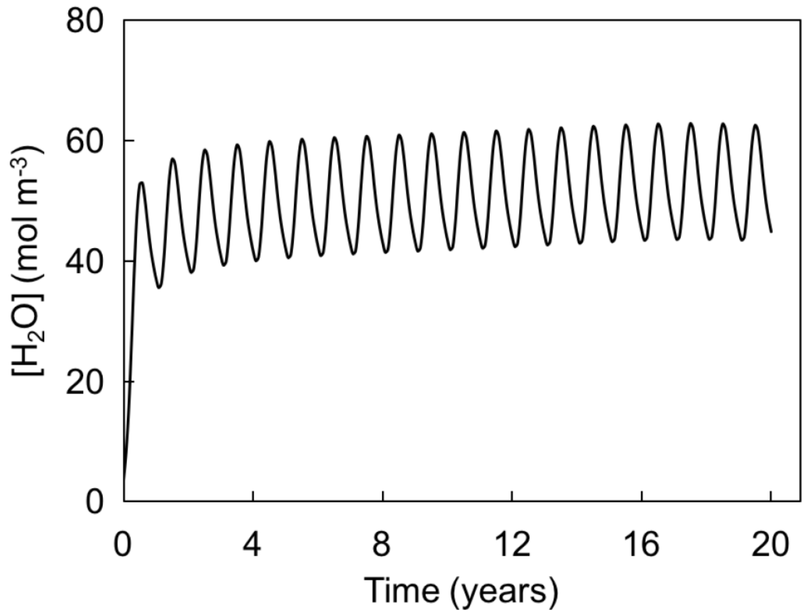




Environmental vs. accelerated aging



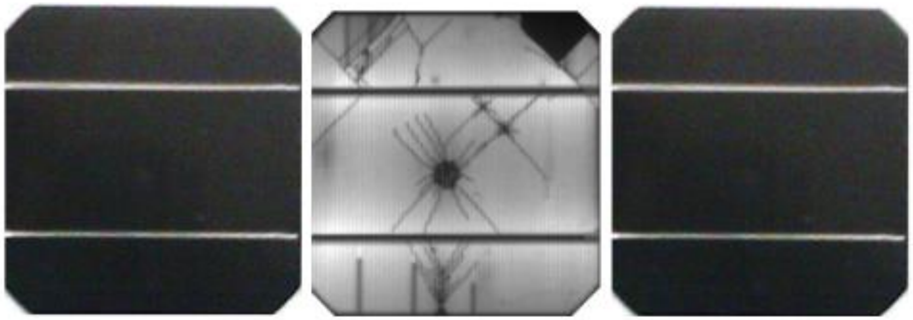
Accelerated aging



Environmental degradation

Acknowledgements

Multi-field and multi-scale Computational Approach to design and durability of Photovoltaic Modules – CA2PVM



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http://musam.imtlucca.it/CA2PVM.html

Mid-term scientific report:
http://musam.imtlucca.it/Mid-term-report.pdf

MUSAM Annual Reports:
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