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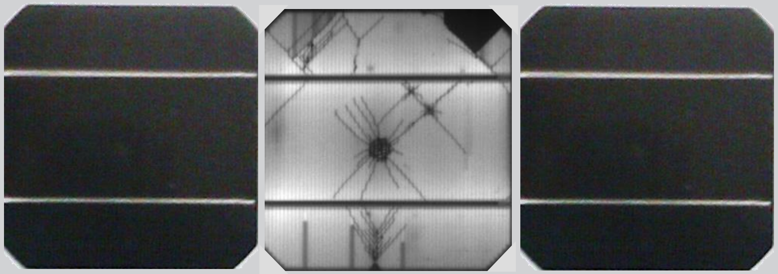
IDEAS

# Durability of photovoltaics modules: modeling, simulation and experiments



**Marco Paggi**

*IMT School for Advanced Studies Lucca*

*Politecnico di Milano*

*March 9, 2017*

# MUSAM Research unit

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- **C. Borri**, Post-doc
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- **M. Gagliardi**, Post-doc
- **F. Fantoni**, Post-doc
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- **V. Carollo**, PhD student (30th cycle)
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- **V. Govindarajan**, PhD student (30th cycle)
- **R. Del Toro**, PhD student (31st cycle)
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- **T. Guillen Hernandez**, PhD student (32nd cycle)

**Visiting professors**

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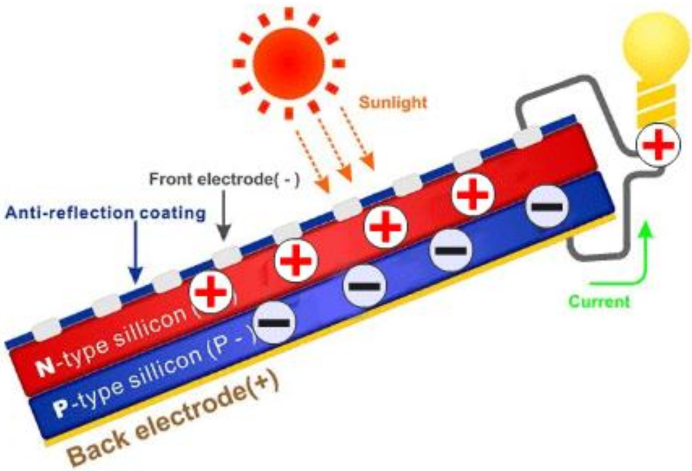
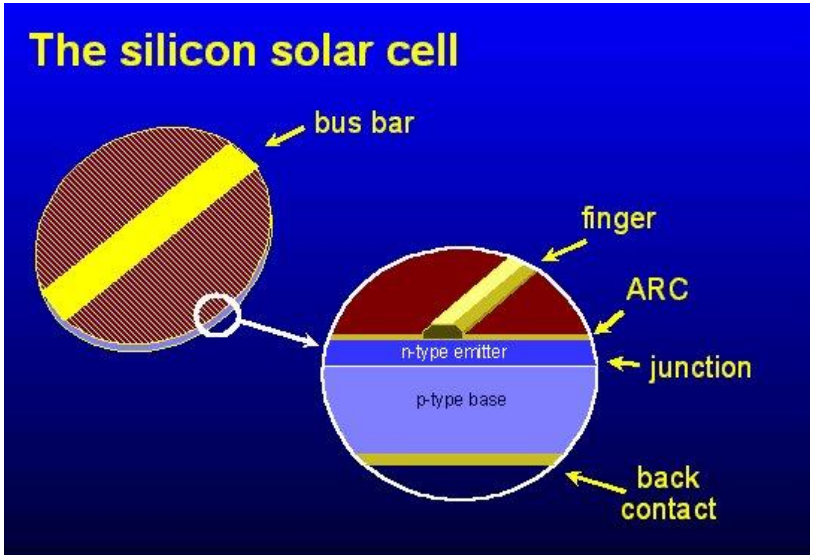
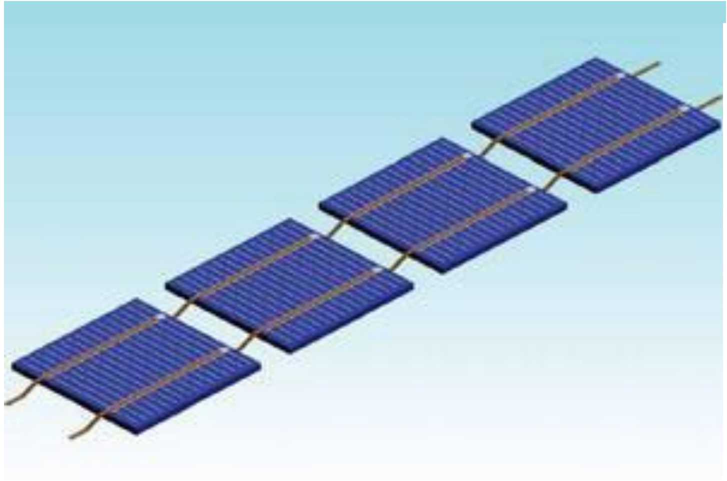
- **J. Reinoso**, Assistant Professor, University of Seville, Spain
- **M. Corrado**, Assistant Professor, PoliTO & Marie Curie Fellow at EPFL
- **A. Gizzi**, Assistant Professor, Università Campus Bio-Medico of Rome

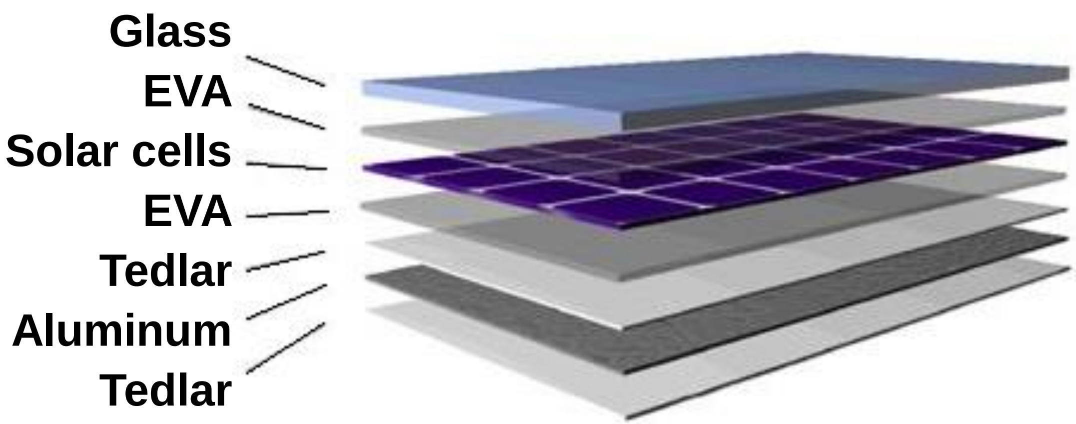
# Introduction, motivation, aims

# Photovoltaics (PV)

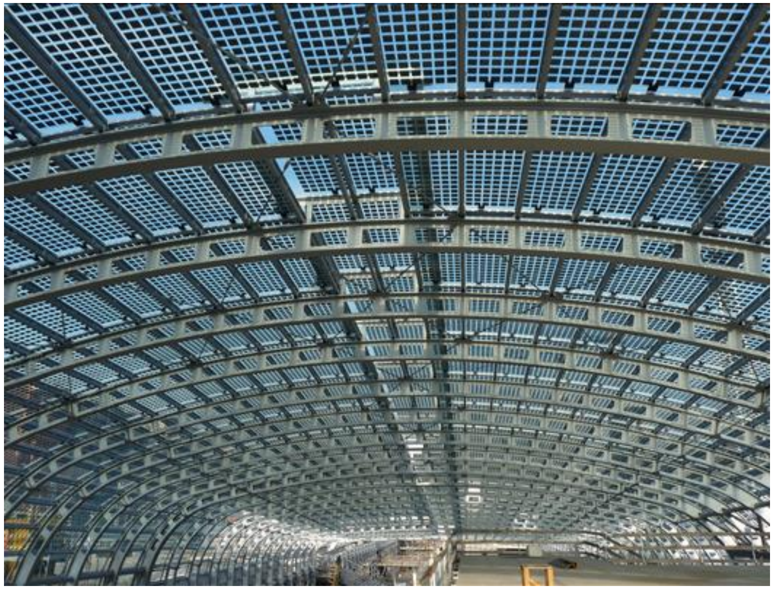




# Applications: from PV parks to BIPV

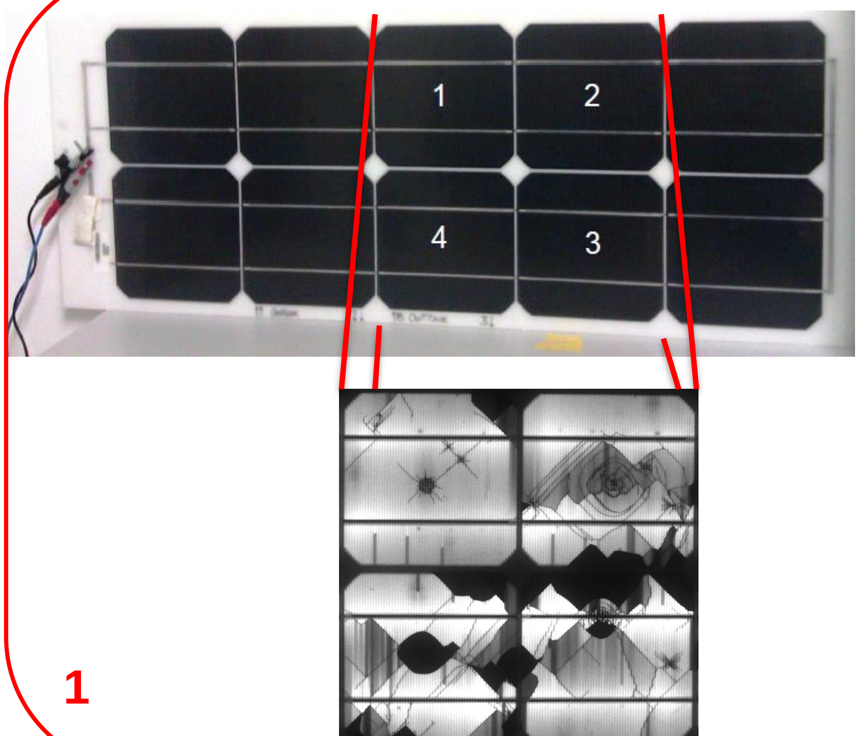


# Durability

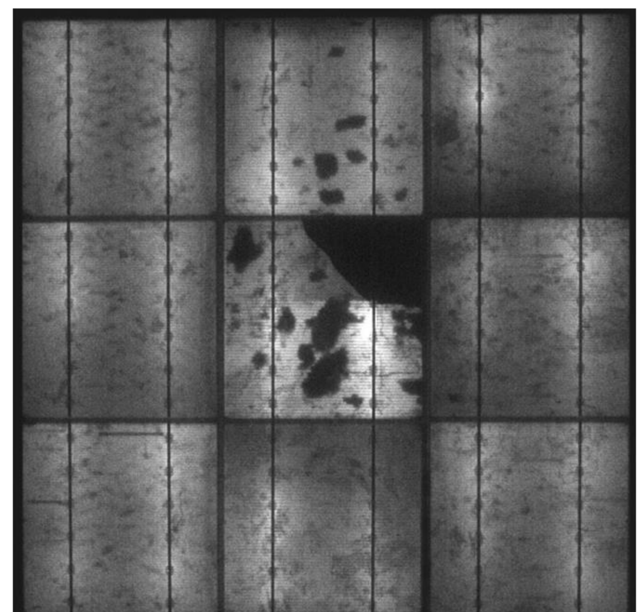
**Some failure modes of PV modules:**

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

2

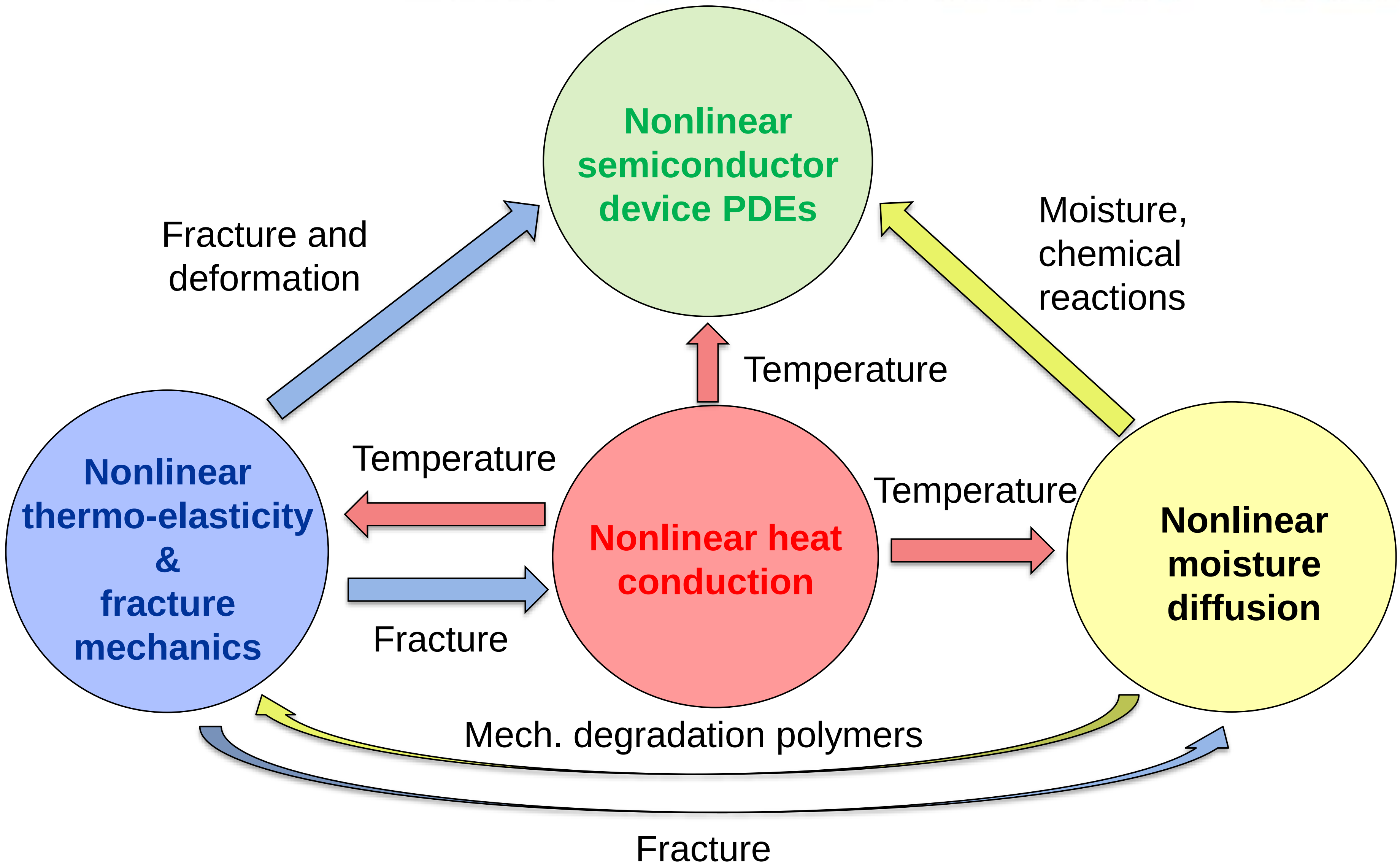



1

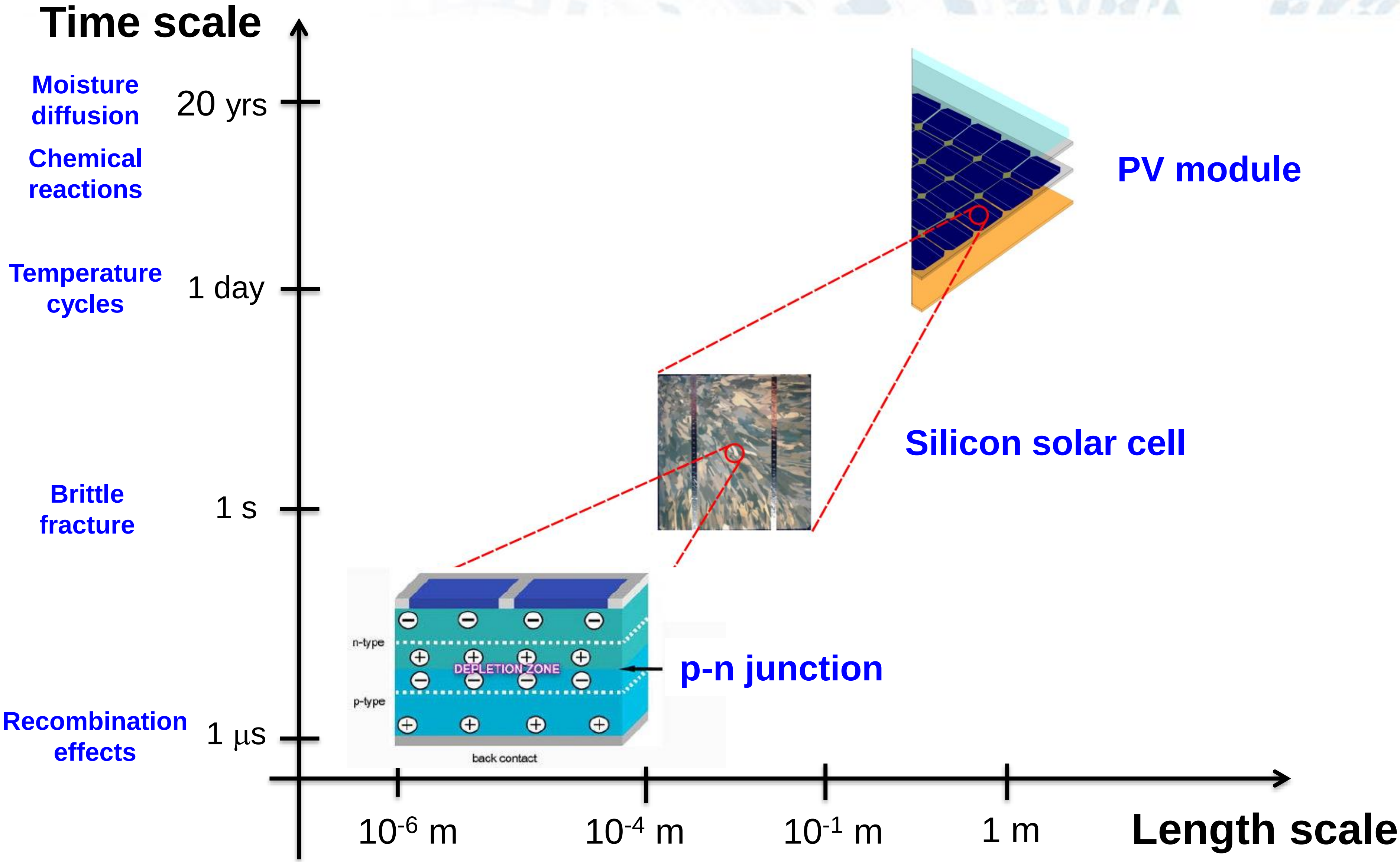


3

# Multi-physics modelling & simulation

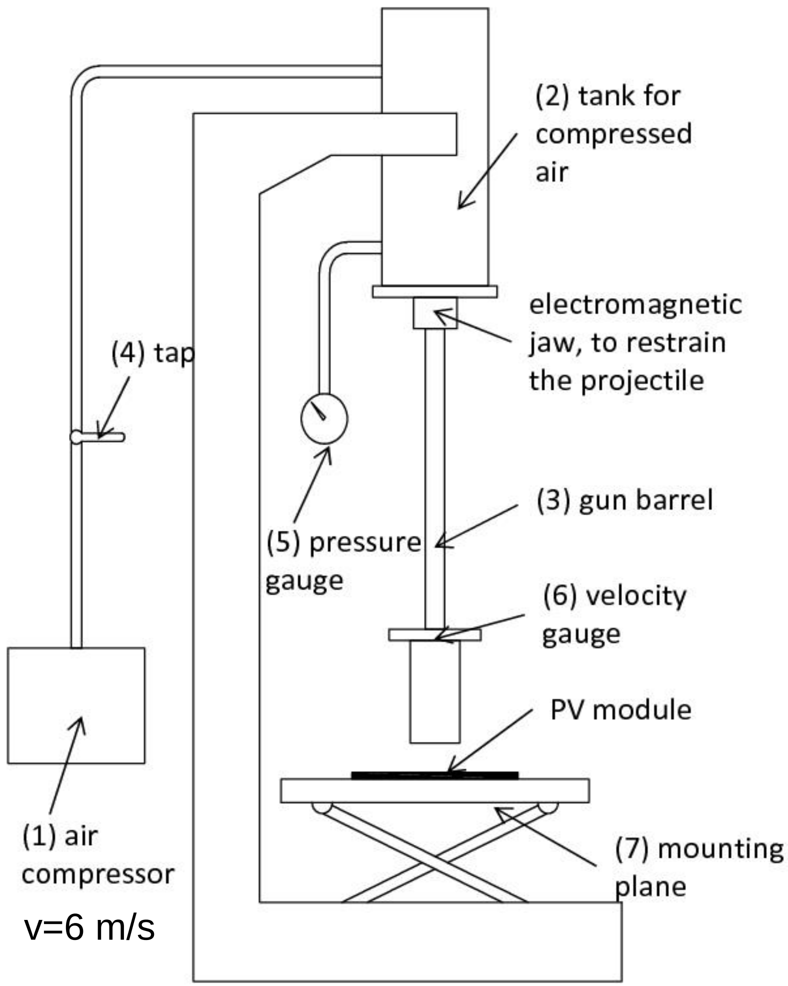


# Length and time scales



# Experimental tests

# Simulated hail impact tests on flexible PV modules




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

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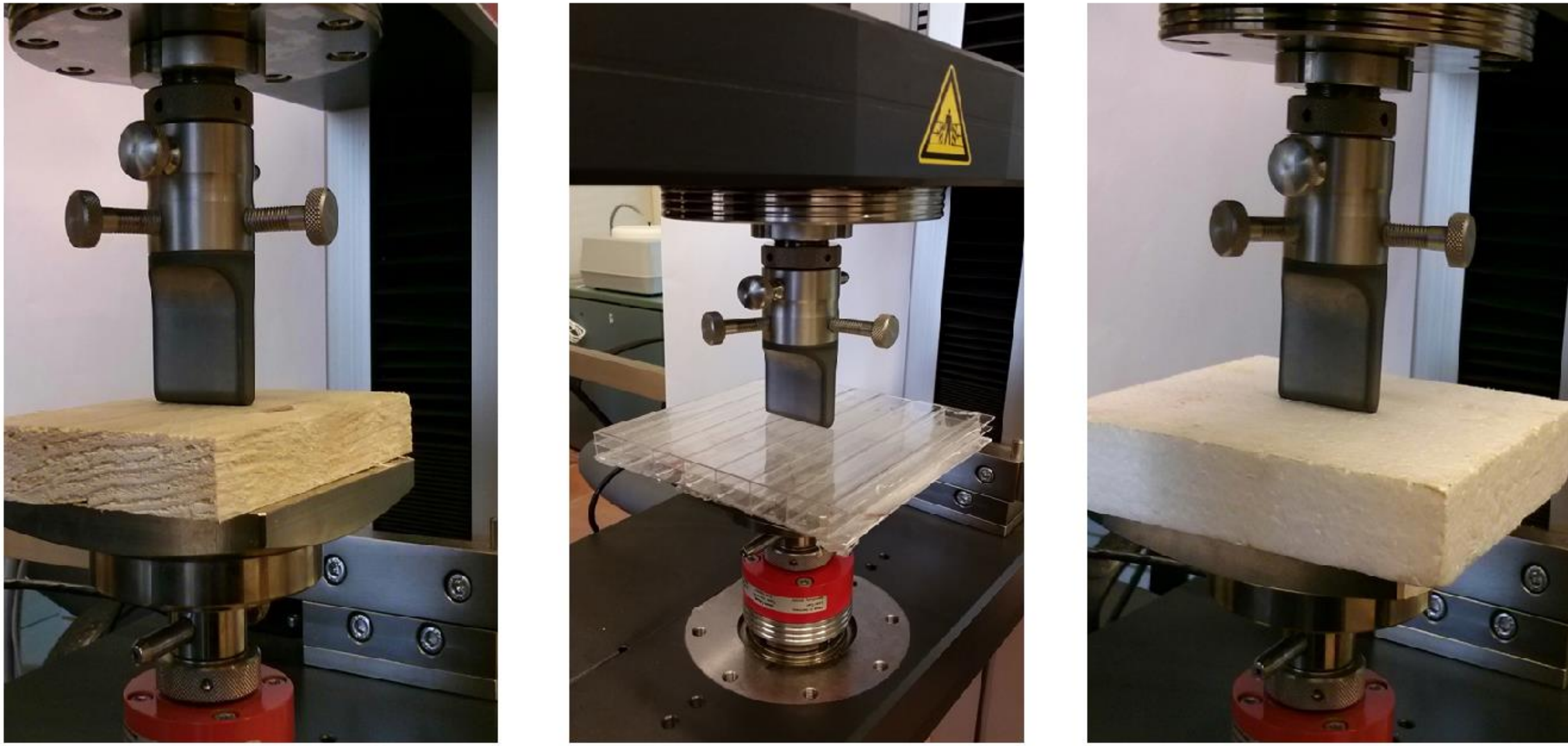
# Substrate stiffness

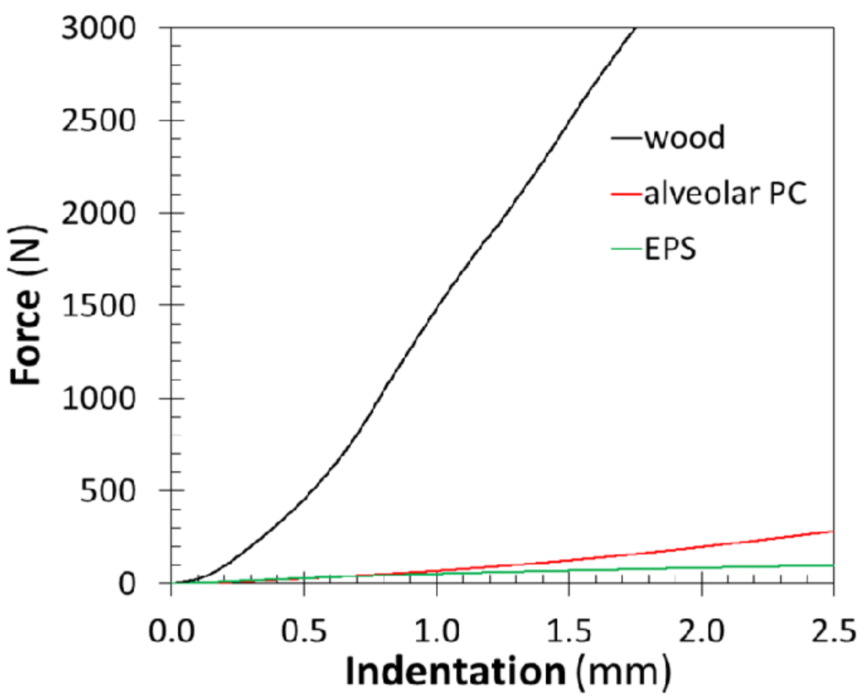


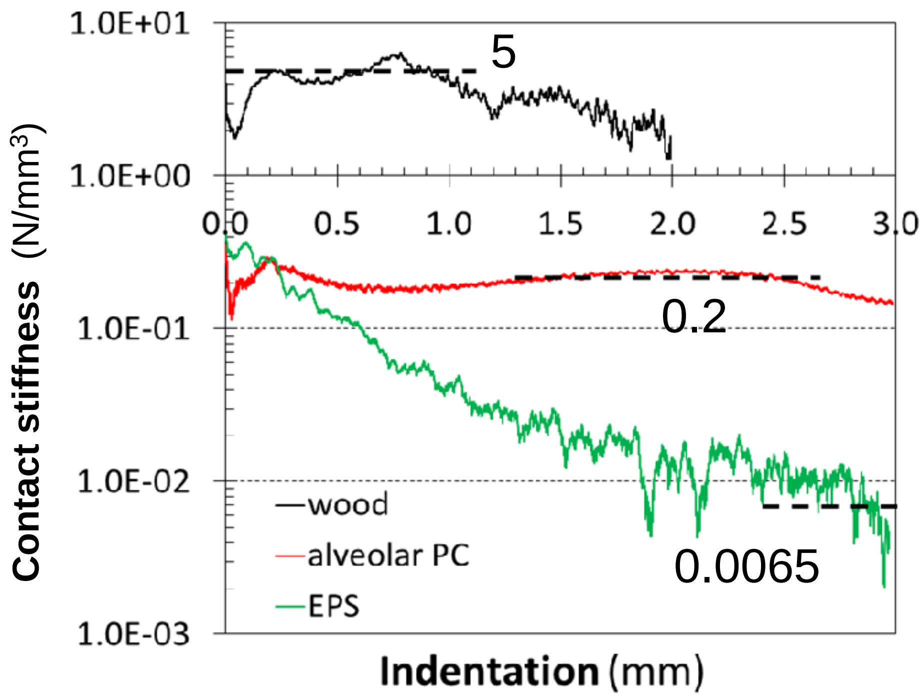
(a) Hard

(b) Medium

(c) Soft

# Substrate stiffness

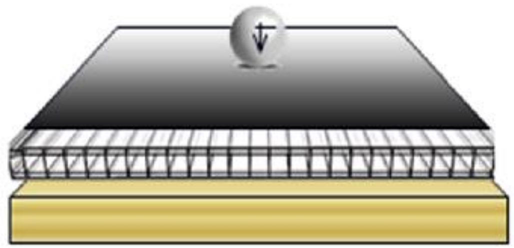


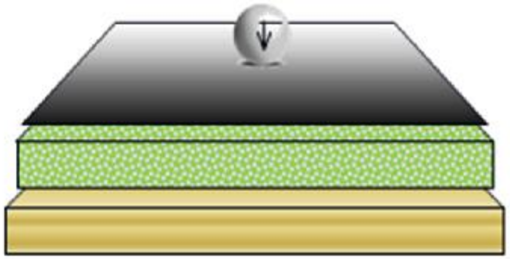

(1 : 30 : 770)

# Crack patterns

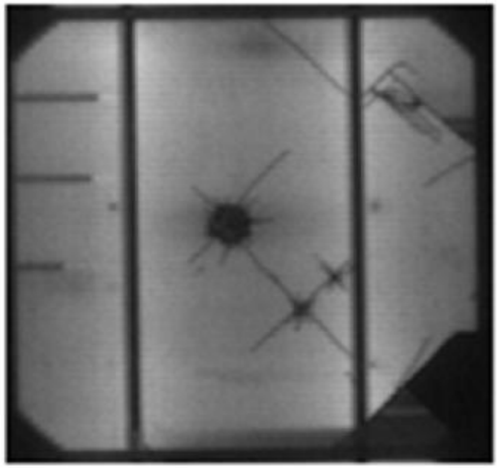
Wooden board



Alveolar PC +
Wooden board

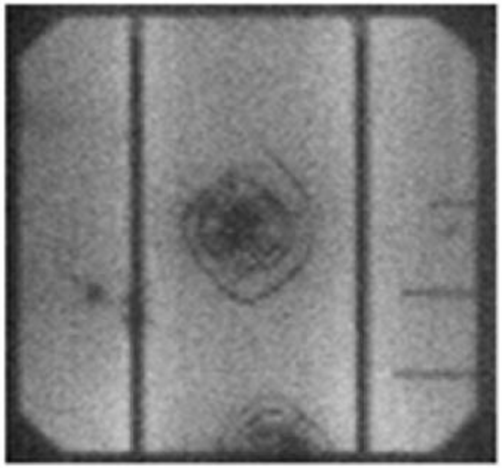


Polystirene +
Wooden board



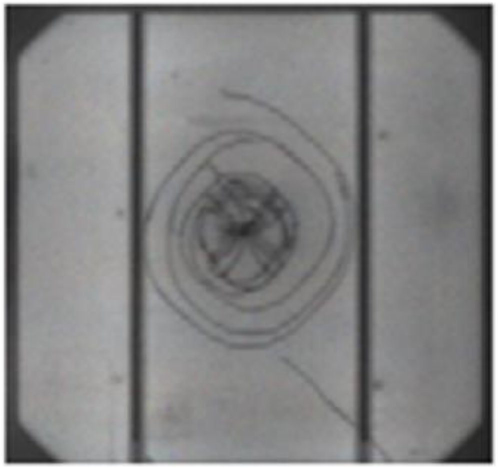
Case A: Hard substrate

r*=7.5 mm



CaseB: Medium substrate

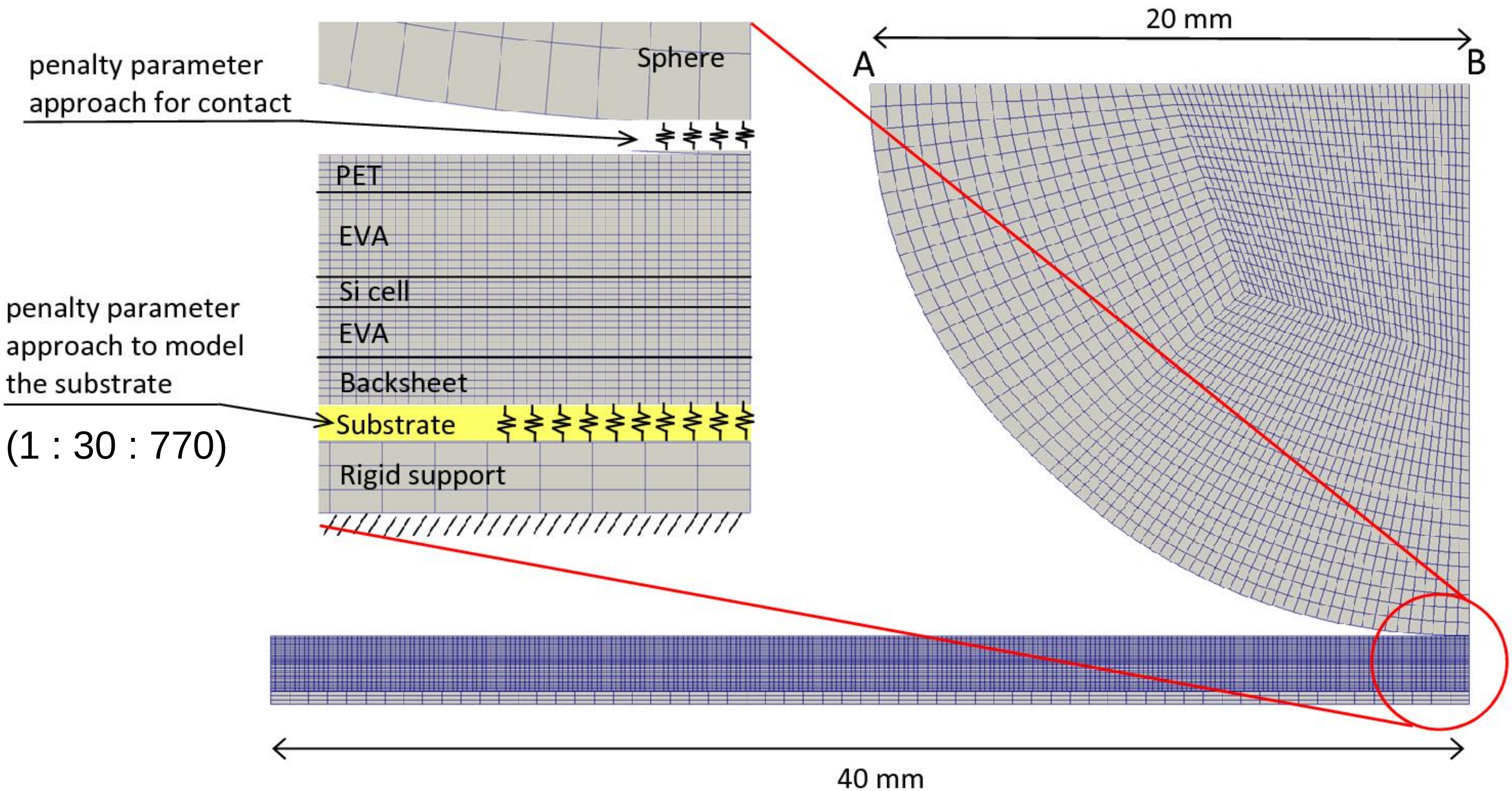
r*=15.8 mm



Case C: Soft substrate

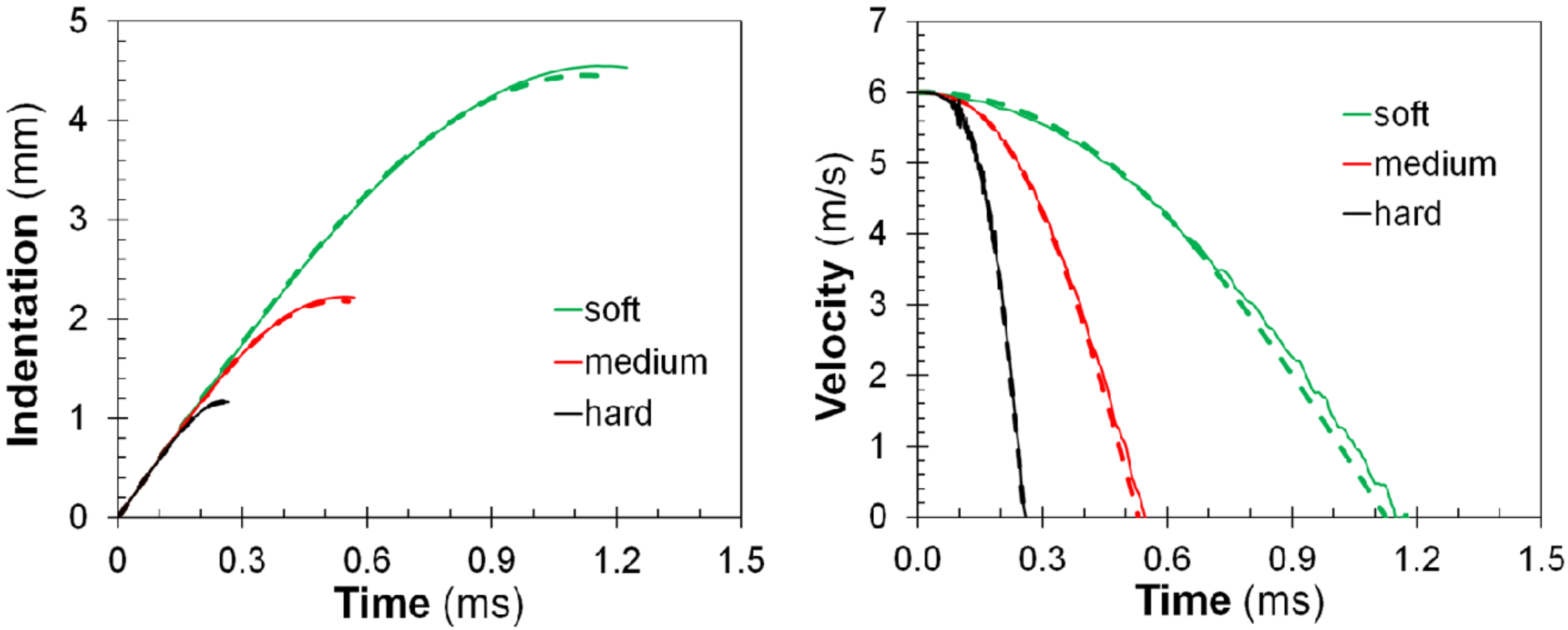
r*=31.0 mm

# Finite element models




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

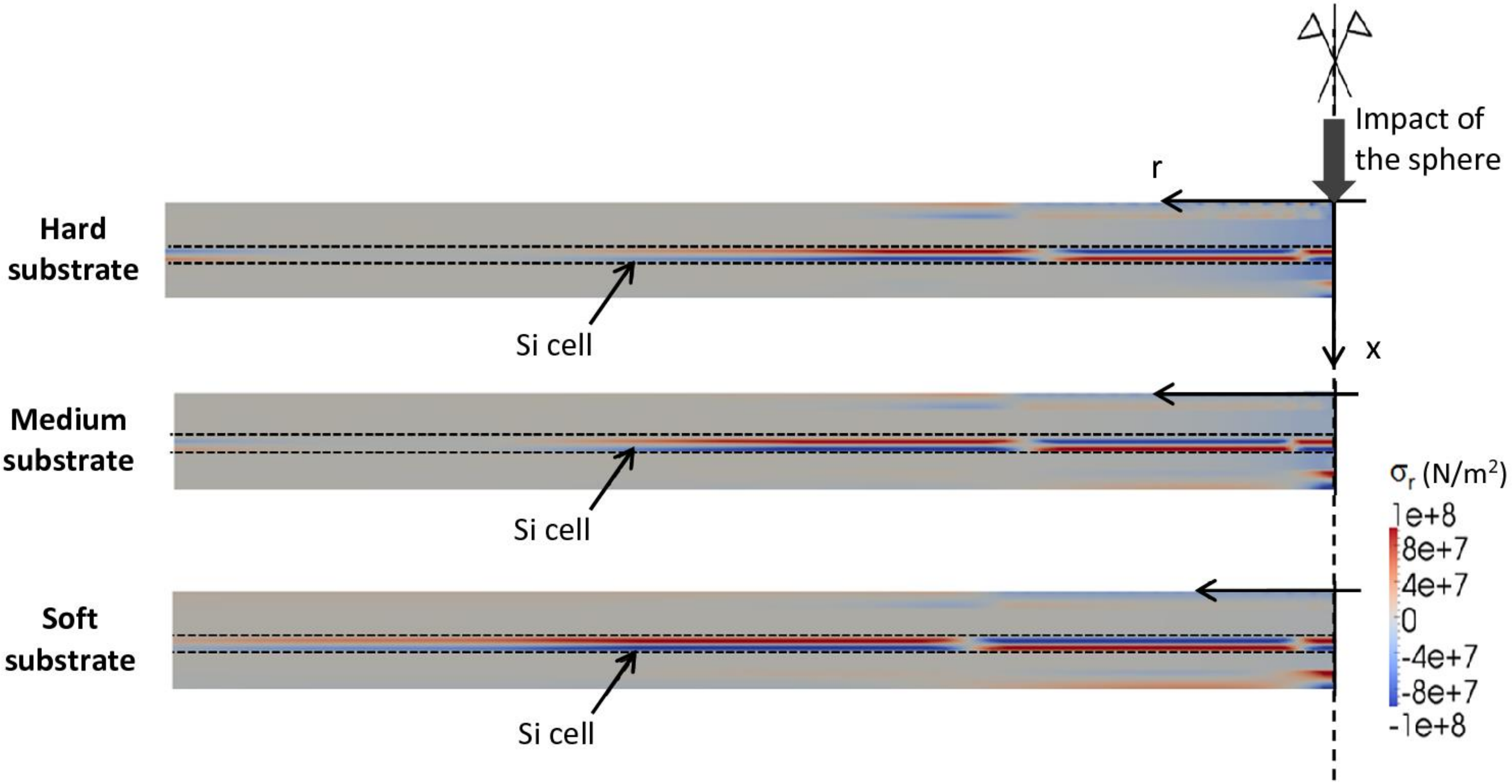
# Dynamic response



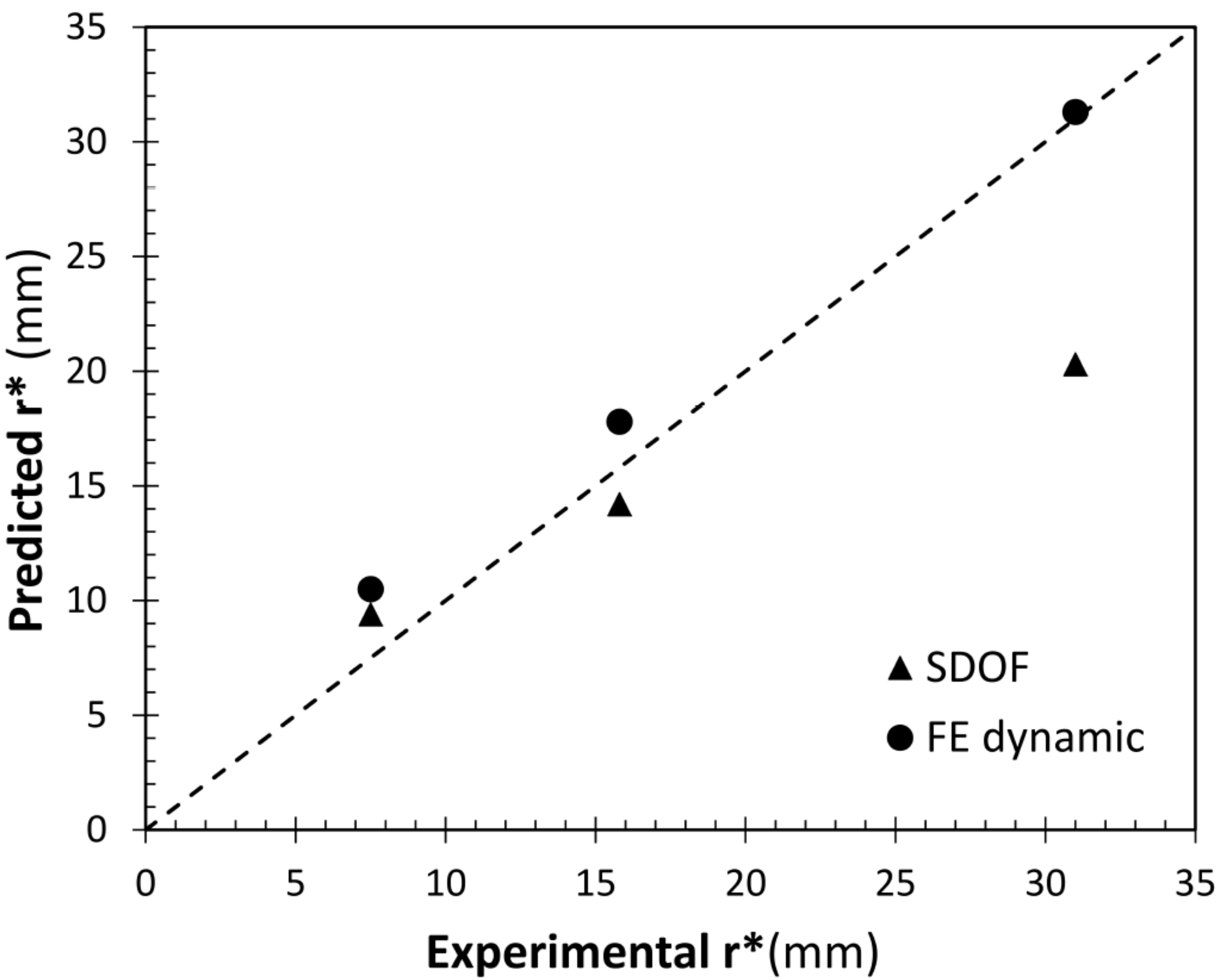

- - - - Approach 1 (simplified)

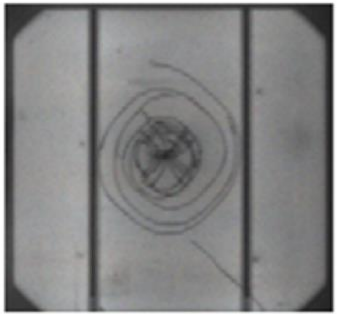
—— Approach 2 (the most accurate)

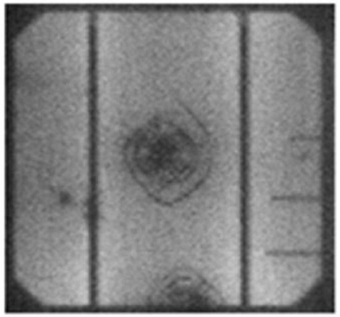
# Radial stresses

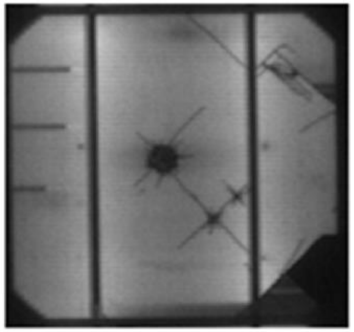


# Size of the crack pattern

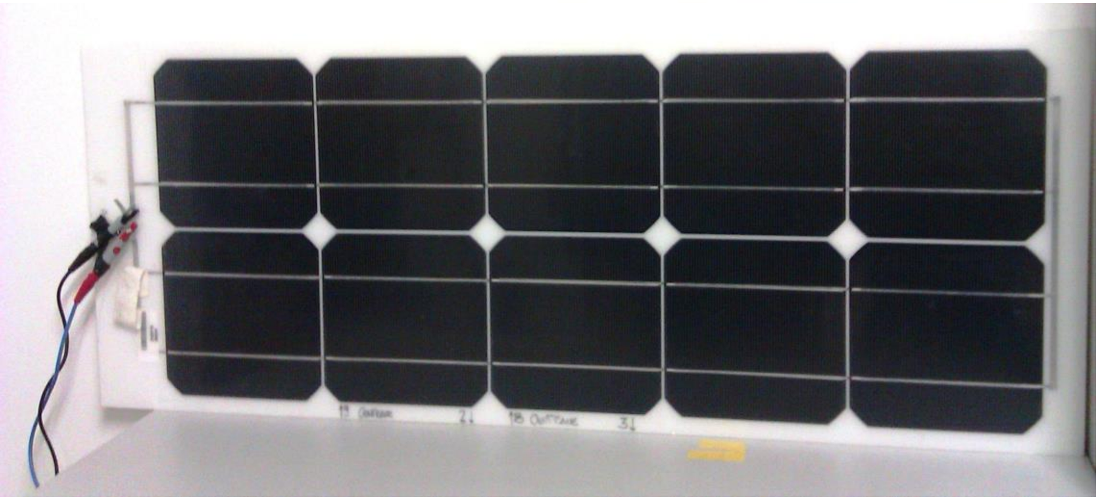


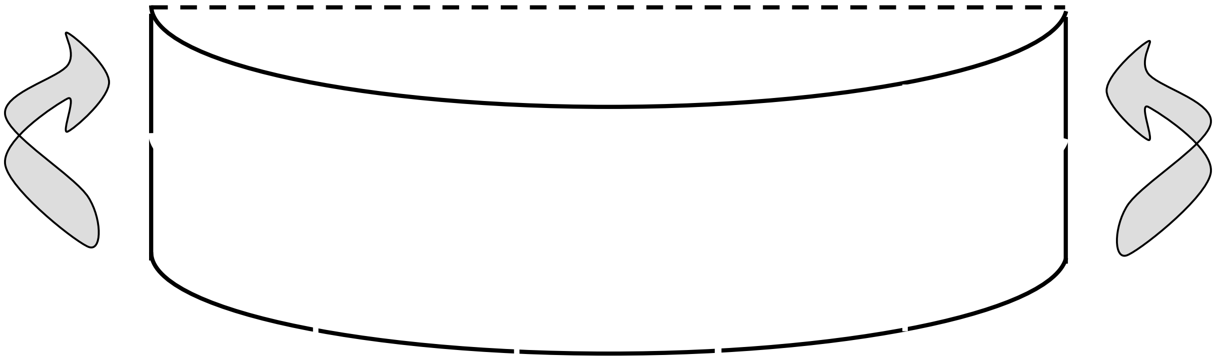





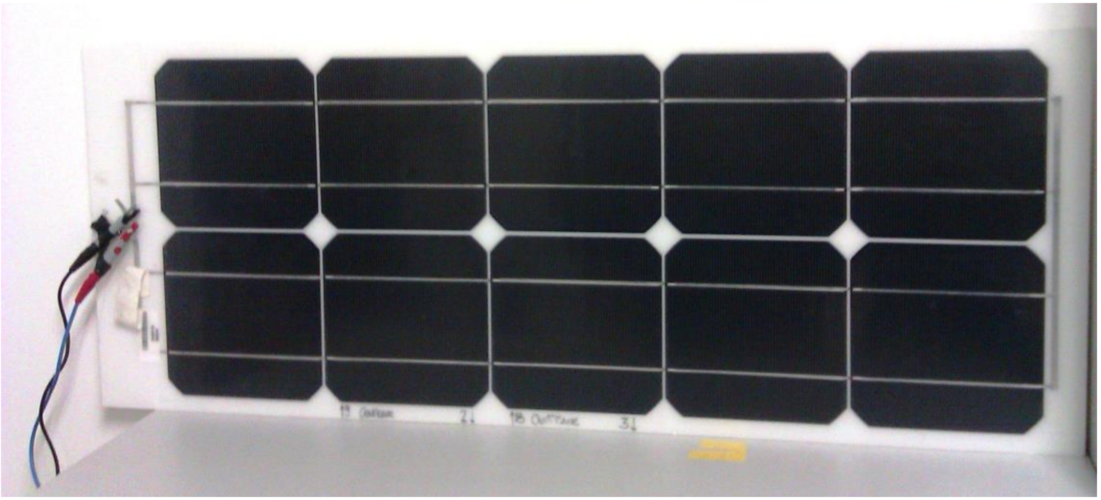


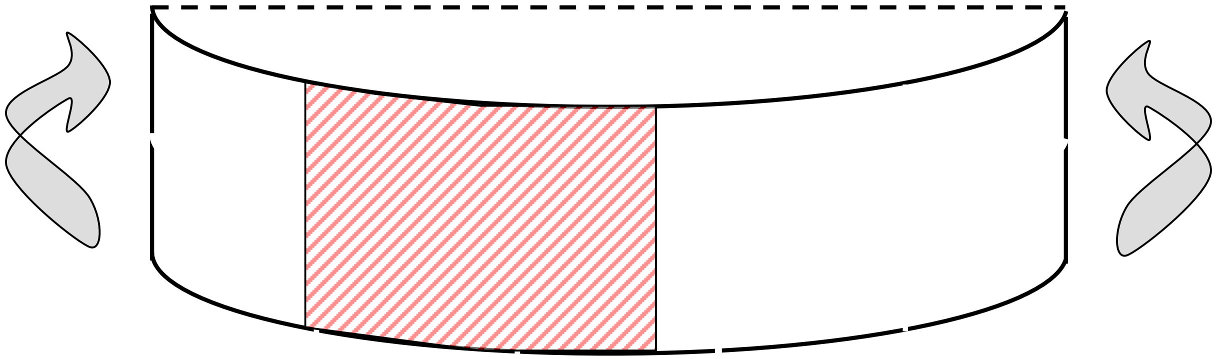
# Influence of cracks and deformation on the electric field





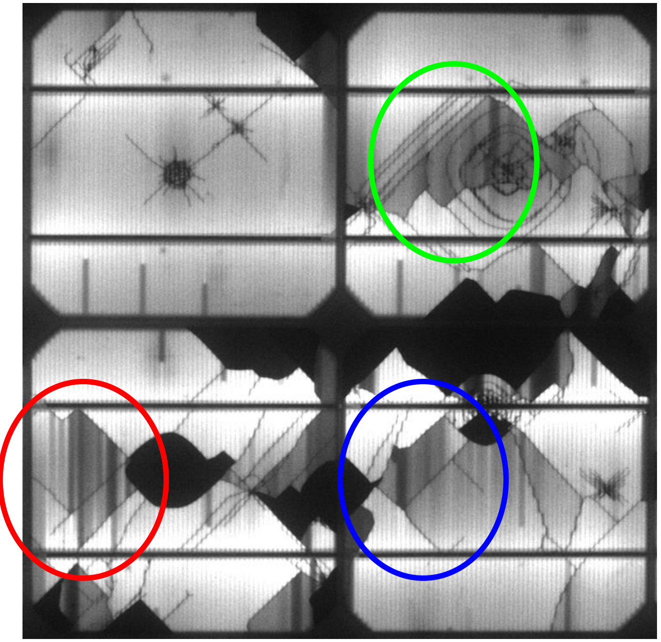
Paggi M, Berardone I, Infuso A, Corrado M (2014) Fatigue degradation and electric recovery in Silicon solar cells embedded in photovoltaic modules. **Sci. Rep.,** 4:4506.



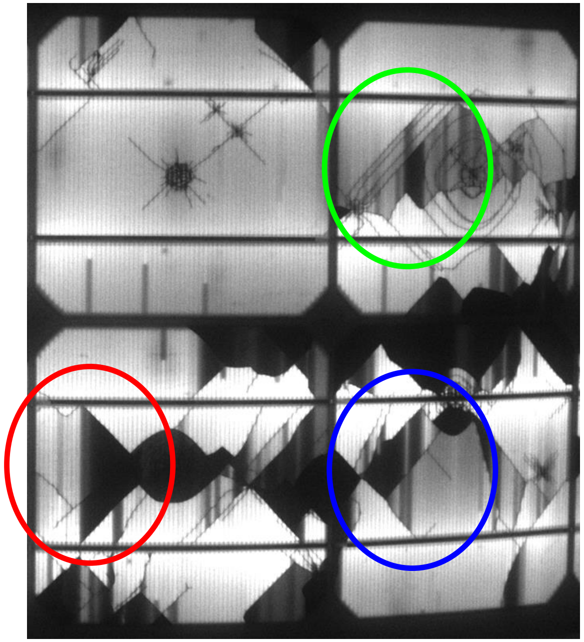


Paggi M, Berardone I, Infuso A, Corrado M (2014) Fatigue degradation and electric recovery in Silicon solar cells embedded in photovoltaic modules. Sci Rep 4:4506.

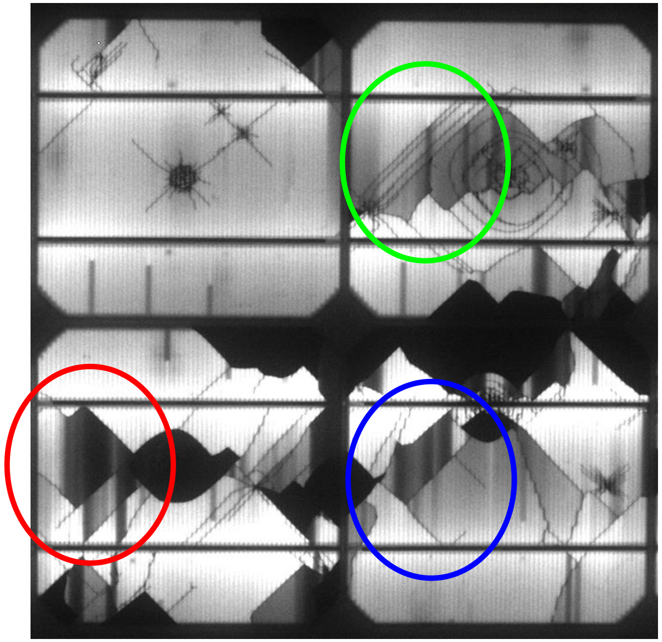
# Results



Initial flat configuration



Max deflection

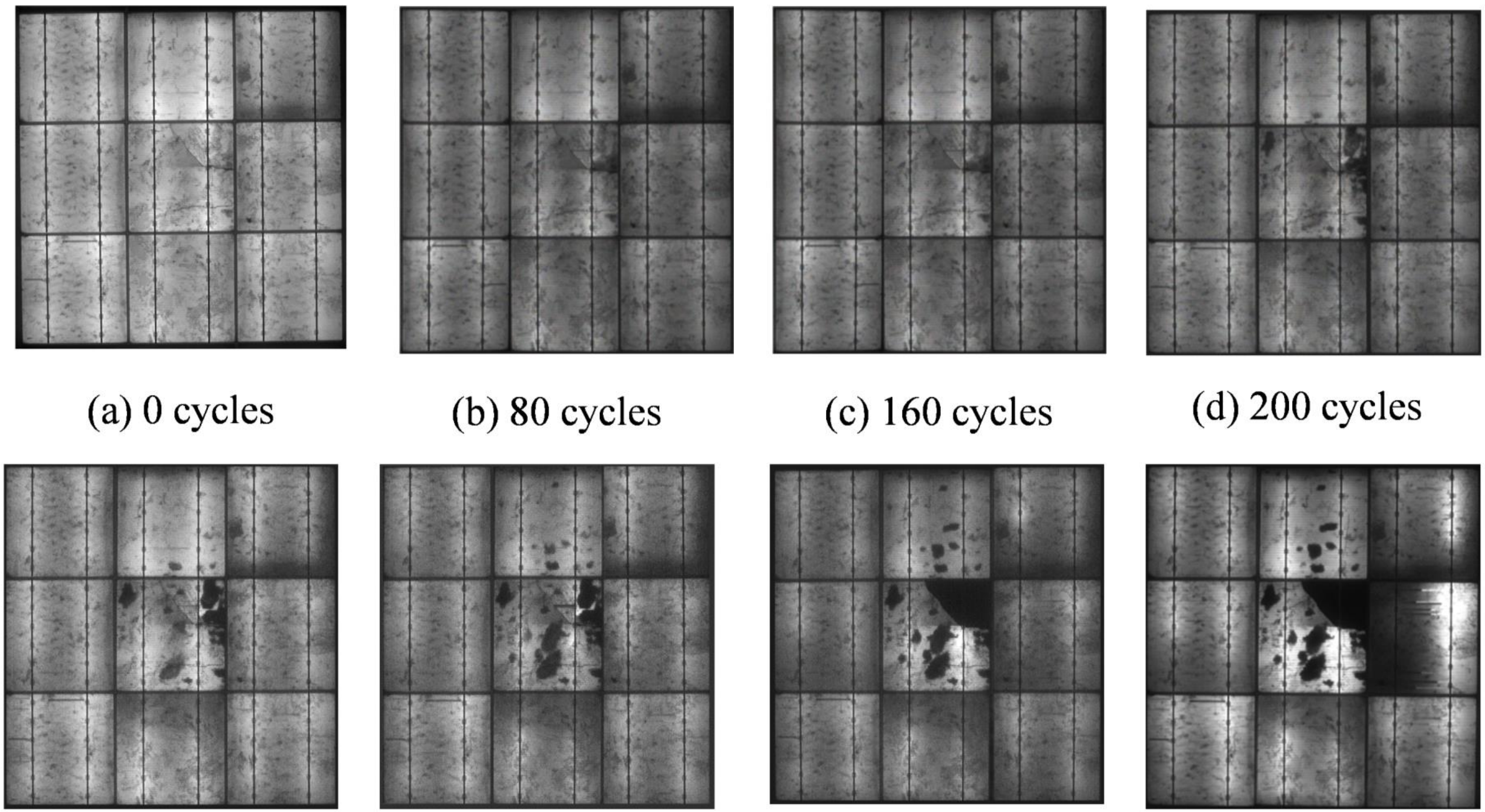


Final flat configuration

- **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

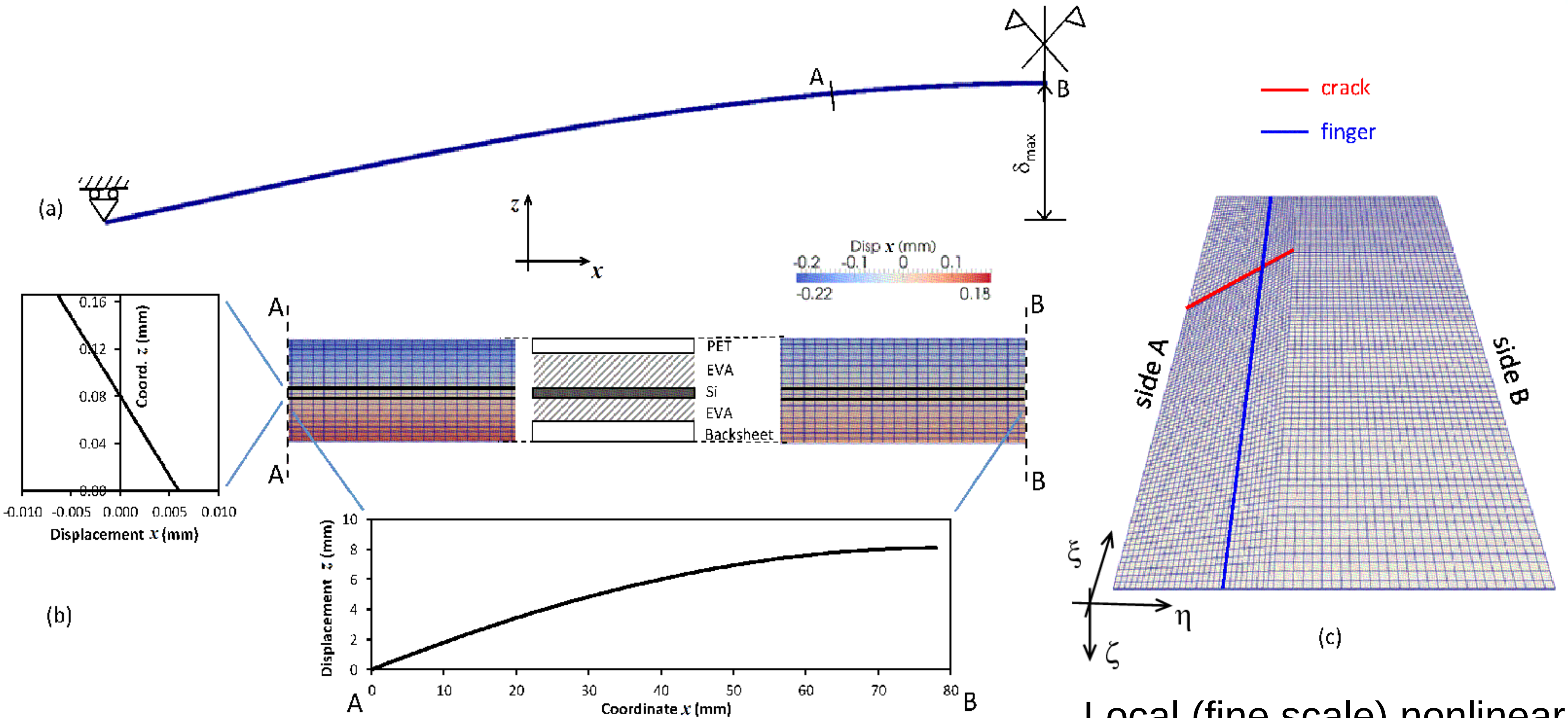


(a) 0 cycles (b) 80 cycles (c) 160 cycles (d) 200 cycles

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

# Computational models

# Global/local FE approach

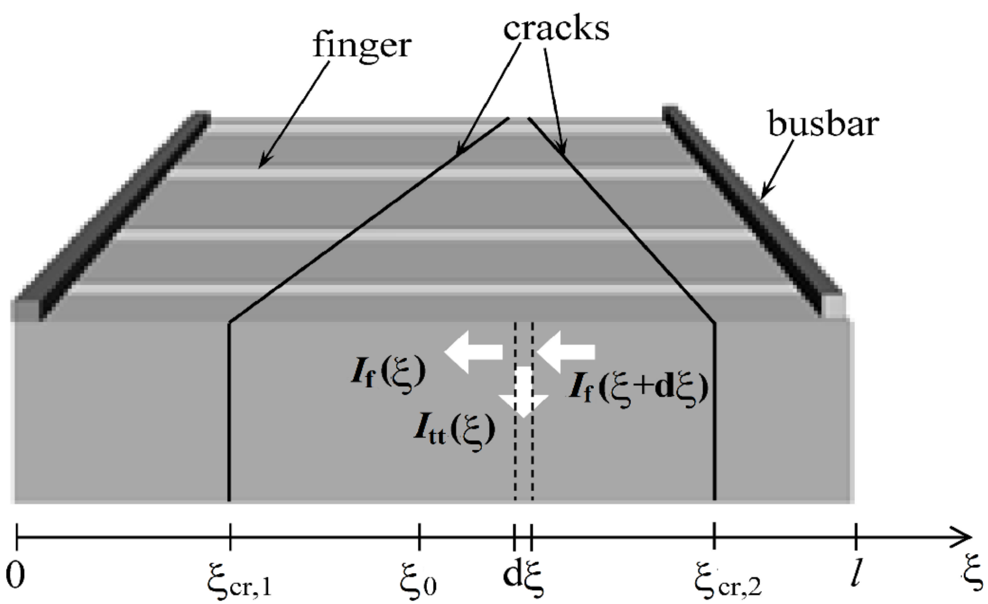



Global (coarse scale) FE model

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

# Electric model




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

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

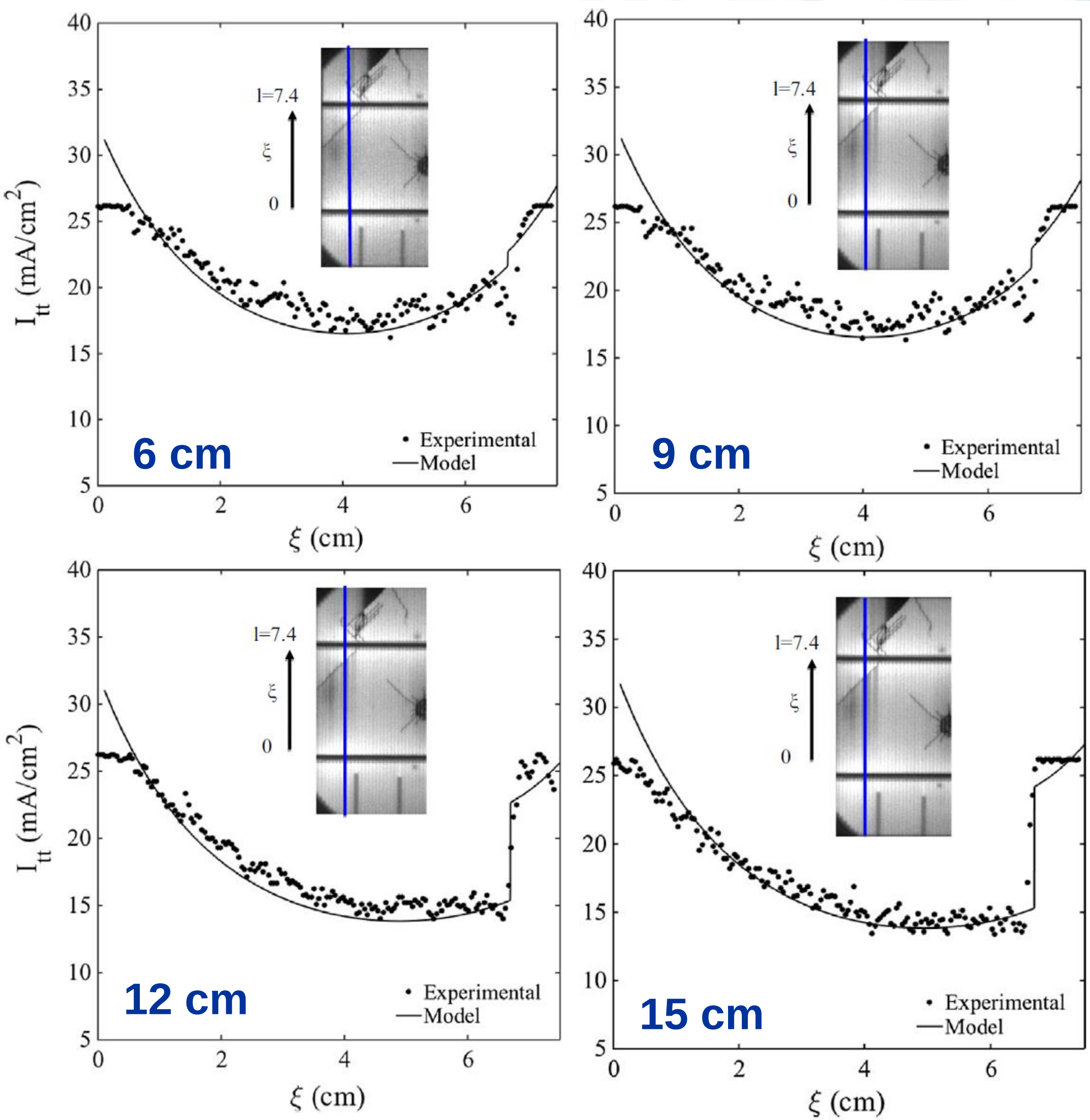
$$I_{tt}(\xi) = I_{01} \exp\left(\frac{V(\xi) - R_{hom} I_{tt}(x)}{n_1 V_T}\right)$$

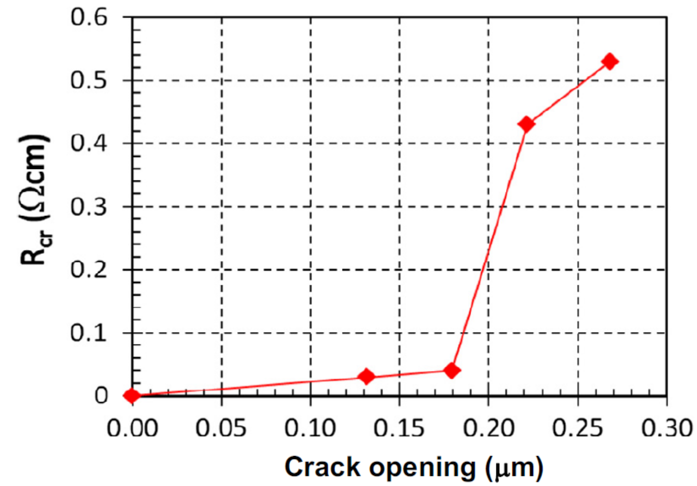
$$V(\xi_{cr,1}^{-}) = V(\xi_{cr,1}^{+}) + R_{cr,1} I_f(\xi_{cr,1})$$


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

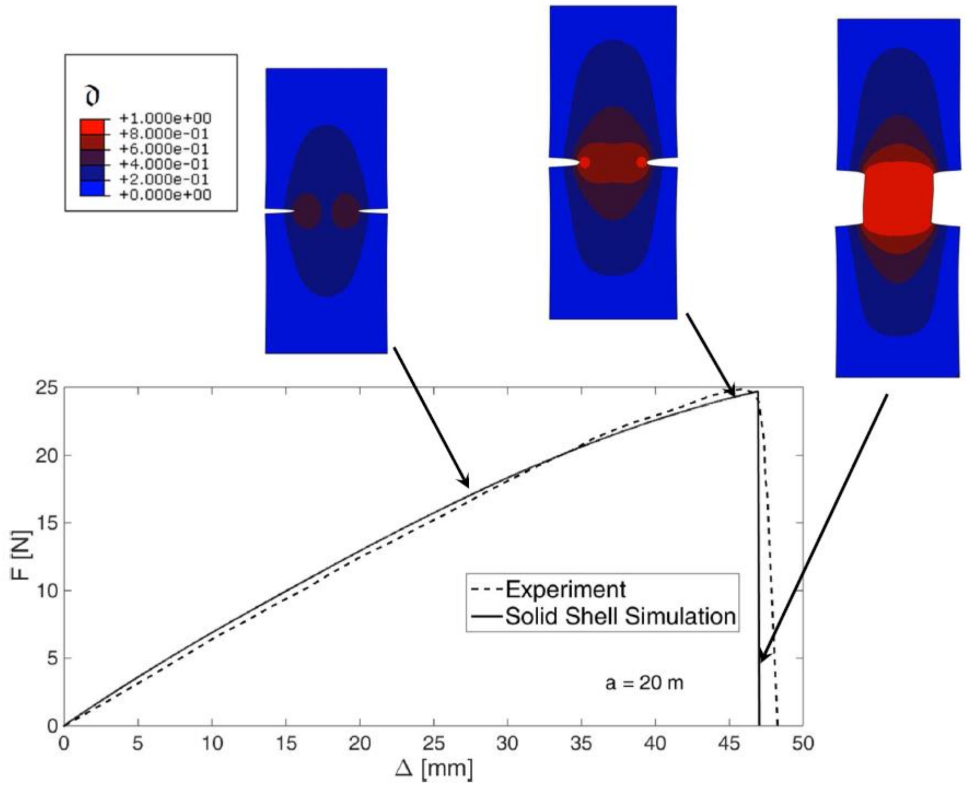
# Electric model



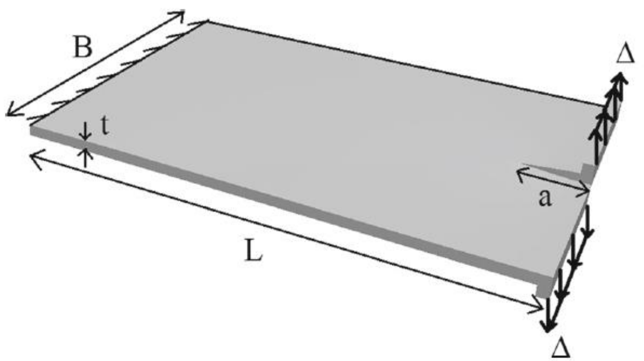
# Phase field modeling of fracture in shells

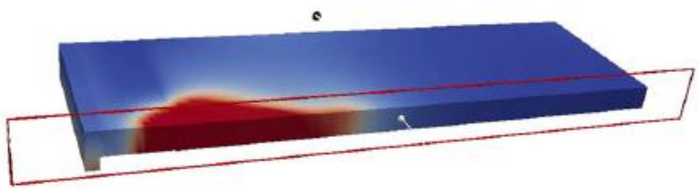
- Solid shell finite element
- Monolithic and implicit formulation
- Phase field interpolation through the shell thickness
- ANS + EAS technologies (for Poisson thickness and volumetric locking pathologies)
- Linear elastic and nonlinear elastic constitutive relations
- FEAP & Abaqus implementation

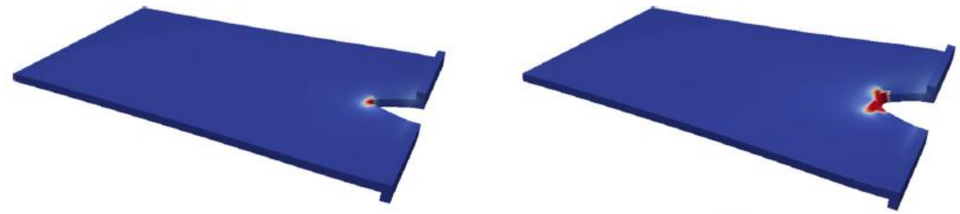



J. Reinoso, M. Paggi, C. Linder (2017) Phase field modeling of brittle fracture for enhanced assumed strain shells at large deformations: formulation and finite element Implementation, Computational Mechanics, DOI 10.1007/s00466-017-1386-3

# Phase field modeling of fracture in shells

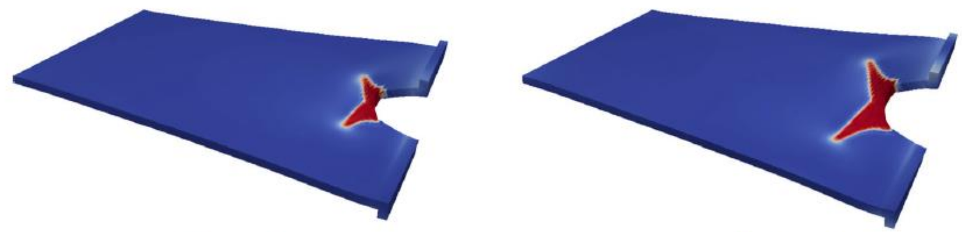




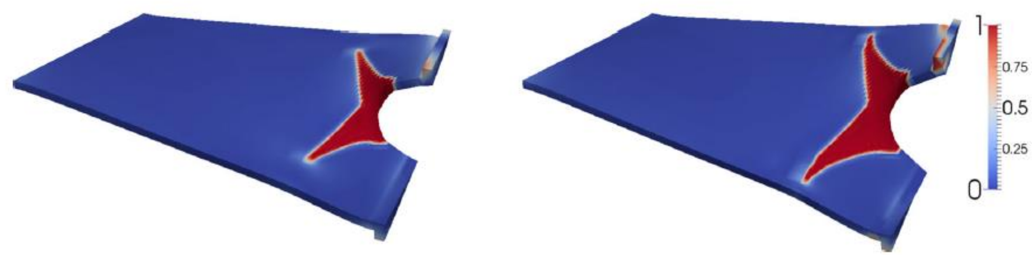
(a) $\Delta = 0.012$ mm

(b) $\Delta = 0.02$ mm



(c) $\Delta = 0.03$ mm

(d) $\Delta = 0.04$ mm

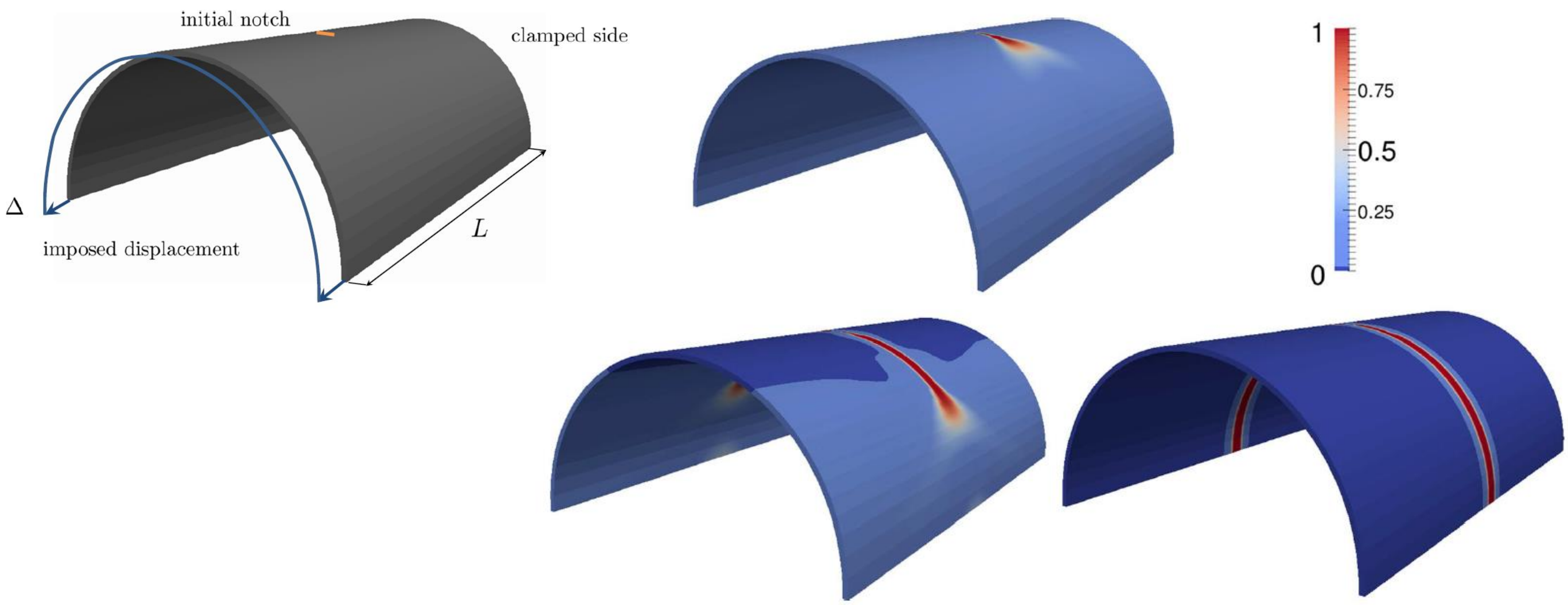



(e) $\Delta = 0.05$ mm

(f) $\Delta = 0.064$ mm

J. Reinoso, M. Paggi, C. Linder (2017) Phase field modeling of brittle fracture for enhanced assumed strain shells at large deformations: formulation and finite element Implementation, Computational Mechanics, DOI 10.1007/s00466-017-1386-3

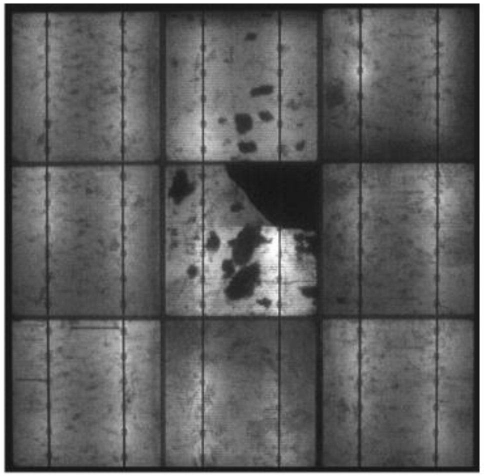
# Phase field modeling of fracture in shells



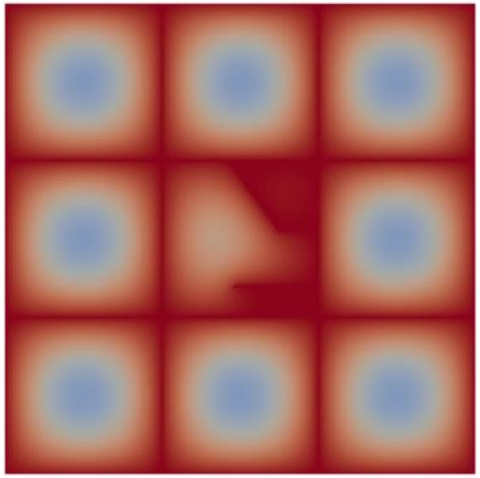

J. Reinoso, M. Paggi, C. Linder (2017) Phase field modeling of brittle fracture for enhanced assumed strain shells at large deformations: formulation and finite element Implementation, Computational Mechanics, DOI 10.1007/s00466-017-1386-3

# Environmental vs. accelerated aging

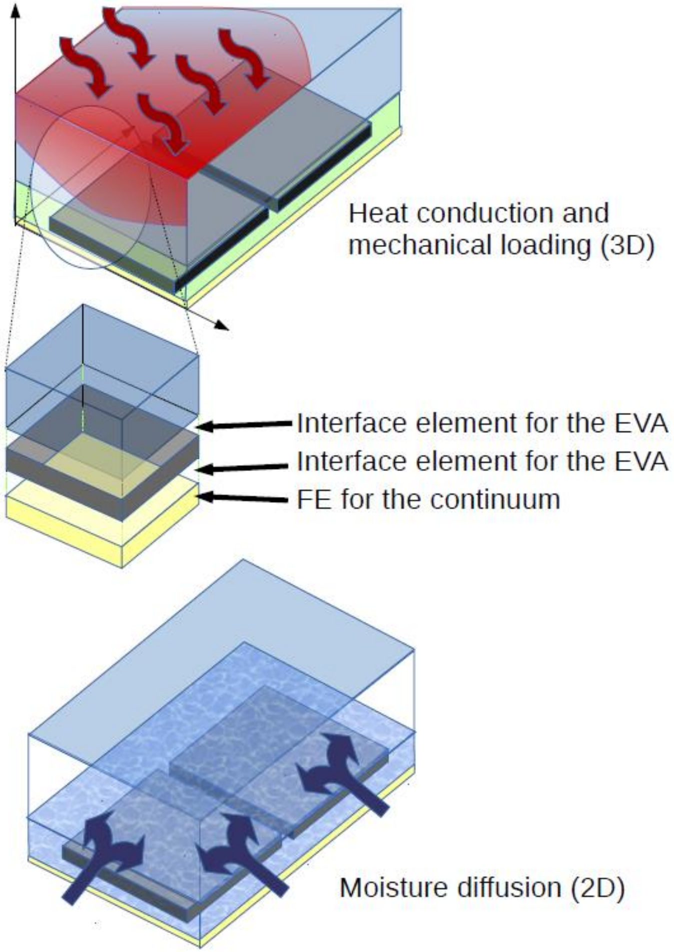
Moisture diffusion and chemical reactions take place inside the EVA layers



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**.

# The role of chemistry

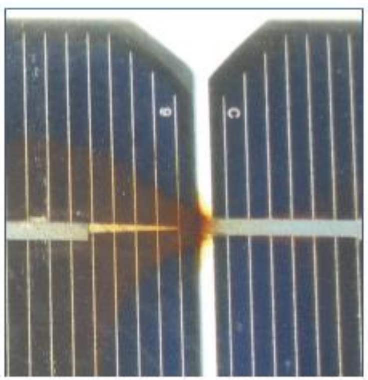
## Yellowing and browning

*Chromophores*

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

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

## Acetic acid ($CH_3COOH$)



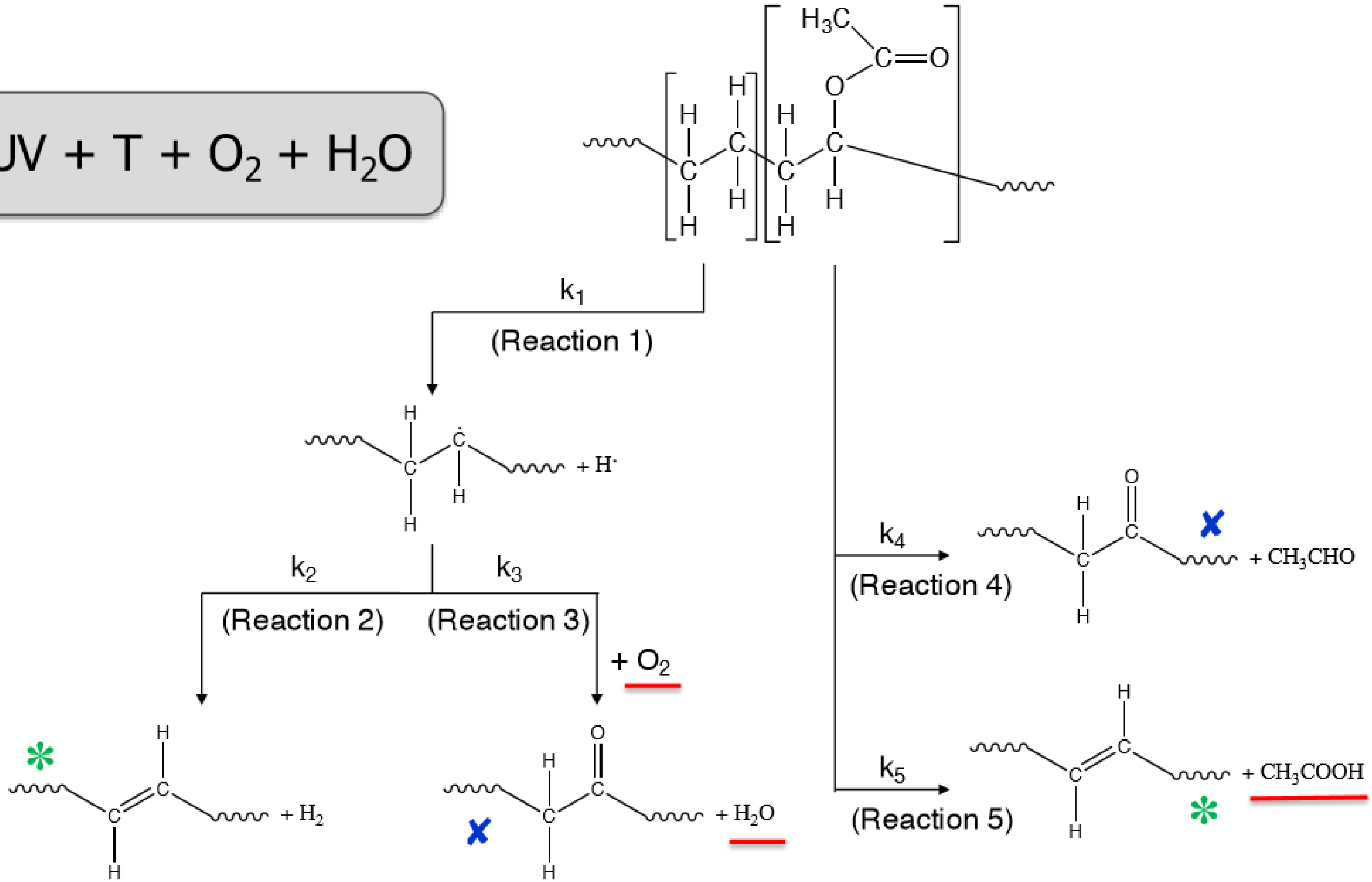
Ag corrosion

Snail trails

## Moisture sorption + gas formation + overheating

# Environmental vs. accelerated aging

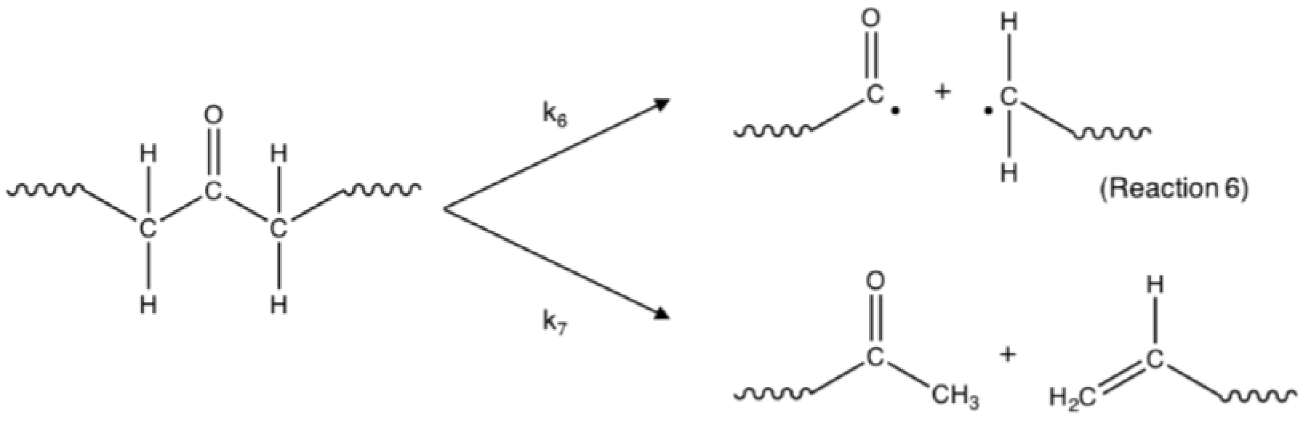
UV + T + $O_2$ + $H_2O$




**Primary reactions**: deprotonation, oxidation, deacetylation

# Environmental vs. accelerated aging

**Secondary following reactions**: polymer chain cleavage

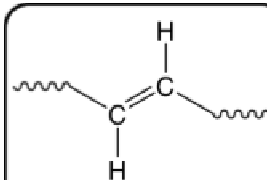



(Reaction 6)

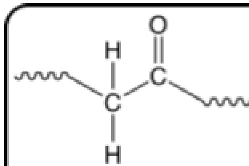
(Reaction 7)

*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 accelerated aging)

## Reaction kinetics ODEs

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

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

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

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

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

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

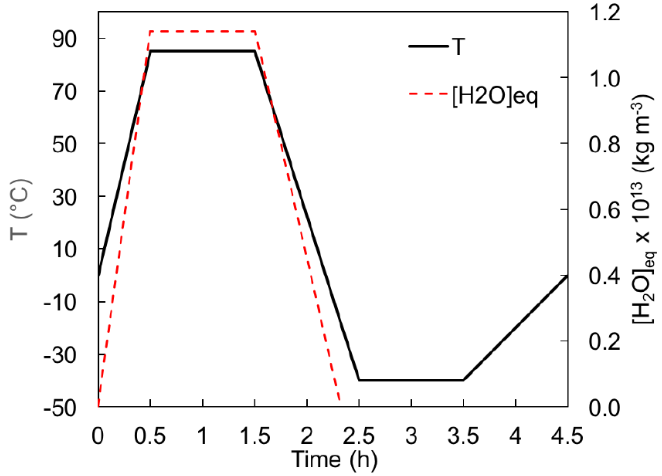
$$\frac{\mathrm{d}[\mathrm{R_t}^\bullet]}{\mathrm{d}t} = k_6[\mathrm{C_b}]$$

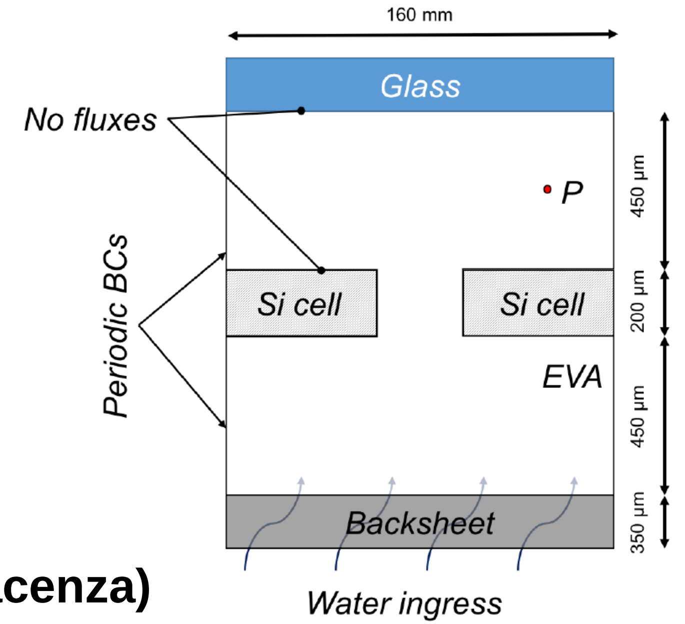
$$\frac{\mathrm{d}[\mathrm{C_bt}]}{\mathrm{d}t} = k_7[\mathrm{C_b}]$$

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

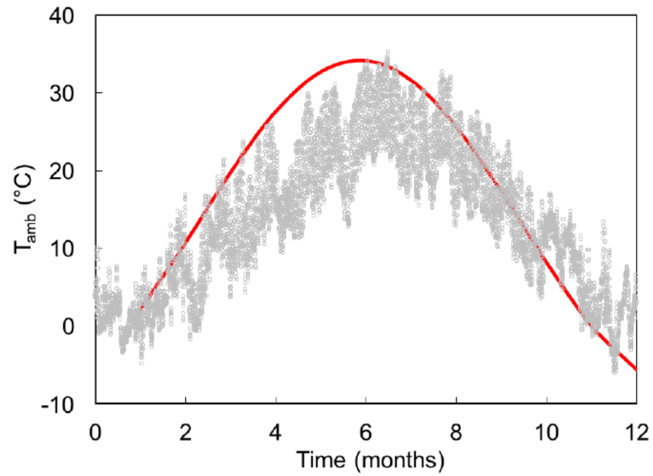
# Environmental vs. accelerated aging

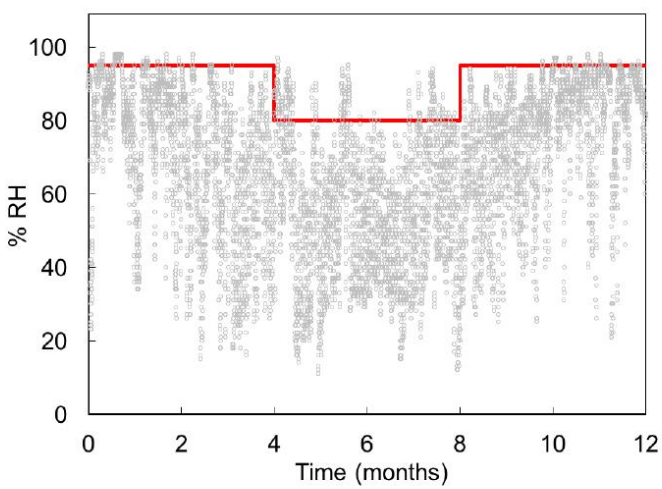
## Accelerated aging (damp-heat test)




## Environmental degradation (climatic data from Piacenza)



## Integration algorithm:

$$\rho c \frac{T^{n+1} - T^n}{\Delta t} - \kappa \nabla^2 T^{n+1} = Q_T$$

$$\frac{\mathbf{C}^{n+1} - \mathbf{C}^n}{\Delta t} + \mathrm{div}(\mathbf{D}(\mathbf{C}^{n+1})\nabla \mathbf{C}^{n+1}) = \mathbf{F}$$

**Input: kinetic and diffusion parameters:**

$k_i^0$, $E_i$, $\Delta H_i$, $D_j^0$, $E_j^d$, $\kappa$, $\rho$, $c$;

**Initialize:** $\{C\}^1$, $T^1$tol, norm $= 1$

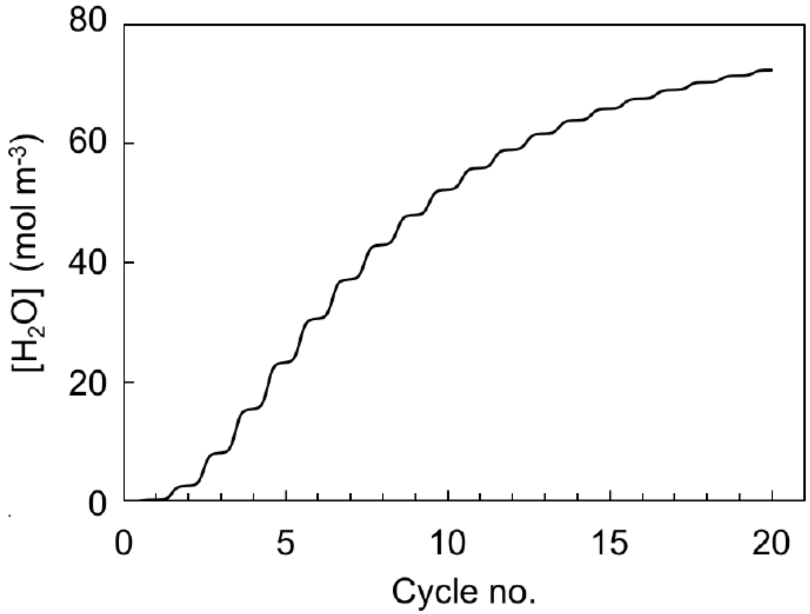
**Given** $\{C\}^n$, $T^n$

**for** $n = 1, \ldots, N$ time steps **do**

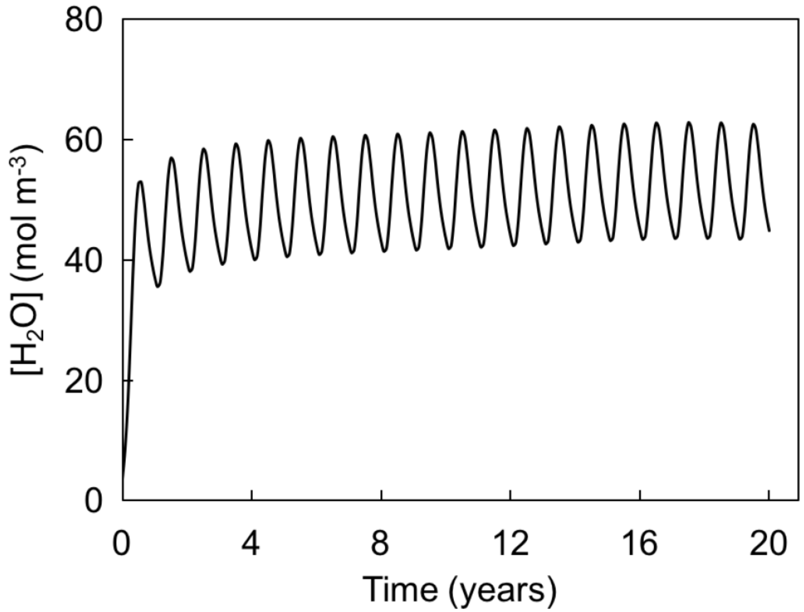
- Compute $k_i(T^n)$, $Q_T(T^n)$;
- Solve the thermal problem:
- $\rho c \partial_t T^{n+1} - \kappa \nabla^2 T^{n+1} = Q_T$;
- Update temperature: $T^{n+1} \leftarrow T^n$;
- Update kinetic constants and diffusion coefficients:
- $k_i(T^{n+1})$, $D_j(T^{n+1})$;
- **while** (norm $\geq$ tol) **do**
  - Update reaction vector and diffusion matrix
  - $\mathbf{F}_{(k)}^{n+1}$, $\mathbf{D}_{(k)}^{n+1}$;
  - Form the residual vector: $\{R\}_{(k)}^{n+1}$;
  - Solve the linearized reaction – diffusion system:
  - $\{C\}_{(k)}^{n+1} \leftarrow \{C\}_{(k)}^{n+1}$
- **end**
- Update the concentration vector:
- $\{C\}^{n+1} \leftarrow \{C\}^n$;

**end**

# Environmental vs. accelerated aging




**Accelerated aging**

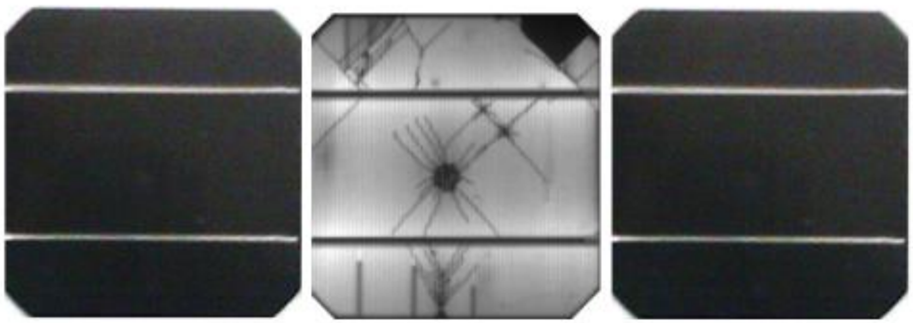



**Environmental degradation**

M. Gagliardi, P. Lenarda, M. Paggi (2017) A reaction-diffusion formulation to simulate EVA polymer degradation in environmental and accelerated ageing conditions, Solar Energy Materials and Solar Cells, 164:93–106.

# Acknowledgements


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



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

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

**MUSAM Annual Reports:**
http://musam.imtlucca.it/Report_2014.pdf
http://musam.imtlucca.it/Report_2015.pdf