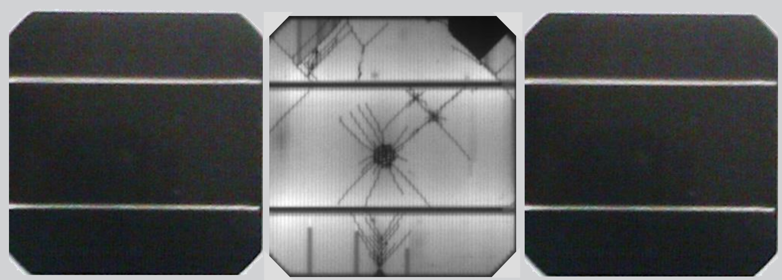
Modelling of fracture in composite structures: Application to photovoltaic modules



Marco Paggi

IMT School for Advanced Studies Lucca

FULLCOMP Workshop, Politecnico di Torino

May 2, 2017

MUSAM
Multi-scale Analysis of Materials

- **M. Paggi**, Associate Professor
- **A. Bacigalupo**, Assistant Professor
- **C. Borri**, Post-doc
- **P. Budarapu**, Post-doc
- **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)
- **V. Govindarajan**, PhD student (30th cycle)
- **R. Del Toro**, PhD student (31st cycle)
- **N. Dardano**, PhD student (32nd cycle)
- **T. Guillen Hernandez**, PhD student (32nd cycle)

Visiting professors

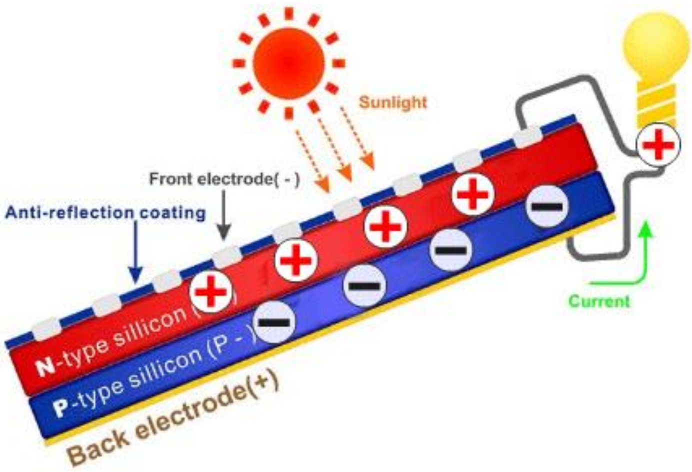
- **D. Bigoni**, Full Professor, University of Trento, ERC AdG, Italy
- **J. Reinoso**, Assistant Professor, University of Seville, Spain
- **M. Corrado**, Assistant Professor, PoliTO & Marie Curie Fellow at EPFL
- **A. Gizzi**, Assistant Professor, Università Campus Bio-Medico of Rome

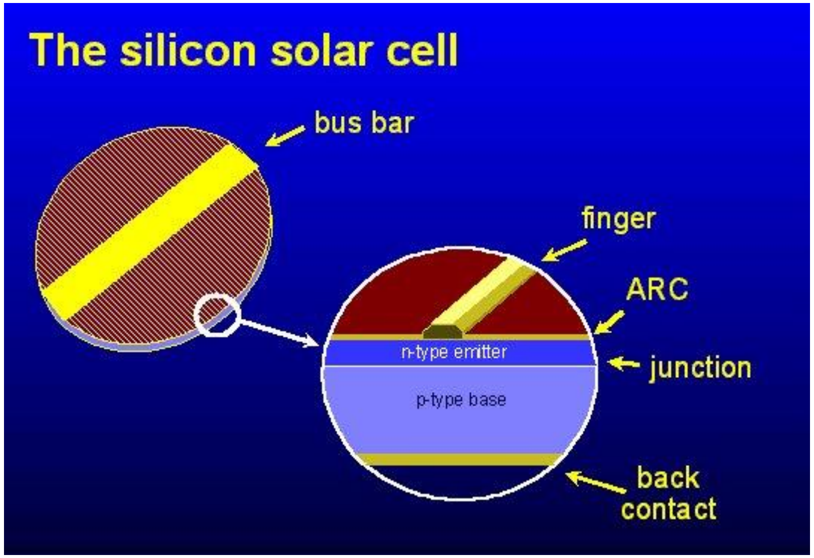
Outline

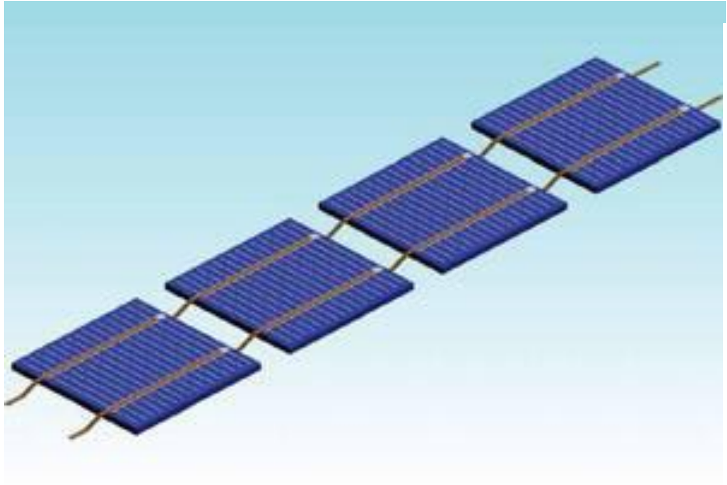
- **Introduction and motivation**
- **Material-based damage and failures in PV laminates**
  - **Hail impacts**
  - **Snow pressure**
  - **Ageing and grid line corrosion due to moisture thermo-diffusion in the encapsulant**
- **Computational methods**

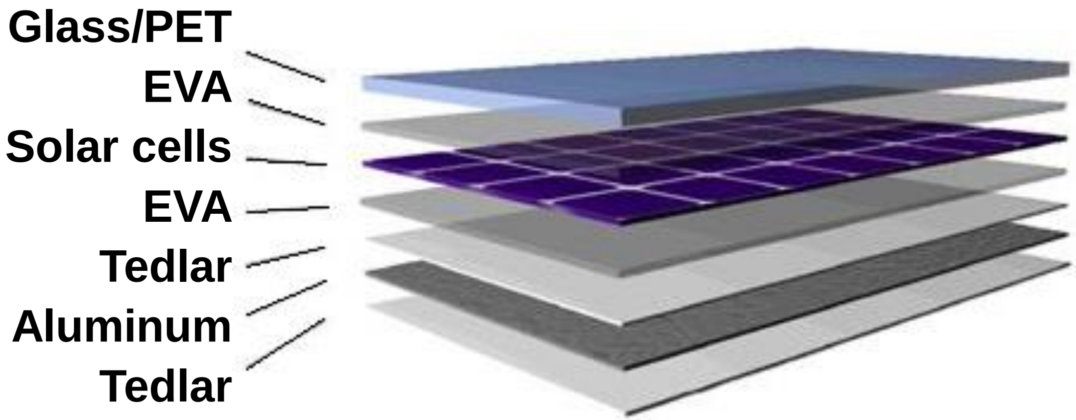
Introduction and motivation

Photovoltaics (PV)





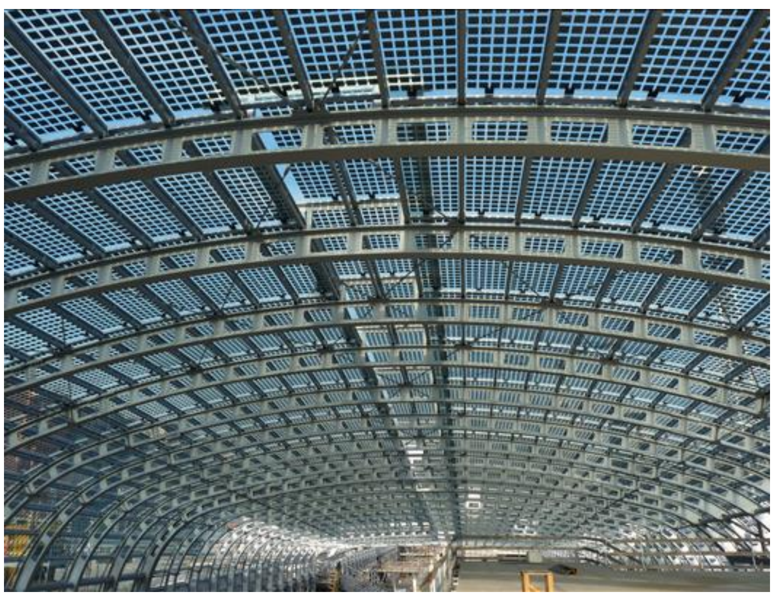




erc
European Research Council
Established by the European Commission

IDEAS

Applications:
from PV parks to building integrated PV

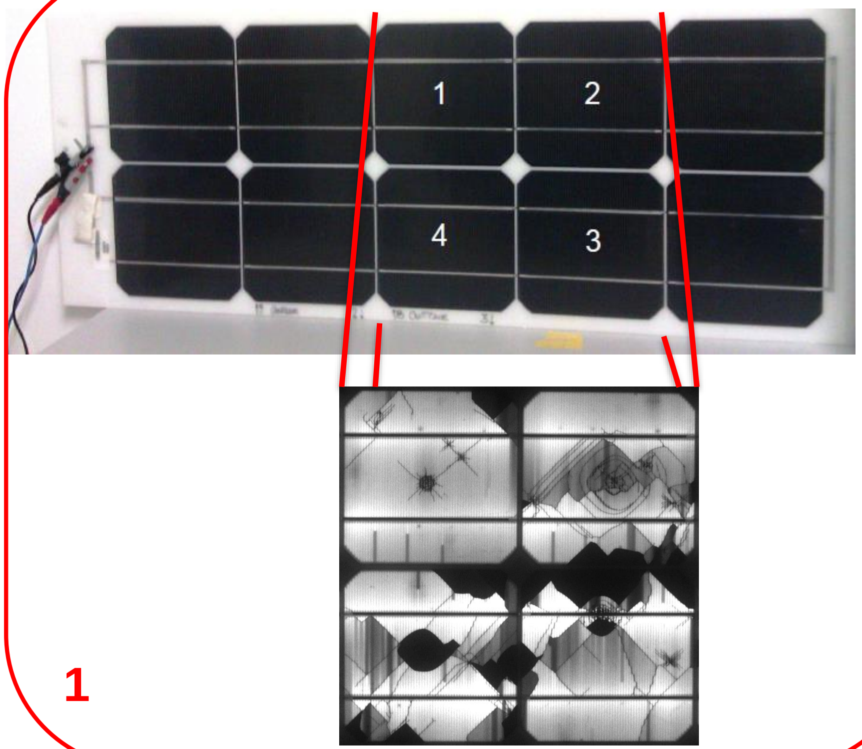


Durability

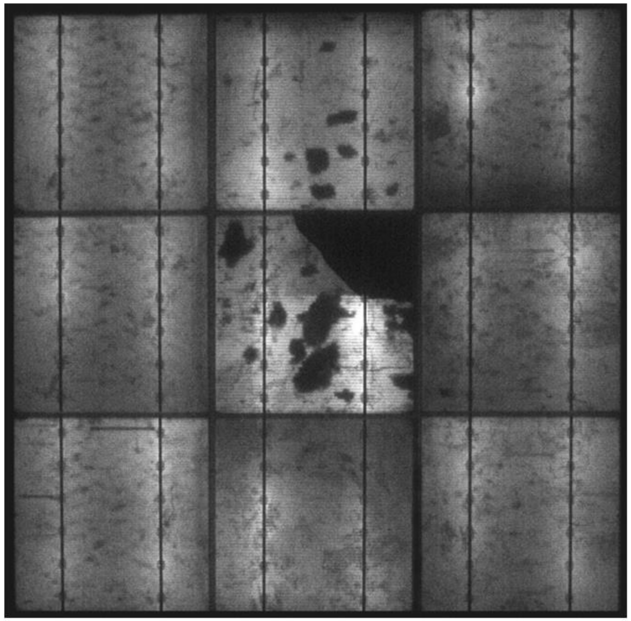
Some failure modes of PV modules:

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

2



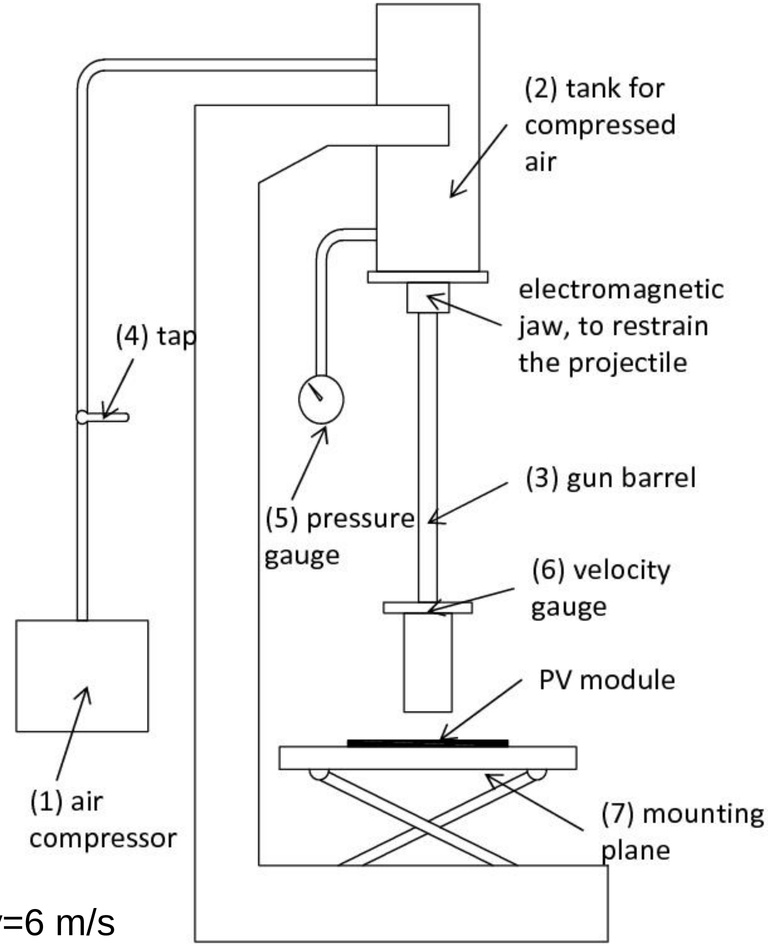
1



3

Simulated hail impacts

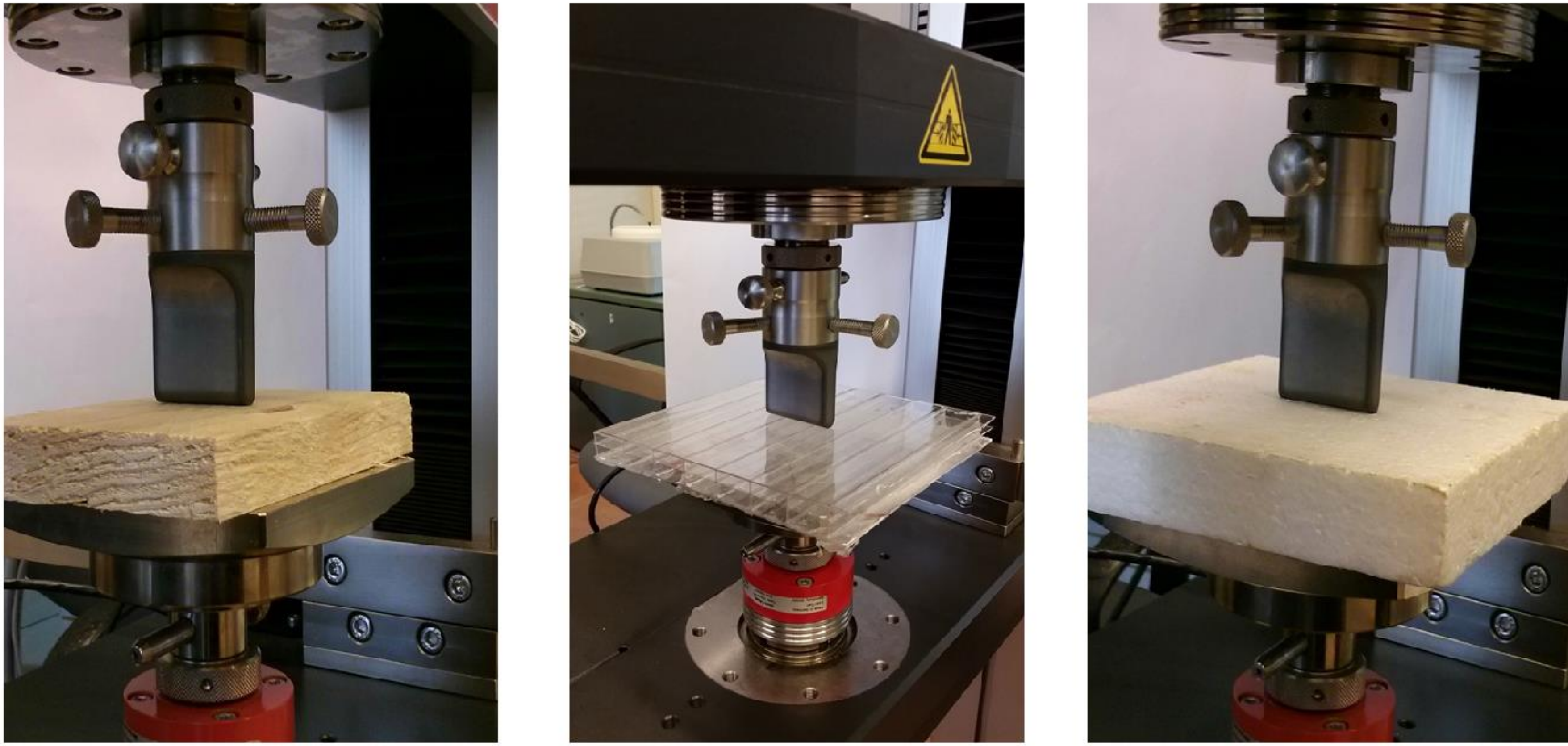
Simulated hail impacts on flexible PV modules



v=6 m/s

M. Corrado, A. Infuso, M. Paggi (2016) Simulated hail impact tests on photovoltaic laminates, **Meccanica**, 52: 1425-1439.

Substrate stiffness



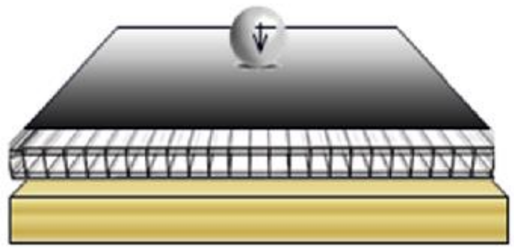
(a) Stiff

(b) Medium

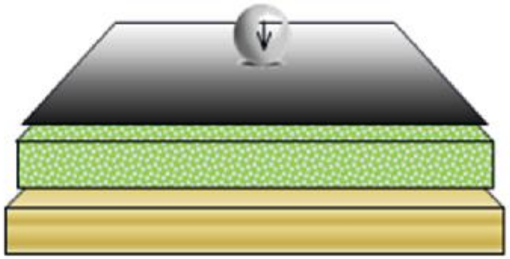
(c) Soft

Crack patterns

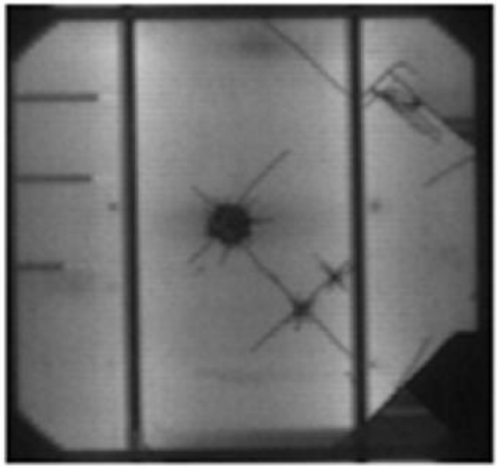
Wooden board



Alveolar PC +
Wooden board

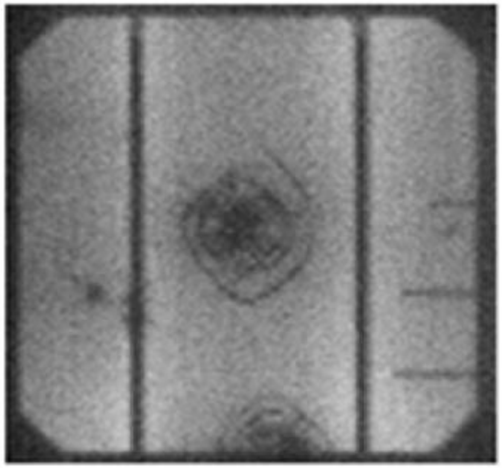


Polystirene +
Wooden board



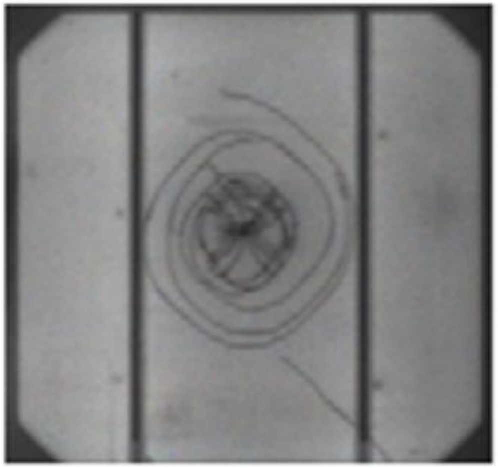
Case A

r*=7.5 mm



Case B

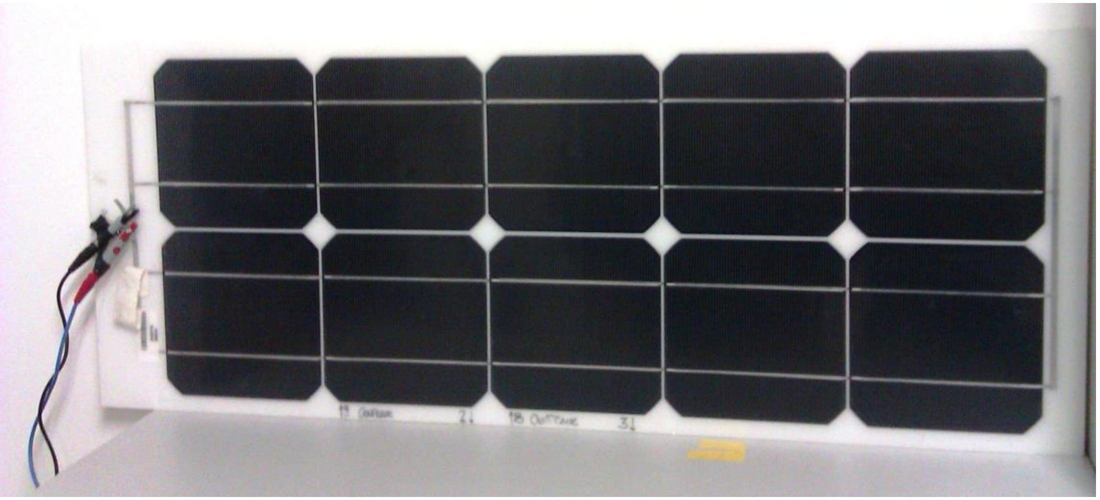
r*=15.8 mm

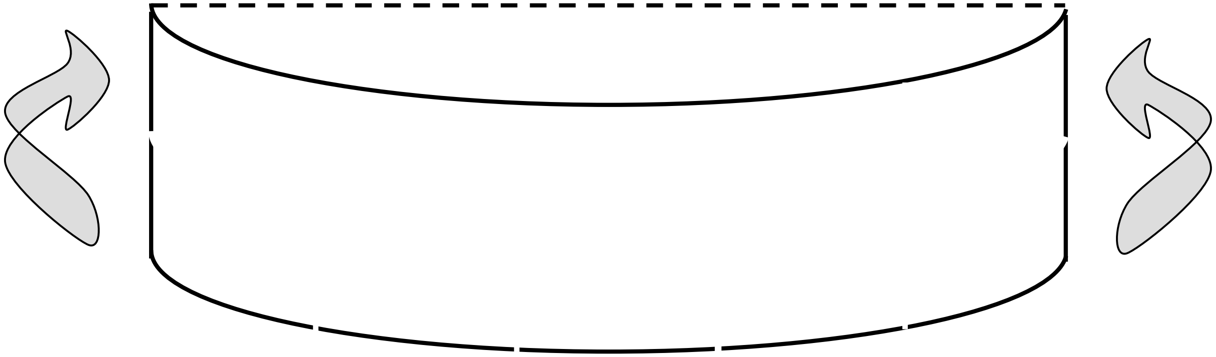


Case C

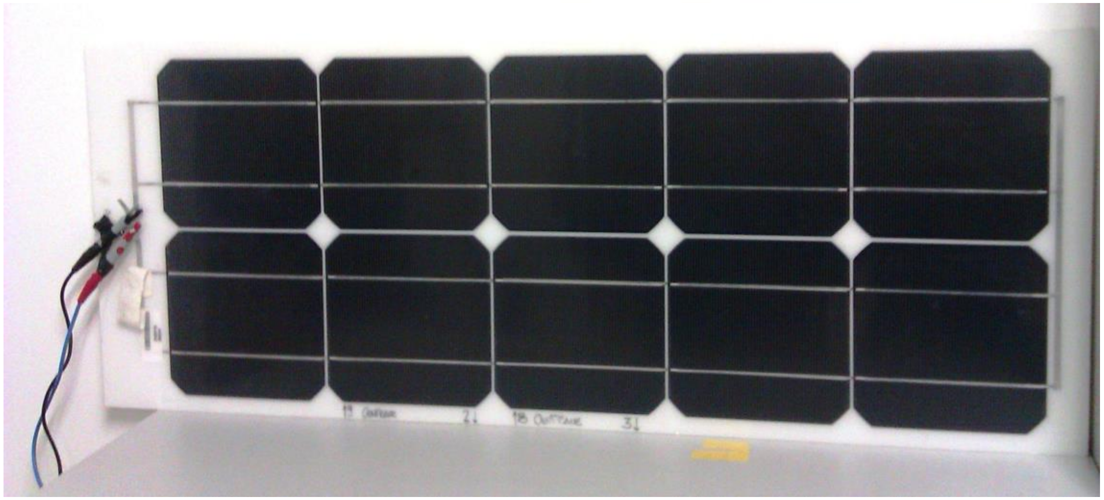
r*=31.0 mm

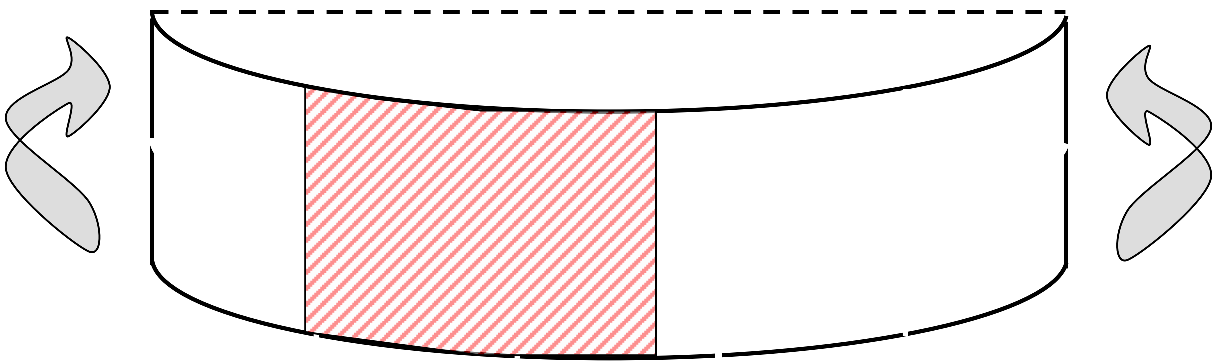
Bending load





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.





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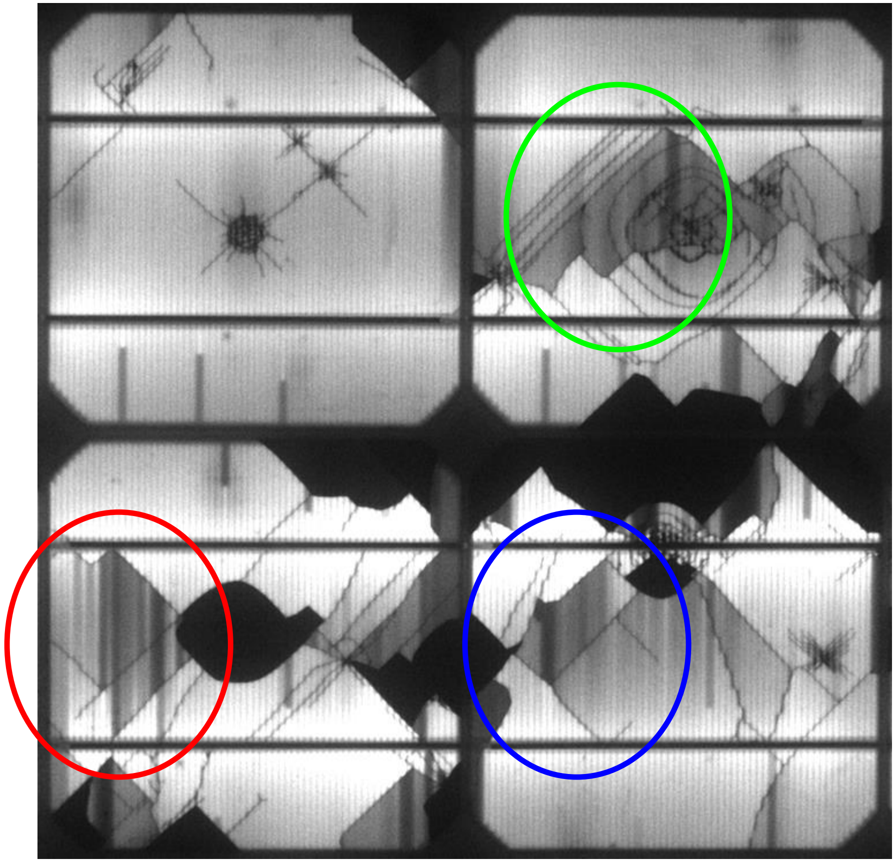
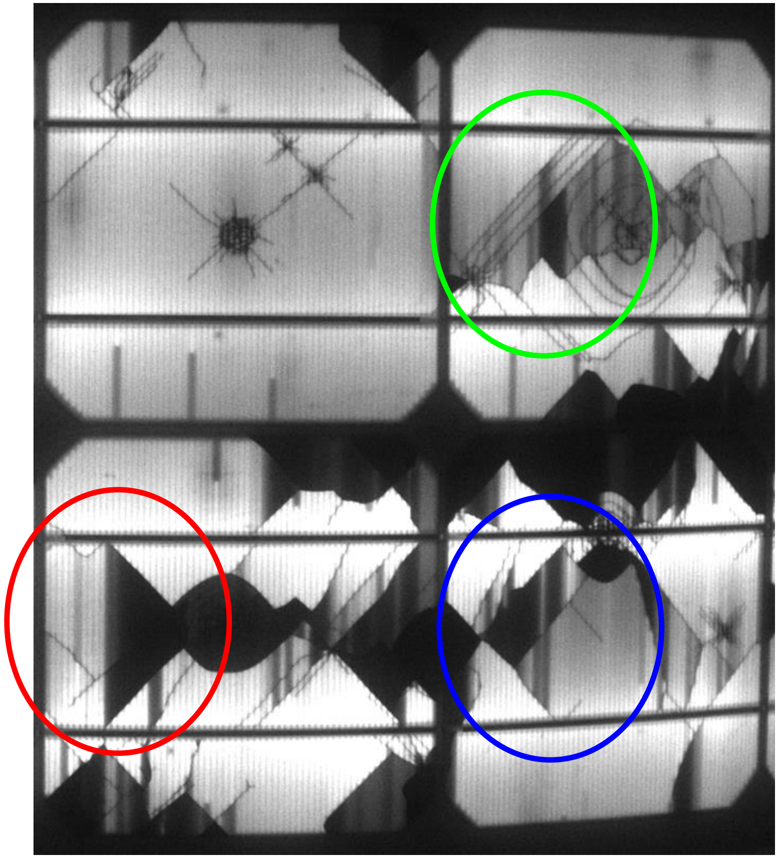


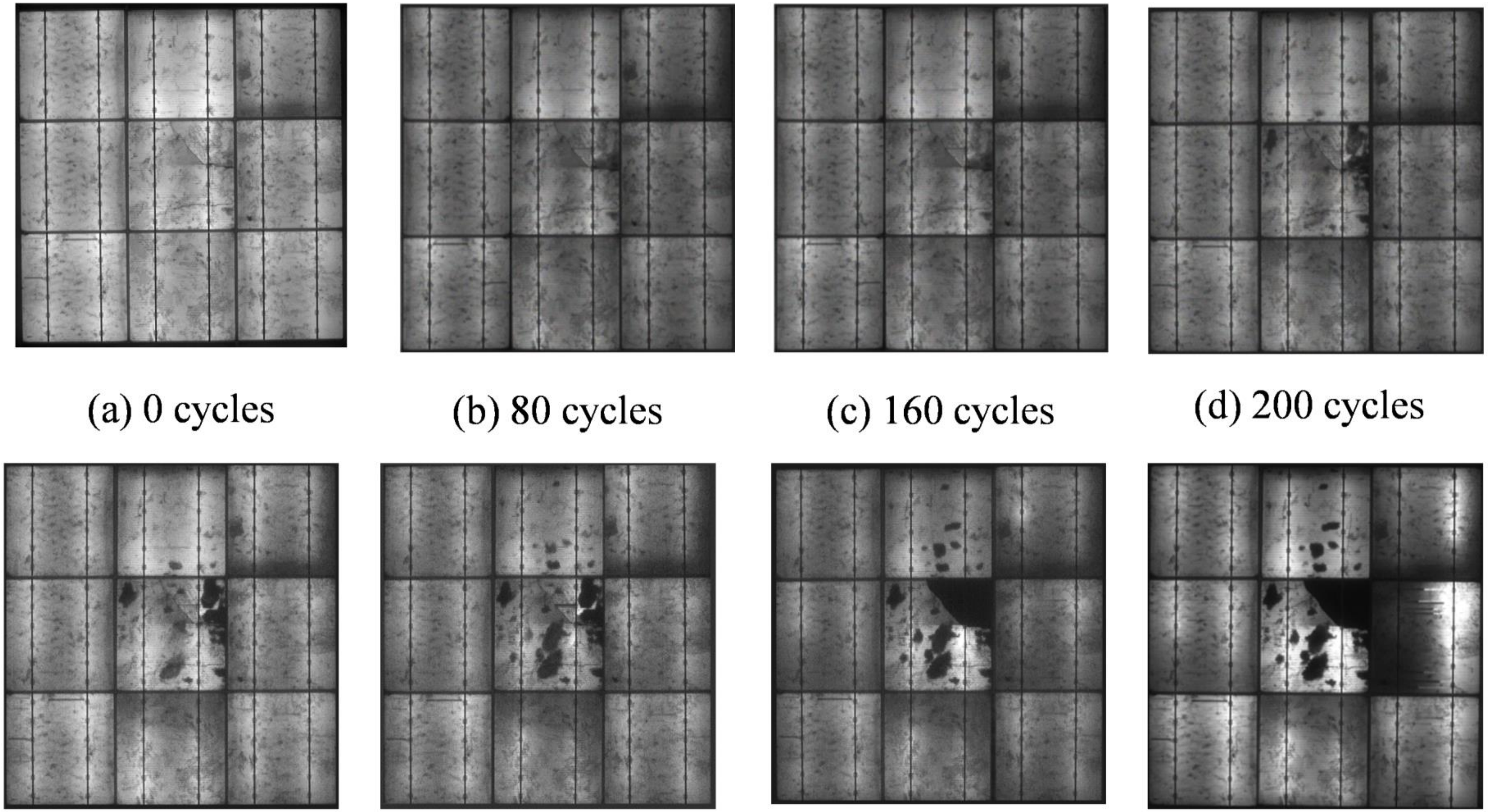
Initial flat configuration



Max deflection

Ageing of PV modules containing cracked solar cells

Accelerated degradation: damp-heat test

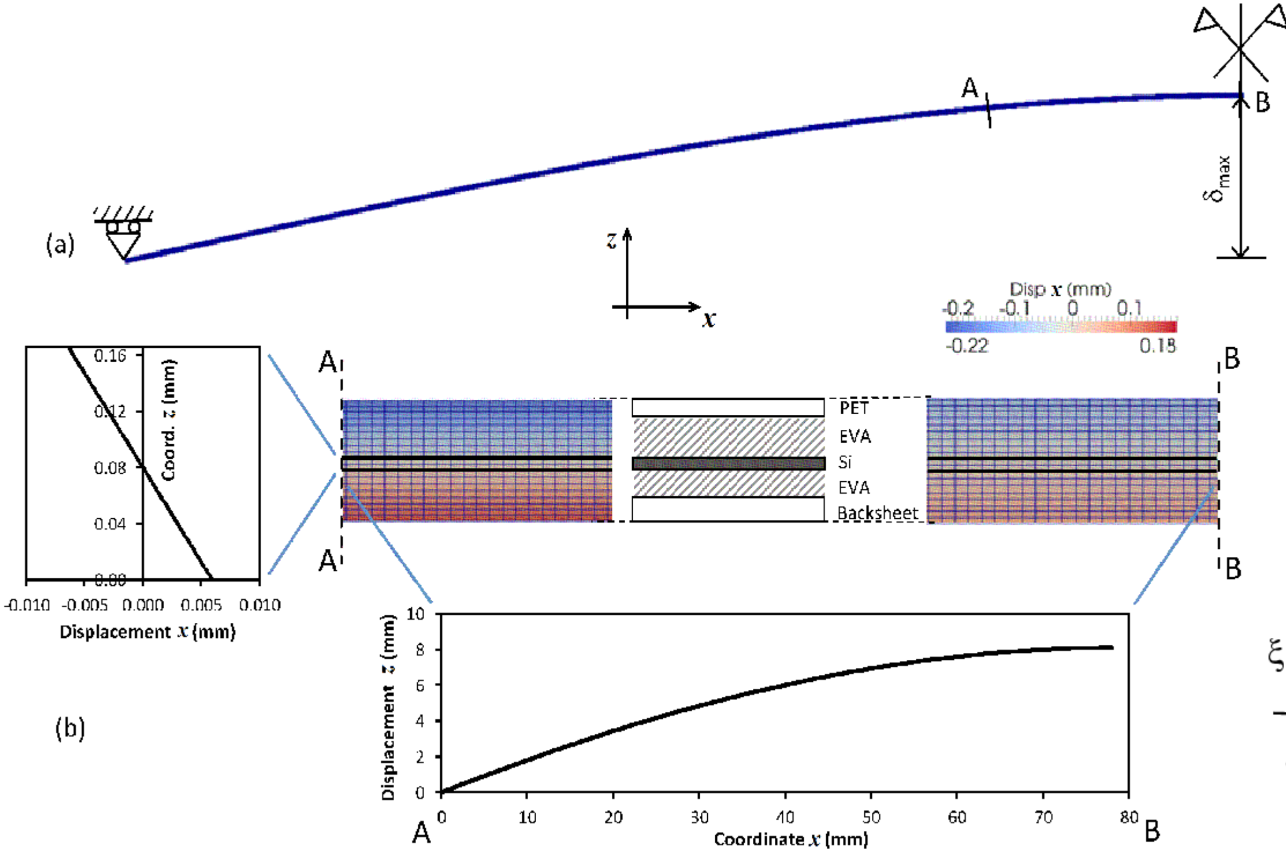


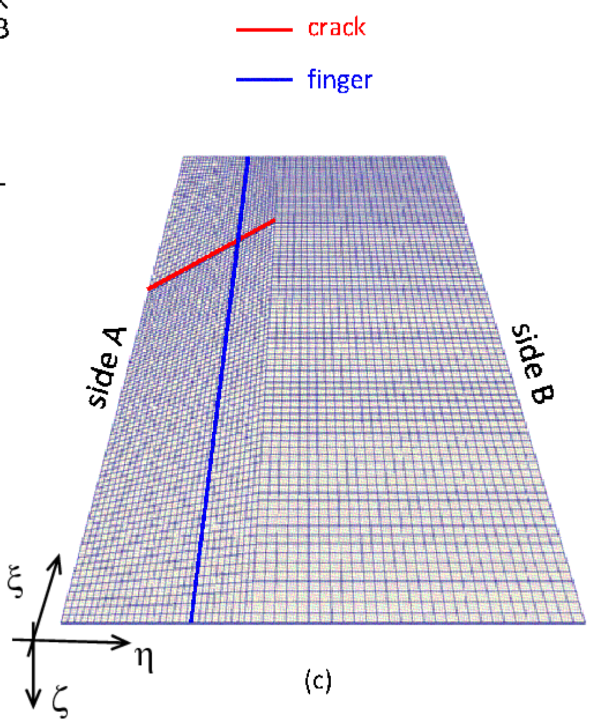
(a) 0 cycles (b) 80 cycles (c) 160 cycles (d) 200 cycles

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

Computational methods

Global/local FE approach



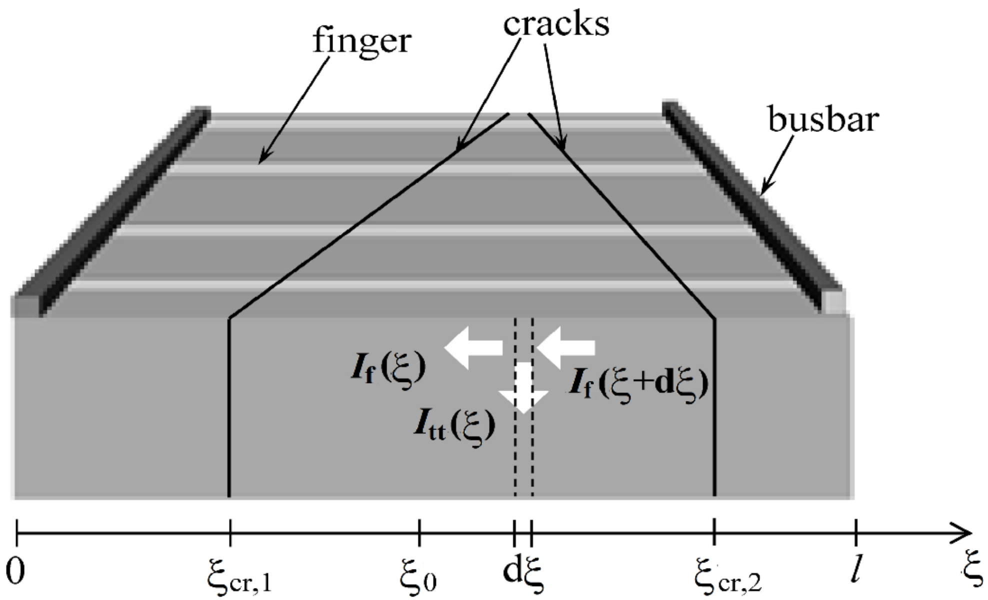


Global (coarse scale) FE model

Local (fine scale) nonlinear FE model of each solar cells with 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. **Eng. Fract. Mech.**, 168:40-57.

Electric model



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

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

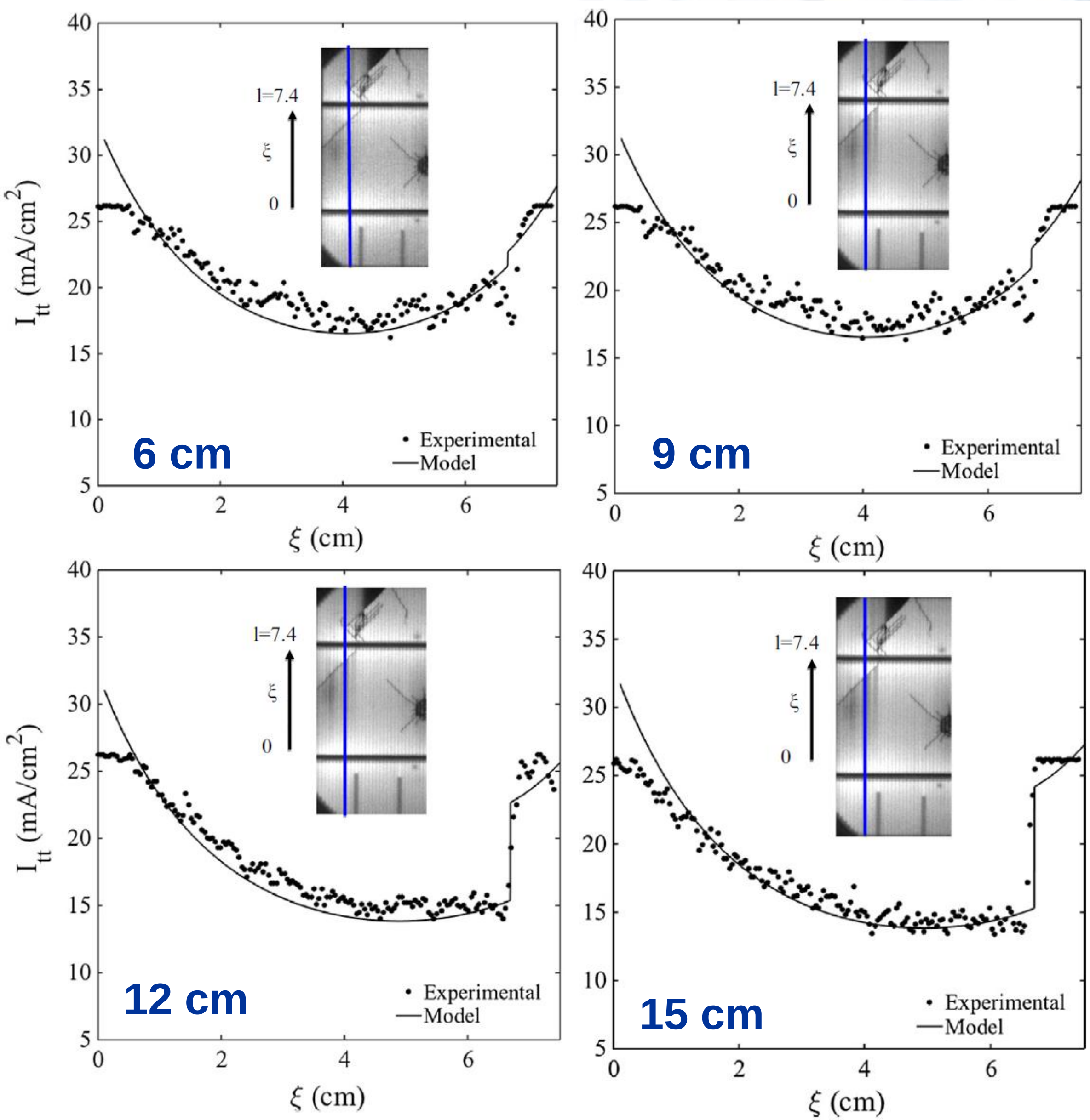
$$I_{tt}(\xi) = I_{01} \exp\left(\frac{V(\xi) - R_{hom} I_{tt}(x)}{n_1 V_T}\right)$$

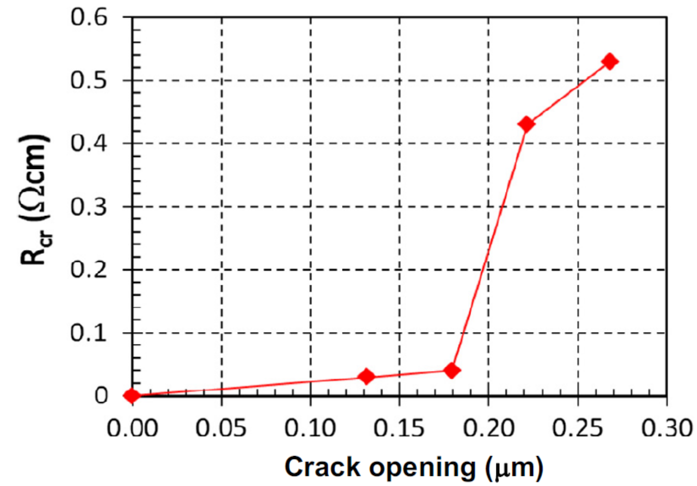
$$V(\xi_{cr,1}^{-}) = V(\xi_{cr,1}^{+}) + R_{cr,1} I_f(\xi_{cr,1})$$

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. **Eng. Fract. Mech.**, 168:40-57.

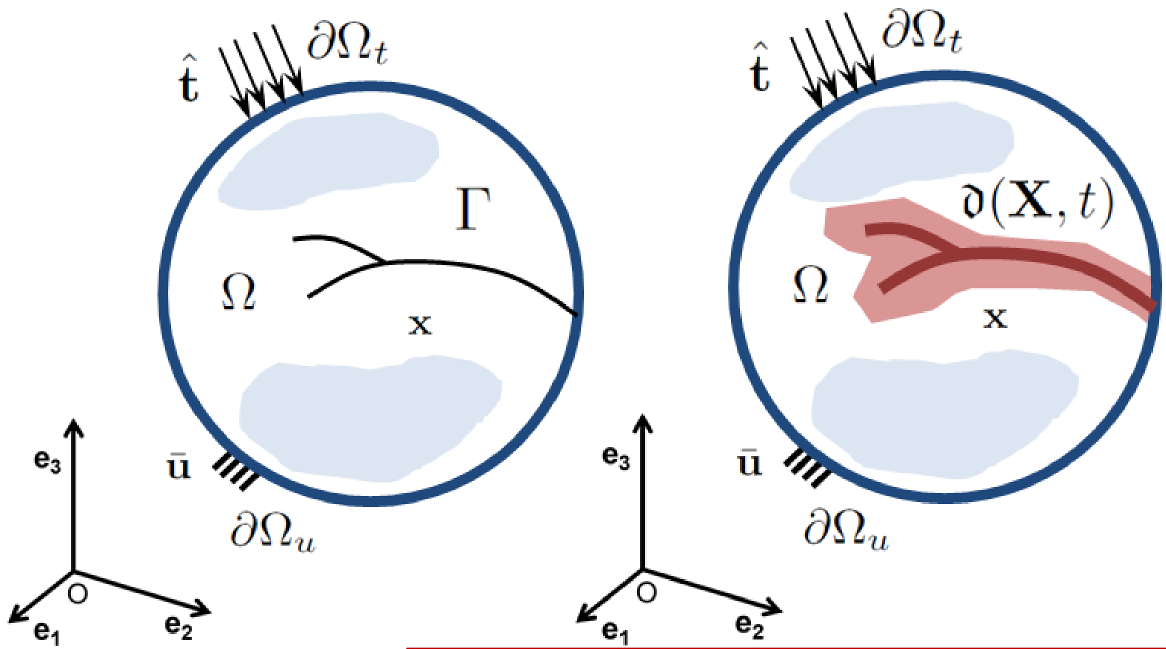
Electric model





Phase field modeling of fracture in shells

Brittle fracture in solids modeled via a nonlocal smeared crack approach



<u>Phase-field</u>

$\mathfrak{d}(\mathbf{X}, t) \in [0, 1]$

Intact **Fully damaged**

Miehe et al. [2010]]

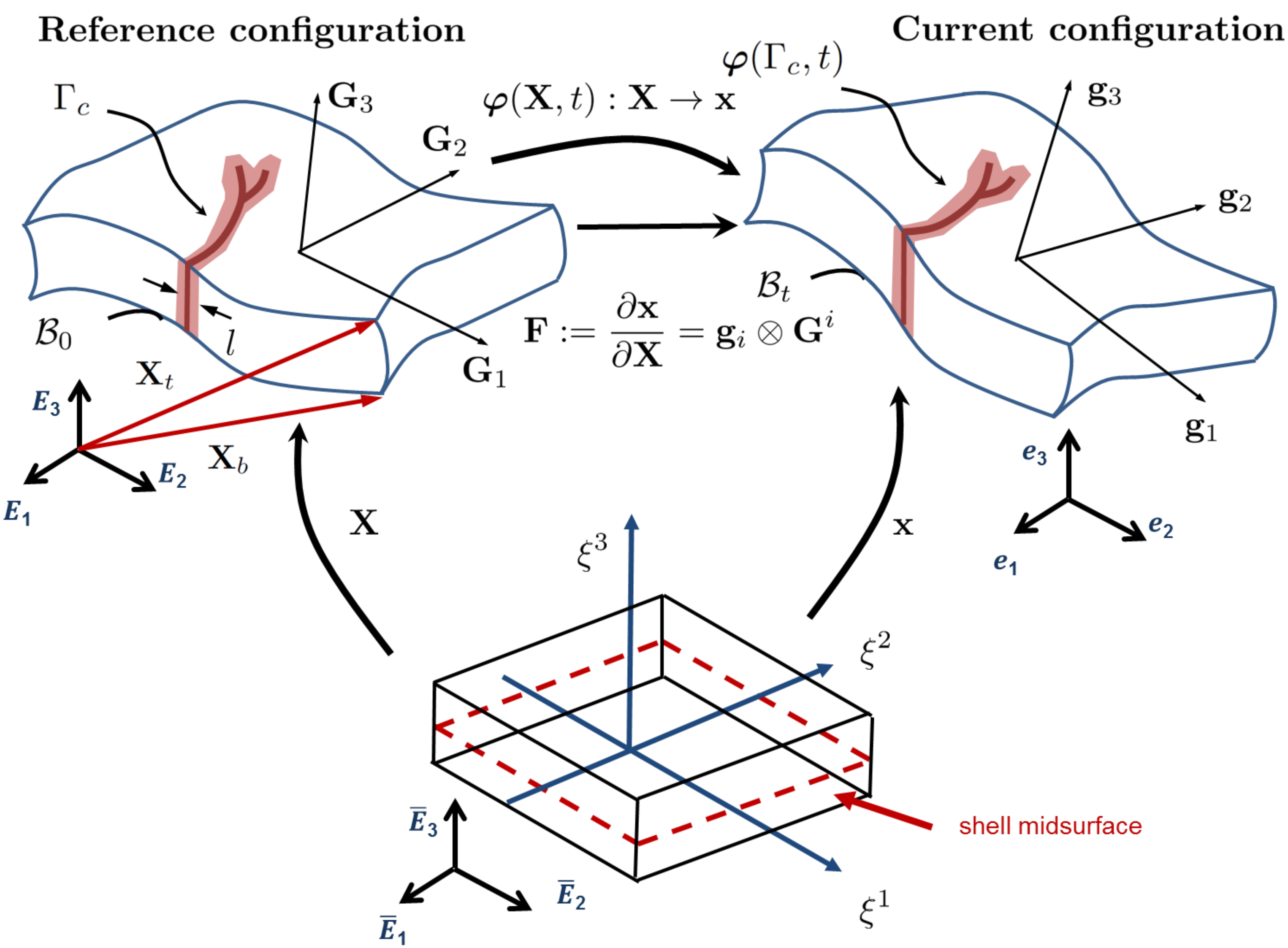
<u>Potential energy of the body</u>

$$\Pi(\mathbf{u}, \Gamma) = \int_\Omega \psi(\boldsymbol{\varepsilon}) \mathrm{d}\Omega + \int_{\Gamma_c} \mathcal{G}_c \mathrm{d}\partial\Omega$$

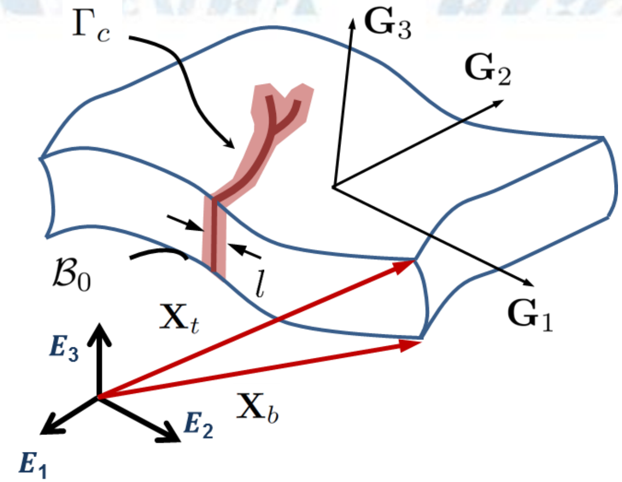
Elastic strain energy **Fracture energy → Griffith approach**

Miehe, C., Hofacker, M., Welschinger F. (2010) A phase field model for rate independent crack propagation: robust algorithmic implementation based on operator splits. Comput. Methods Appl. Mech. Engrg. 199(45-48):2765--2778.

Phase field modeling of fracture in shells



Phase field modeling of fracture in shells



Geometry interpolation

$$\mathbf{X}(\boldsymbol{\xi}) = \frac{1}{2}\left(1+\xi^3\right)\mathbf{X}_t(\xi^1,\xi^2) + \frac{1}{2}\left(1-\xi^3\right)\mathbf{X}_b(\xi^1,\xi^2)$$

Phase field interpolation

$$\mathfrak{d}(\xi^1,\xi^2,\xi^3) = \frac{1}{2}\left(1+\xi^3\right)\mathfrak{d}_t(\xi^1,\xi^2) + \frac{1}{2}\left(1-\xi^3\right)\mathfrak{d}_b(\xi^1,\xi^2)$$

Variational form including the EAS method to prevent locking

$$\Pi(\mathbf{S},\tilde{\mathbf{E}},\mathbf{u},\mathfrak{d}) = \int_{\mathcal{B}_0} \mathfrak{g}(\mathfrak{d})\Psi(\mathbf{E}^u,\tilde{\mathbf{E}})\,\mathrm{d}\Omega - \int_{\mathcal{B}_0} \mathbf{S}:\tilde{\mathbf{E}}\,\mathrm{d}\Omega + \int_{\mathcal{B}_0} \frac{\mathcal{G}_c l}{2}\left(\frac{\mathfrak{d}^2}{l^2} + |\nabla_{\mathbf{X}}\mathfrak{d}|^2\right)\mathrm{d}\Omega + \Pi_{\text{ext}}$$

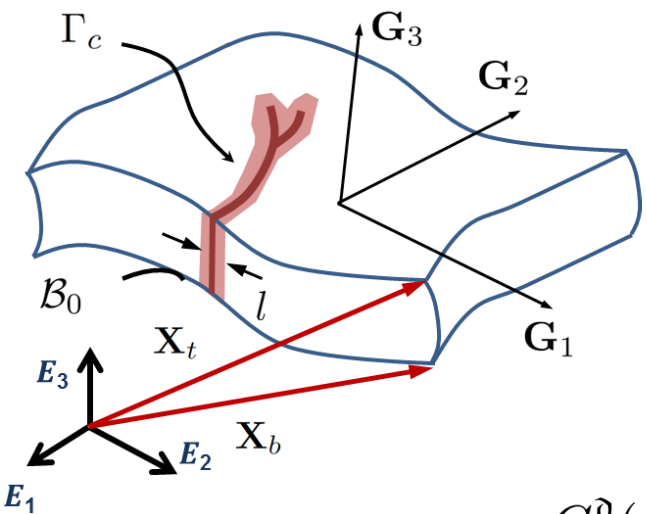
$$\overline{\Psi}(\mathbf{E}^u,\tilde{\mathbf{E}},\mathfrak{d}) = \mathfrak{g}(\mathfrak{d})\Psi(\mathbf{E}^u,\tilde{\mathbf{E}}), \quad \text{with} \quad \mathfrak{g}(\mathfrak{d}) = [1-\mathfrak{d}]^2 + \mathcal{K}$$

Phase-field stiffness degradation

Intact free energy accounting for incompatible strains

- **Poisson thickness locking**
  Unmodified 3D material laws
- **Volumetric locking**

Phase field modeling of fracture in shells



Construction of the residual equations

$$G^{\tilde{E}}(\mathbf{u}, \tilde{\mathbf{E}}, \delta\tilde{\mathbf{E}}, \mathfrak{d}) = \int_{\mathcal{B}_0} \mathfrak{g}(\mathfrak{d}) \left[\frac{\partial \Psi}{\partial \mathbf{E}} : \delta\tilde{\mathbf{E}} \right] \, \mathrm{d}\Omega = 0$$

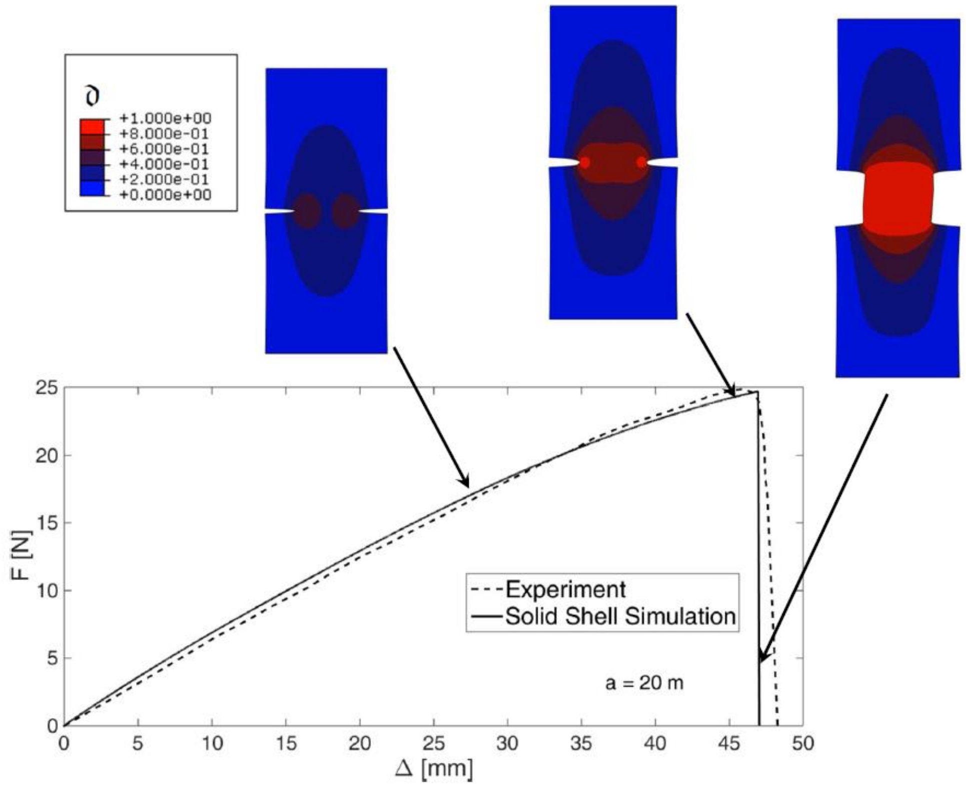
$$G^{\mathfrak{d}}(\mathbf{u}, \tilde{\mathbf{E}}, \mathfrak{d}, \delta\mathfrak{d}) = \int_{\mathcal{B}_0} -2(1-\mathfrak{d})\delta\mathfrak{d}\Psi(\mathbf{E}^u, \tilde{\mathbf{E}}) \, \mathrm{d}\Omega +$$

$$\int_{\mathcal{B}_0} \mathcal{G}_c l \left[\frac{1}{l^2}\mathfrak{d}\delta\mathfrak{d} + \nabla_{\mathbf{X}}\mathfrak{d} \cdot \nabla_{\mathbf{X}}(\delta\mathfrak{d}) \right] \, \mathrm{d}\Omega = 0$$

$$G^u(\mathbf{u}, \delta\mathbf{u}, \tilde{\mathbf{E}}, \mathfrak{d}) = G^u_{\text{int}} - G^u_{\text{ext}} = \int_{\mathcal{B}_0} \mathfrak{g}(\mathfrak{d}) \left[\frac{\partial \Psi}{\partial \mathbf{E}} : \frac{\partial \mathbf{E}^u}{\partial \mathbf{u}} \delta\mathbf{u} \right] \, \mathrm{d}\Omega + \delta\Pi_{\text{ext}}(\mathbf{u}) = 0$$

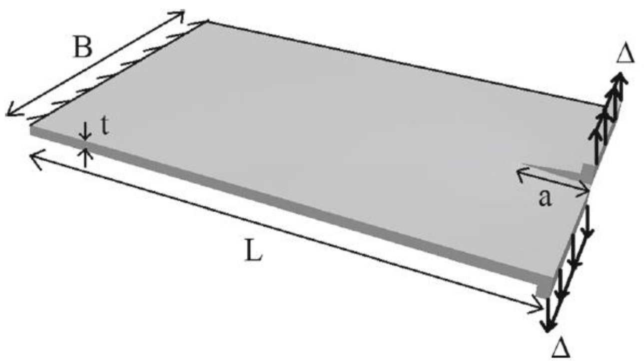
Phase field modeling of fracture in shells

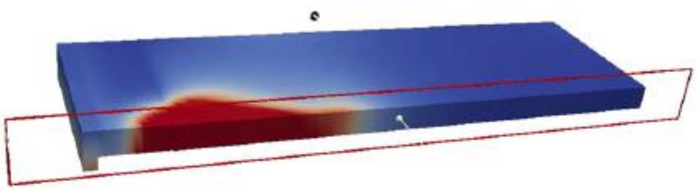
- Monolithic and full implicit formulation
- Phase field interpolation through the shell thickness
- ANS + EAS technologies (for Poisson thickness and volumetric locking pathologies)
- Linear elastic and nonlinear elastic constitutive relations
- FEAP & Abaqus implementation

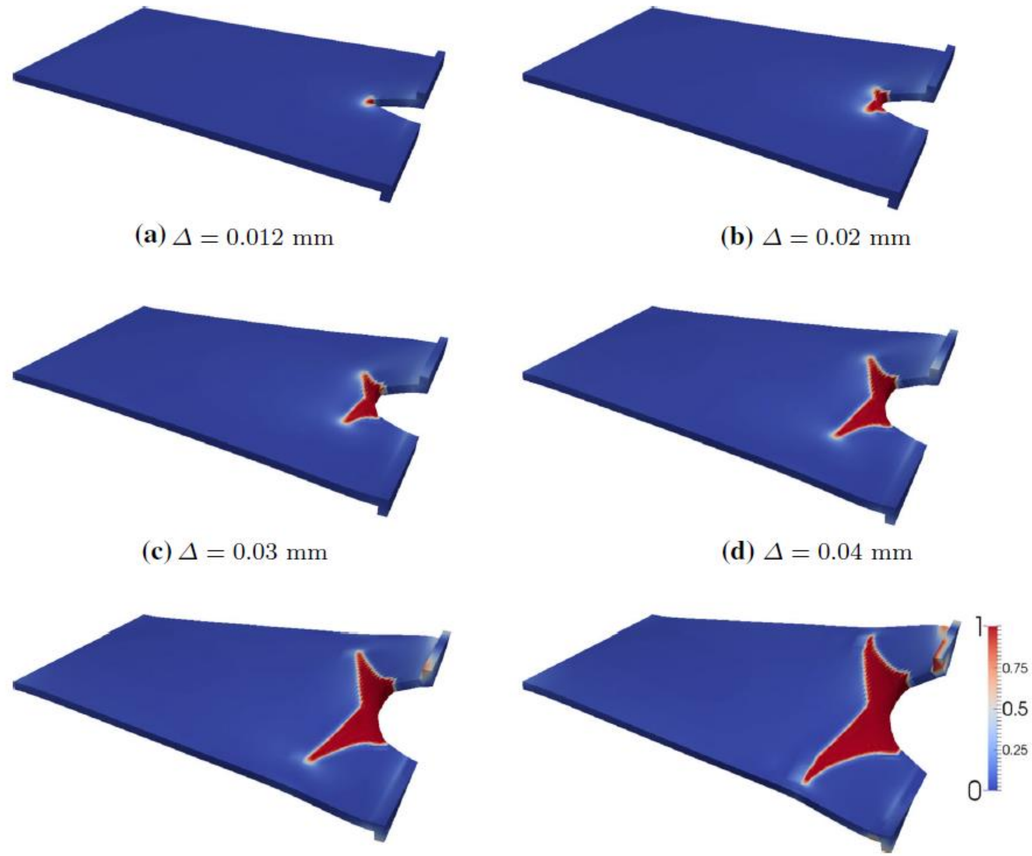


J. Reinoso, M. Paggi, C. Linder (2017) Phase field modeling of brittle fracture for enhanced assumed strain shells at large deformations: formulation and finite element implementation, **Computational Mechanics**, DOI 10.1007/s00466-017-1386-3

Phase field modeling of fracture in shells







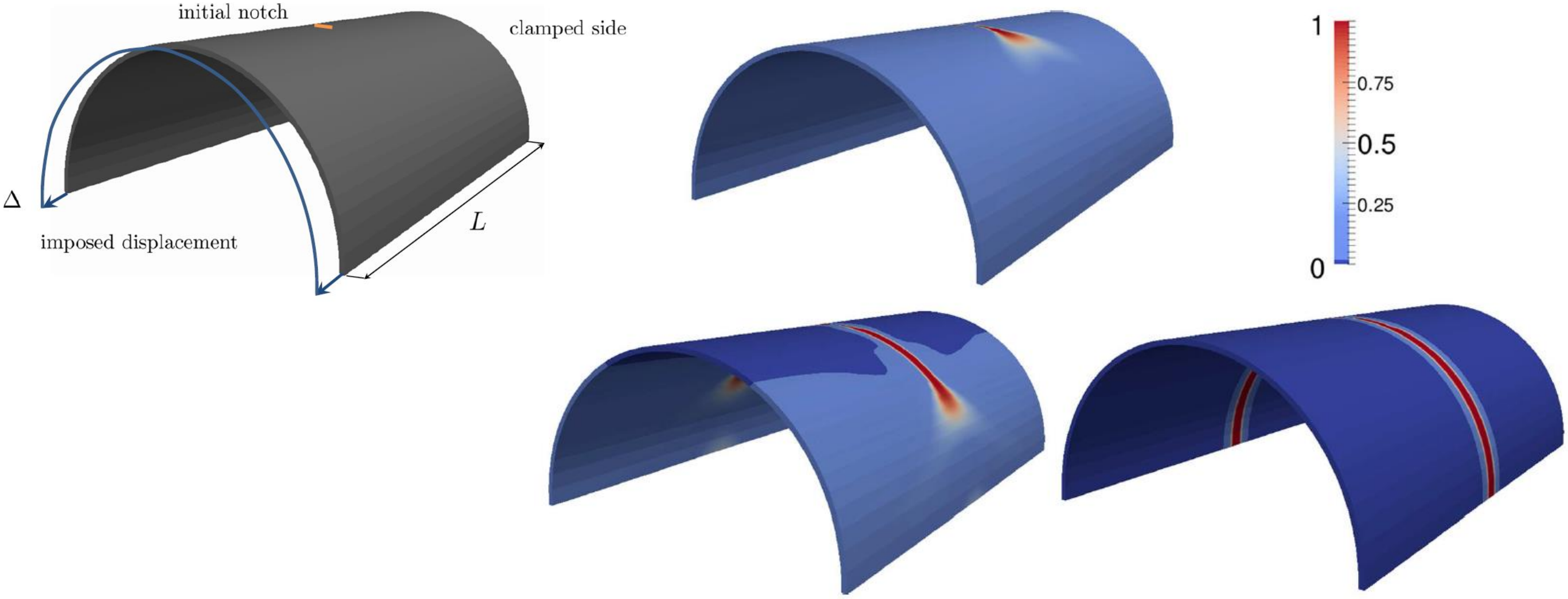
(a) $\Delta = 0.012$ mm (b) $\Delta = 0.02$ mm

(c) $\Delta = 0.03$ mm (d) $\Delta = 0.04$ mm

(e) $\Delta = 0.05$ mm (f) $\Delta = 0.064$ mm

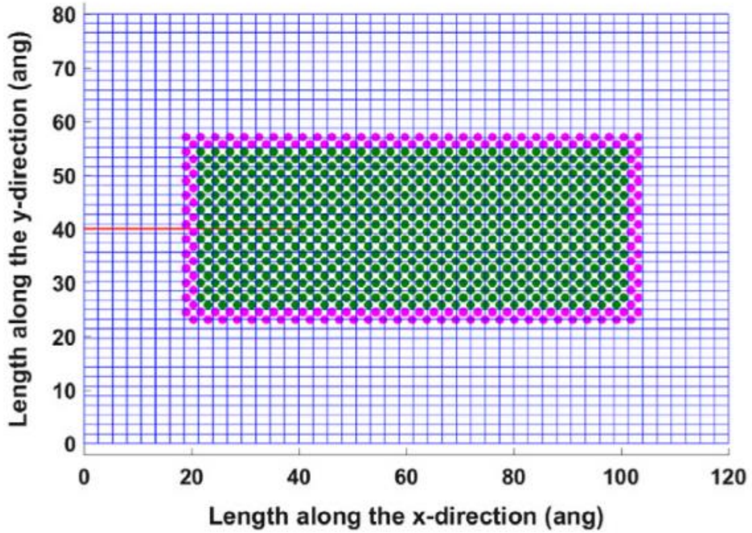
J. Reinoso, M. Paggi, C. Linder (2017) Phase field modeling of brittle fracture for enhanced assumed strain shells at large deformations: formulation and finite element implementation, **Computational Mechanics**, DOI 10.1007/s00466-017-1386-3

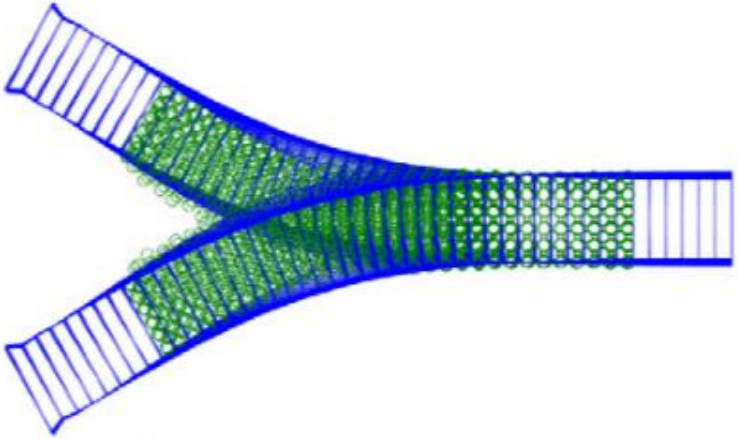
Phase field modeling of fracture in shells

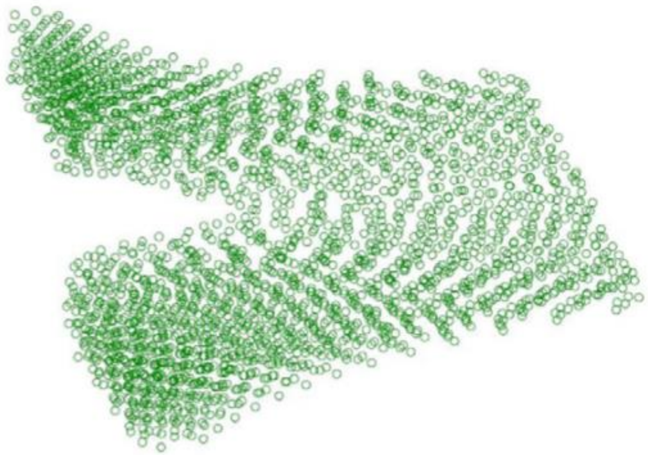


J. Reinoso, M. Paggi, C. Linder (2017) Phase field modeling of brittle fracture for enhanced assumed strain shells at large deformations: formulation and finite element implementation, **Computational Mechanics**, DOI 10.1007/s00466-017-1386-3

Concurrent coupling of solid shells and molecular dynamics via phantom nodes





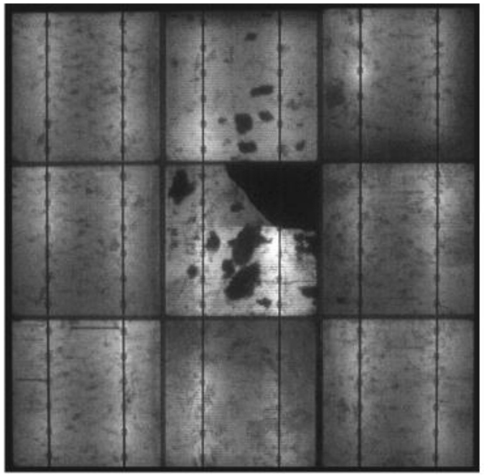


- Coarse scale model using solid shells
- Crack growth using phantom node method
- Fine scale model based on MD for crack branching and propagation

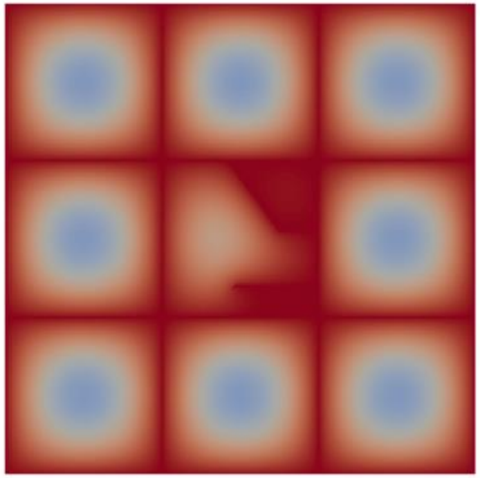
P.R. Budarapu, J. Reinoso, M. Paggi (2017) Concurrently coupled solid shell-based adaptive multiscale method for fracture, **Comput. Methods Appl. Mech. Engrg.** 319:338-365.

Environmental vs. accelerated ageing

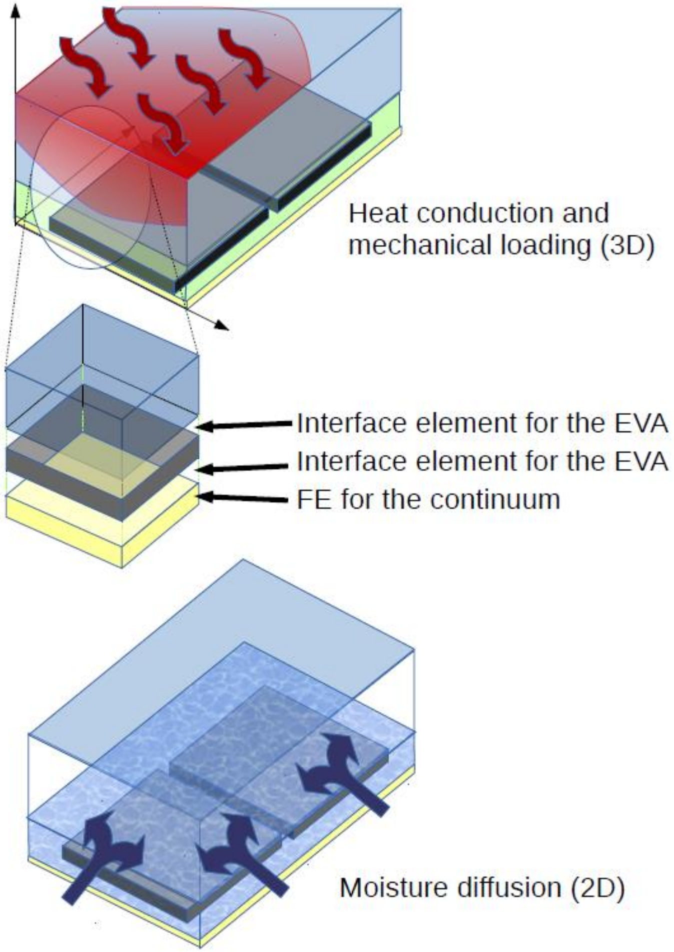
Moisture diffusion and chemical reactions take place inside the EVA layers



EL image



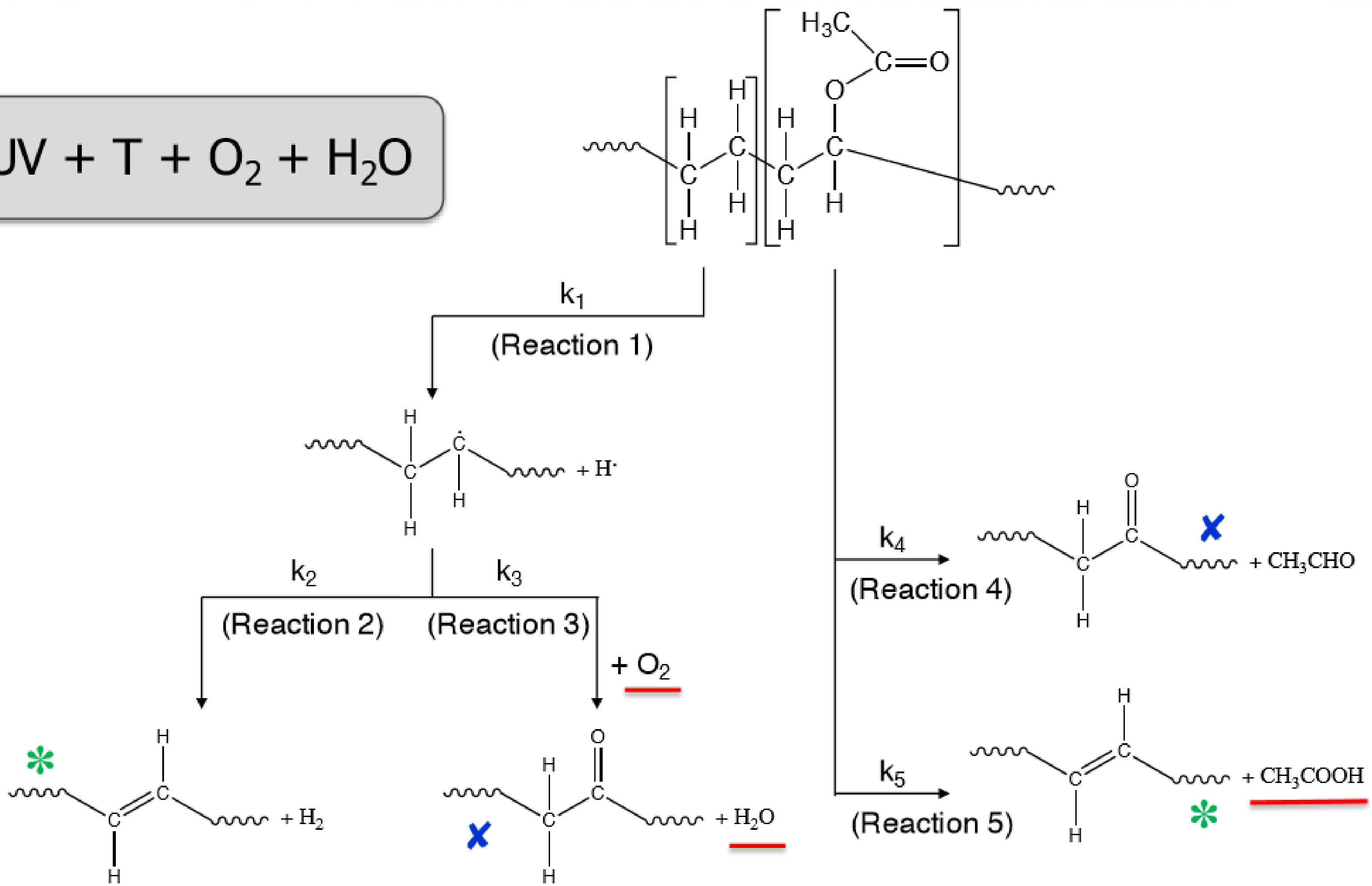
Predicted moisture concentration



P. Lenarda, M. Paggi (2016) A geometrical multi-scale numerical method for coupled hygro-thermo-mechanical problems in photovoltaic laminates. **Computational Mechanics**, 57:947-963.

Environmental vs. accelerated ageing

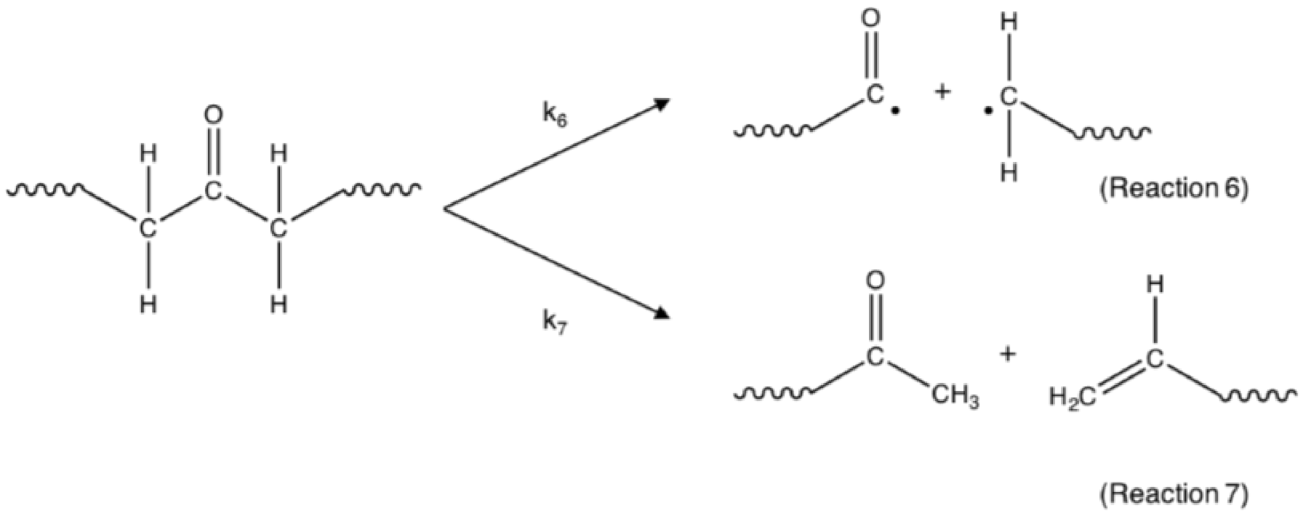
$UV + T + O_2 + H_2O$



Primary reactions: deprotonation, oxidation, deacetylation

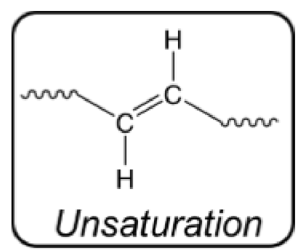
Environmental vs. accelerated ageing

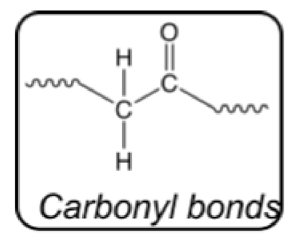
Secondary following reactions: polymer chain cleavage



Degradation products:

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





Environmental vs. accelerated ageing

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 ageing)

Reaction kinetics ODEs

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

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

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

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

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

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

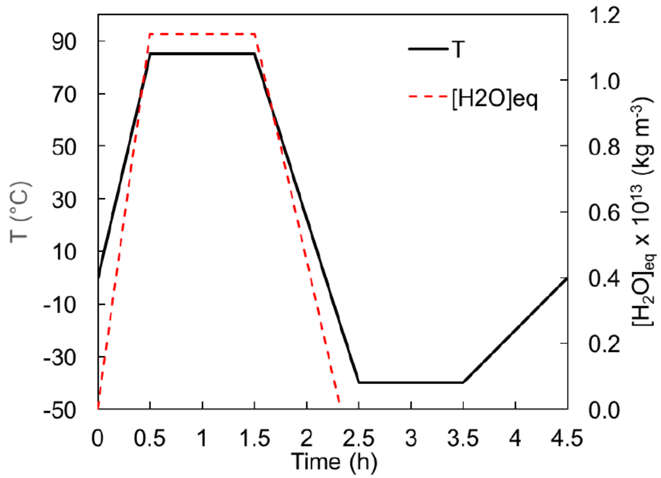
$$\frac{\mathrm{d}[\mathrm{R_t}^\bullet]}{\mathrm{d}t} = k_6[\mathrm{C_b}]$$

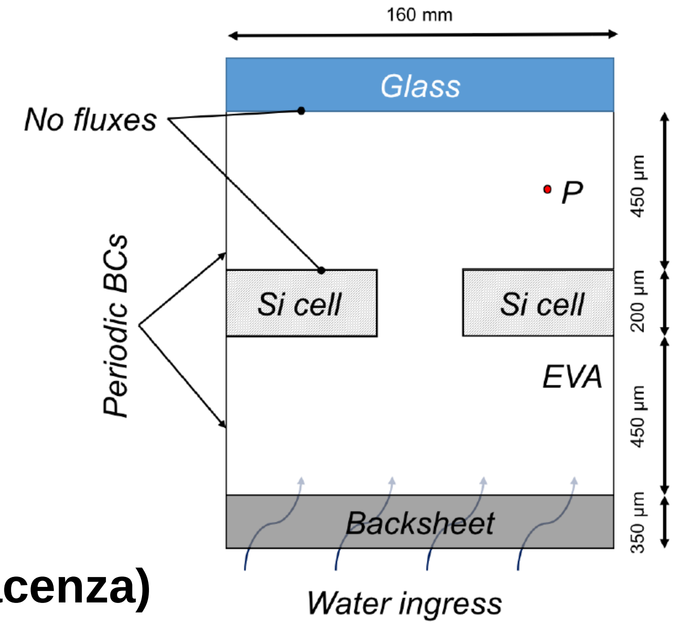
$$\frac{\mathrm{d}[\mathrm{C_bt}]}{\mathrm{d}t} = k_7[\mathrm{C_b}]$$

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

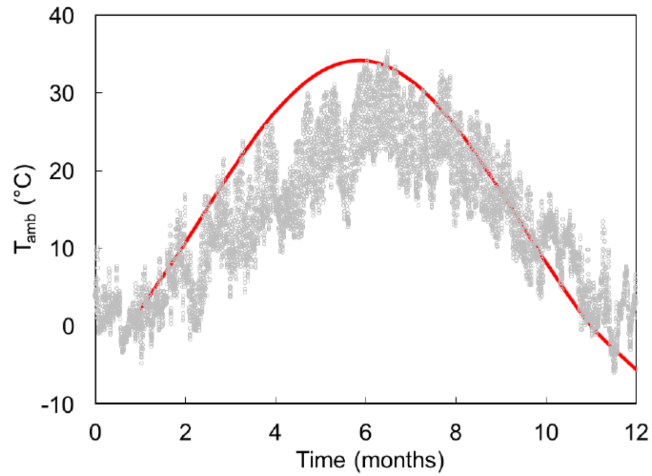
Environmental vs. accelerated ageing

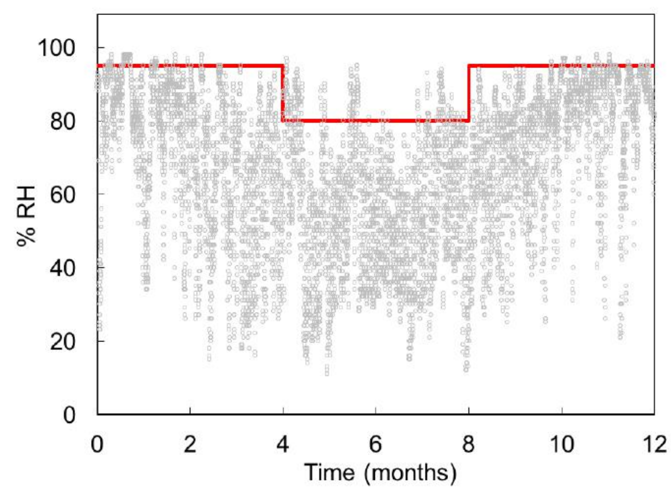
Accelerated ageing (damp-heat test)





Environmental degradation (climatic data from Piacenza)





Integration algorithm:

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

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

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 $= 1$

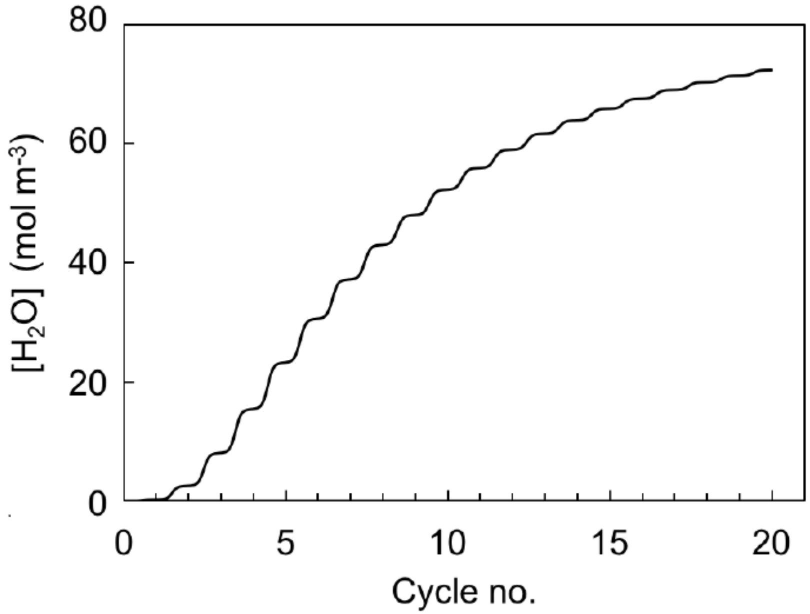
Given $\{C\}^n,\ T^n$

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

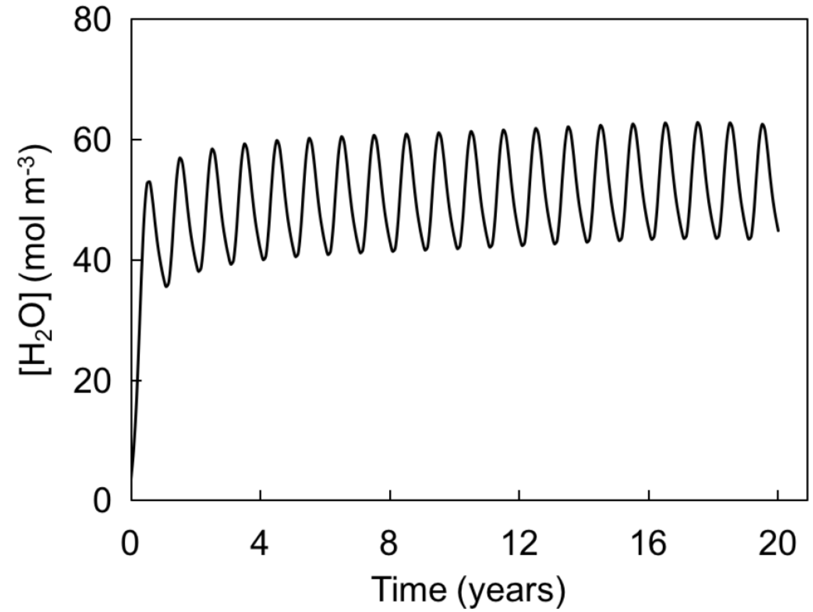
- **Compute** $k_i(T^n),\ Q_T(T^n);$
- **Solve the thermal problem:**
  $\rho c \partial_t T^{n+1} - \kappa \nabla^2 T^{n+1} = Q_T;$
- **Update temperature:** $T^{n+1} \leftarrow T^n;$
- **Update kinetic constants and diffusion coefficients:**
  $k_i(T^{n+1}),\ D_j(T^{n+1});$
- **while** (norm $\geq$ 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 ageing



Accelerated ageing



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.

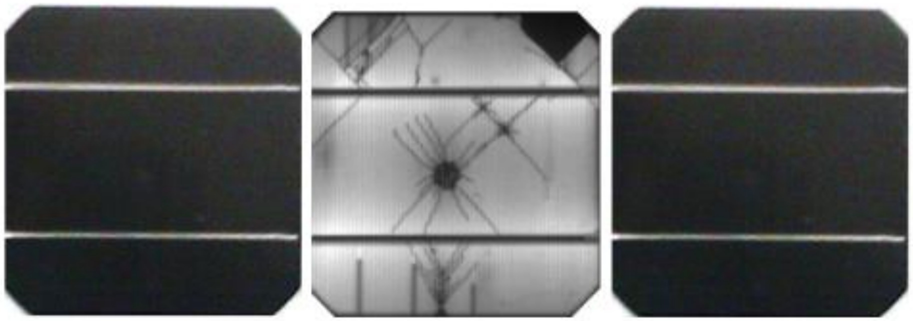
Conclusions

- **Material-related failure modes of PV modules require structural mechanics models**

- **A multi-field finite element-based computational framework has been proposed to effectively predict:**
  - ➢ **Silicon fracture, using cohesive zone model, phase field model, or phantom node method coupled with MD**
  - ➢ **Electrical power losses due to cracks**
  - ➢ **Chemical reactions and diffusion in the encapsulant**
  - ➢ **Ageing effects due to environmental loading or in accelerated degradation tests**

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