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

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

Displacement x(mm)
Digital image correlation
Contact mechanics
Introduction and motivations
PV modules
Durability: state-of-the-art

Electroluminescence image of cracking

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

Weinreich et al., 2011
Experimental investigation
Paggi, Berardone, Infuso, Corrado (2014)
• Some electrically inactive areas conduct again after unloading (crack closure & contact)

• The amount of electrically inactive areas increases after the loading cycle (fatigue effects)
- Crack propagation cycle after cycle
- Crack branching
- Strain localization near newly propagated cracks
Computational modelling
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

Displacement BCs, thermal field

Updated stiffness, thermal properties, inactive cell 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
No contact

Stress-free crack

Partial contact

Partial decohesion

Full contact

Perfect bonding

\[ p = p_C \]

\[ p = -\sigma \]

\[ p = 0 \]

\[ g_n = 0 \]

\[ g_n = g_{nc} \]
\[
\sigma = \begin{cases} 
\sigma_{\text{max}} \exp \left( \frac{-l_0 - |g_t|}{R} \right) \frac{g_n}{l_0}, & \text{if } 0 \leq \frac{g_n}{R} < \frac{l_0}{R} \\
\sigma_{\text{max}} \exp \left( \frac{-g_n - |g_t|}{R} \right), & \text{if } \frac{l_0}{R} \leq \frac{g_n}{R} < \frac{g_{nc}}{R} \\
0, & \text{if } \frac{g_n}{R} \geq \frac{g_{nc}}{R}
\end{cases}
\]

Exponential decay inspired by micromechanical contact models:

Thermal conductance proportional to the normal stiffness:

\[ k_{\text{int}} = \begin{cases} 
  \frac{1}{\rho_{\text{int}}}, & \text{if } 0 \leq \frac{g_n}{R} < \frac{l_0}{R} \\
  \frac{2\sigma}{\rho_{\text{int}}E_{\text{int}}R}, & \text{if } \frac{l_0}{R} \leq \frac{g_n}{R} < \frac{g_{nc}}{R} \\
  0, & \text{if } \frac{g_n}{R} \geq \frac{g_{nc}}{R}
\end{cases} \]

\[ Q = -k_{\text{int}}(g_n) \Delta T \]

Paggi and Barber (2011) Int. J. Heat Mass Transfer
Strong form: $\nabla^T \mathbf{S} + \mathbf{f} = 0$

Weak form:

$$\int_{V} \mathbf{S} : \nabla(\delta \mathbf{w}) dV = \int_{V} \mathbf{f}^T (\delta \mathbf{w}) dV + \int_{S} \overline{\mathbf{\sigma}}^T (\delta \mathbf{w}) dS + \int_{S_{\text{int}}} \mathbf{\sigma}^T (\delta \mathbf{w}) dS$$

$V$: volume
$S$: surface
$\mathbf{S}$: Cauchy stress tensor
$\mathbf{f}$: body force vector
$\mathbf{w}$: displacement vector
\[ -\nabla^T q + Q = \rho c \dot{T} \]

Strong form:

Weak form (energy balance):

\[ \int_V q^T \nabla (\delta T) \, dV = \int_V (\rho c \dot{T} - Q) \delta T \, dV + \int_S \bar{q}^T (\delta w) \, dS + \int_{S_{int}} q(\delta T) \, dS \]
Gap vector: 
\[ \mathbf{g} = (g_t, g_n, g_T)^T \]

Traction and flux vector: 
\[ \mathbf{p} = (\tau, \sigma, q)^T \]

Weak form for the interface elements: 
\[ \delta G_{\text{int}} = \int_{S_{\text{int}}} \delta \mathbf{g}^T \mathbf{p} \, dS \]

Consistent linearization of the interface constitutive law (implicit scheme):
\[ \mathbf{p} = C \mathbf{g} \quad \rightarrow \quad \delta G_{\text{int}} = \int_{S_{\text{int}}} \delta \mathbf{g}^T C \mathbf{g} \, dS \]
If $k_{int}=const$ (Kapitza model):

$$\frac{\partial q}{\partial g_t} = \frac{\partial q}{\partial g_n} = 0$$

Tangent stiffness matrix of the interface element:

$$K = R^T \int_{S_{int}} B^T C B dS_R$$
Stress-free temperature coincident with the lamination temperature ($T_0=150^\circ C$)
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:

\[ V(x_0) = V_0; \quad V'(x_0) = 0 \]
Example (1)

(a) Unloaded condition. 
\( x_0 = 3.33 \text{ cm}, \ V_0 = 0.579 \text{ V}, \ R_{ct} = 0.096 \text{ \(\Omega\) cm}^2 \)

(b) Loaded condition. 
\( x_0 = 3.03 \text{ cm}, \ V_0 = 0.580 \text{ V}, \ R_{ct} = 0.22 \text{ \(\Omega\) cm}^2 \)
(a) Unloaded condition.
\[ x_0 = 3.73 \text{ cm}, \ V_0 = 0.572 \text{ V}, \ R_{c1} = R_{c2} = 0.0 \Omega \text{ cm}^2 \]

(b) Loaded condition.
\[ x_0 = 3.72 \text{ cm}, \ V_0 = 0.572 \text{ V}, \ R_{c1} = 1.13 \Omega \text{ cm}^2, \ R_{c2} = 0.48 \Omega \text{ cm}^2 \]
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

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FIRB Future in Research 2010

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