Numerical modelling of microcracking in PV modules induced by thermo-mechanical loads

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• A multi-physics and multi-scale computational approach
• Micro-cracking in polycrystalline Silicon cells
• A thermo-mechanical nonlinear fracture mechanics model
A multi-physics approach

- **Thermo-elastic field**: coupling due to thermoelasticity
- **Thermo-electric field**: coupling in the Schrödinger equation
- **Electro-elastic field**: coupling due to microcracks
A multi-scale solution strategy

Macro-model: Multi-layered plate (homogeneous cells)

Micro-model: Polycrystalline Si cells with grain boundaries

Paggi et al., Comp. Struct., 2013
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
- Update cell stiffness

Displacement BCs, thermal field

Updated stiffness, thermal properties, inactive cell area
Electrically inactive cell areas: numerical results

Paggi et al., 2013

Open issues:
- Limit case scenario of perfectly insulated cracks
- Model parameter identification
Effect of cracking on the thermal field

- High temperature near cracks (additional thermal resistance)
- Cracks are source of recombination effects
Interaction between thermal and elastic fields

Weinreich et al., 2011
A thermo-mechanical cohesive zone model

\[ \sigma = \sigma(g_n) \]

\[ G_{IC} \]

\[ \sigma_{max} \]

\[ g_{nc}, g_n \]
A thermo-mechanical cohesive zone model

\[ \sigma = \sigma(g_n) \]

\[ G_{IC} = -k_{int}(g_n) \Delta T \]

Kapitza model
Analogy between fracture and contact mechanics

Hypotheses:
- Estimate cohesive tractions from a micromechanical contact model (Greenwood & Williamson, 1966)
- Interface conductance proportional to the normal stiffness (Paggi & Barber, 2011)
A thermo-mechanical cohesive zone model

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

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

Model parameters: \( l_0, \text{rms}, \sigma_{\text{max}} + (\rho_{\text{int}}, E_{\text{int}}) \)
Weak form of the problem and solution scheme

\[
\int_{V} \sigma^{T} (\nabla \delta u) dV = \int_{V} f^{T} (\delta u) dV + \int_{\partial V} \bar{\sigma}^{T} (\delta u) dS + \int_{S} t^{T} (\delta g) dS
\]

\[
\int_{V} q^{T} (\nabla \delta T) dV = \int_{V} \rho_{V} c_{V} \dot{T} \delta T dV + \int_{\partial V} \bar{q} \delta T dS + \int_{S} q \delta g_{T} dS
\]

Staggered solution scheme:

(1) **SOLVE** the thermal problem (freezing the elastic one)

(2) **SOLVE** the thermo-elastic problem, determine crack opening and update the crack conductance

(3) **ITERATE** (1) and (2) until convergence
Numerical example

\begin{align*}
T &= 70^\circ C \\
T &= 40^\circ C
\end{align*}

\begin{align*}
\delta \\
x
\end{align*}
Conclusions and future developments

- A thermo-mechanical cohesive zone model for polycrystalline Silicon has been proposed.

- Due to the analogy with contact mechanics, only 3 model parameters need to be identified by experiments.

- Future developments will concern the coupling with the electric field and the experimental validation of the multiphysics computational approach.
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Multi-field and multi-scale Computational Approach to Design and Durability of PhotoVoltaic Modules

FIRB Future in Research 2010

Structural mechanics models for renewable energy applications

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