Recent progresses on modelling of cracking in Polycrystalline Silicon for Photovoltaic Applications

Andrea Infuso, Mauro Corrado, Marco Paggi

Department of Structural, Geotechnical and Building Engineering
Politecnico di Torino, Italy

andrea.infuso@polito.it
Composite geometry

- A multi-scale and multi-physics computational approach to fracture
- Micro-cracking in polycrystalline Silicon cells

Paggi, Kajari-Schröder, Eitner, 2011
Electroluminescence image of microcracking

M. Köntges, I. Kunze, S. Kajari-Schröder, X. Breitenmoser, B. Bjørneklelett
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
A multiscale-multiphysics FE model

Macro-model of PV panel:
- Multi-layered plate
- Compute displacements
- Compute power-loss

Micro-model of Si cell:
- Heterogeneous with interfaces
- Micro-cracks
- Compute inactive area
- Update cell stiffness

Updated stiffness, thermal properties, inactive cell area

Displacement BCs, thermal field
Macro-model computations

\[
\left( \int_{\Omega} (\nabla N)^T D \nabla N \, d\Omega \right) \eta = \int_{\Omega} N^T q \, d\Omega
\]

where: \( w = N\eta \), \( \theta = N_\theta \eta \)

where \( \eta = [w_1, \theta_{x1}, \theta_{y1}, \ldots, w_4, \theta_{x4}, \theta_{y4}]^T \) and:

\[
N = [N_1, 0, 0, \ldots, N_4, 0, 0]
\]

\[
N_\theta = \begin{bmatrix}
0 & N_1 & 0 & \cdots & 0 & N_4 & 0 \\
0 & 0 & N_1 & \cdots & 0 & 0 & N_4
\end{bmatrix}
\]

\[
D = K \begin{bmatrix}
1 & \nu & 0 \\
\nu & 1 & 0 \\
0 & 0 & \frac{1-\nu}{2}
\end{bmatrix}
\]

In-plane displacements:

\[
u = -\theta_x z
\]

\[
u = \theta_y z
\]
Micro-model computations using NLFM

\[
\int_V (\nabla \delta u)^T \sigma \, dV - \int_S \delta g^T t \, dS = \int_{\partial V} \delta u^T f \, dS
\]

CZM contribution

\[
\Delta \delta W_{\text{int}} = \delta u^T R^T \int_S B^T C B R u \, dS
\]

Linearization for the Newton-Raphson algorithm (FEAP)

A thermo-mechanical cohesive zone model

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

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

Interaction between thermal and elastic fields

- High temperature near cracks (additional thermal resistance)
- Cracks are source of recombination effects

Weinreich et al., 2011
Damage variable and electrically inactive cell area

\[ I = I_{\text{ph}} - I_s e^{\frac{q(V + IR_s)}{AKT}} - 1 \left( \frac{V + IR_s}{R_p} \right) \]

\[ I_s(D) = I_s^{D=0} (1 - D) \]

\[ I_{\text{ph}} = I_{\text{ph}}^{D=0} (1 - D) \]

\[ D = \frac{A_{\text{inactive}}}{A} \]

Simply supported plate subjected to a uniform (snow) pressure of 5400 Pa
Micro-crack pattern in Silicon cells
Distribution of crack orientation angles

(C5) Central (C9) Bottom Right corner (7) Bottom Left corner (9) Bottom Right corner
Electrically inactive cell areas: numerical results
**Electrically inactive cell areas: electric damage $D$**

<table>
<thead>
<tr>
<th>Section</th>
<th>D Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32%</td>
</tr>
<tr>
<td>2</td>
<td>11%</td>
</tr>
<tr>
<td>3</td>
<td>12%</td>
</tr>
<tr>
<td>4</td>
<td>4%</td>
</tr>
<tr>
<td>5</td>
<td>5%</td>
</tr>
<tr>
<td>6</td>
<td>79%</td>
</tr>
<tr>
<td>7</td>
<td>12%</td>
</tr>
<tr>
<td>8</td>
<td>30%</td>
</tr>
<tr>
<td>9</td>
<td>0%</td>
</tr>
</tbody>
</table>
Effect of microcracking (worst case scenario)

Electric efficiency of the intact module (fill factor): 65%
Electric efficiency of the microcracked module: 15%
Conclusions

- The effect of microcracking on the electric performance can only be quantified according to a multi-physics approach.
- A multiscale solution strategy is effective to reduce the computational cost in case of large panels and to simplify the 3D problem.
- 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.
Partially conductive microcracks (so far, microcracks have been considered as electrically insulated)

Coupling with the electric and the thermal field to predict the degradation rate of PV panels exposed to environmental conditions

Modelling of transgranular cracking

Parameter identification and model validation with experiments
Acknowledgements

ERC Starting Grant IDEAS 2012

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

Photovoltaics (POLITO)  MEMS for wind energy harvesting (UNISAL)  Solid oxide fuel cells (UNITN)