TOPIC 5: Operations, Performance and Reliability of Photovoltaics (from Cells to Systems)

Sub-Topic 5.3: PV Modules

Numerical model for the prediction of the electric response of Solar Cells in presence of cracks

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Abstract

The durability of photovoltaic (PV) modules is under debate by the scientific Community [1-3] and international organizations [4]. The reduction of the feed-in tariffs gives prominence to the understanding of the sources of losses in the energy production and to the quantification of the degradation of PV systems. The problem of durability is expected to be even more relevant in the next few years due to the rapid progress of building-integrated photovoltaics with the use of not standardized modules. In these cases, in addition to energy production, PV modules have also to guarantee a safe structural performance and other architectonic specifics like shadowing. All of these aspects will have to be taken into account when designing their layer composition.

At present we are still far from having a simulation tool able to quantify the impact of cracks on the electric response and on the durability of PV modules. Under the assumption of a worst case scenario, cracks have been treated in [1] as defects interrupting fingers and leading to insulated portions of the Silicon cell. Using an electric model accounting for the active cell area, an estimate of maximum power-losses has also been made in [1]. The position and the orientation of cracks with respect to busbars were discovered to be among the most relevant quantities, since they impact on the electric performance in different ways in relation to the size of the portion of the solar cell that becomes insulated. Alternatively to the direct experimental approach, a method to estimate the probability of cracking has been proposed in [5] based on Weibull statistics of Silicon and on the stress level in solar cells predicted by a linear elastic stress analysis.

From the computational point of view, since cracks depend significantly on the type of solar cell technology (mc or pc-Silicon), on their position with respect to the busbars, and also on the direction of principal stresses induced by loading, a multi-physics and multi-scale finite element (FE) approach with non linear fracture mechanics has firstly been proposed in [6] and further extended in [7] to deal with thermo-mechanical loading.

In the present work we propose an advancement with respect to [6] in terms of computational modeling. First, we propose a more general global/local finite element approach which provides a more accurate prediction of relative opening displacements between crack faces inserted in solar cells. Second, the simple one-diode electric model with parameters dependent on the potentially electrically inactive area used in [6] is replaced here by a more accurate electric model for solar cells with cracks [8] able to take into account partial electric insulation depending on the applied loading, which is the situation observed in experiments [9].

To make an insight into the mechanisms leading to coupling between the electric and the mechanical fields and have an experimental case study for model validation, a bending test on a flexible (PET-covered) PV module with cracks has been performed by the present authors. Solar cells are made of mc-

Silicon and the module is made of 2 rows of 5 cells each (see [9] for more details). The electric insulation induced by cracks in solar cells provoked by hail impacts has been monitored by the electroluminescence technique.

Methodology and results: the global/local finite element model and comparison with experiments

The displacement and stress fields inside the PV module in bending have been simulated by a global (coarse scale) plane stress finite element model of its cross-section, see Fig. 1. A mid-span displacement is imposed as in Fig. 1 to induce a tensile stress state in the solar cells. The computed displacements at the boundary of the solar cell located from point A to B in Fig. 1(a) are passed as input to the local model of the solar cell, where three dimensional finite elements are used to discretize the continuum and interface elements with a cohesive zone model are employed to simulate cracks as in [6].

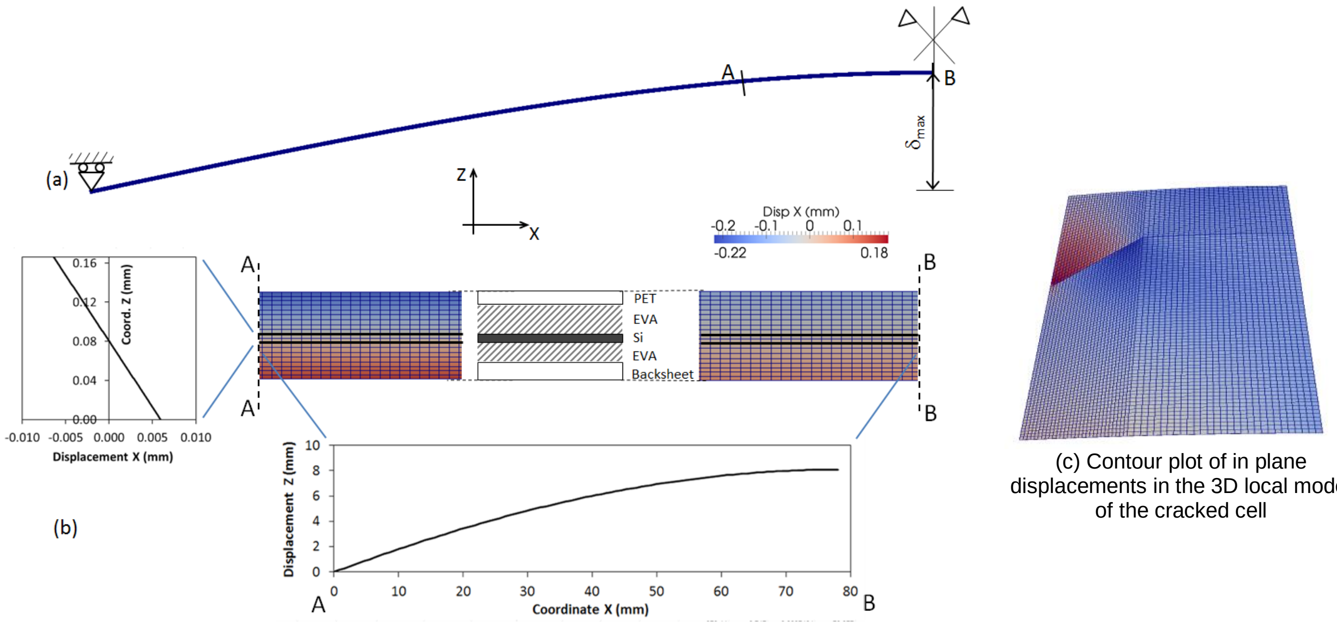


FIG. 1. (a) The global FE model of the PV module tested in bending; (b) displacements passed to the local model of the solar cell located between points A and B; (c) contour plot of the in plane displacements predicted by the local model. Note the jump of displacements in correspondence to the discontinuity represented by the crack faces.

Different mid-span displacements (6, 9, 12, 15 cm) have been imposed. For each deformation level the relative opening displacement is computed along the crack, considering the cohesive traction-separation relation as in Fig. 2 (a). To match the experimental values of the vertical current I_v deduced from EL data, a relation between the localized electric resistance at the crack and the crack opening displacement is established (see Fig. 2 (b)).

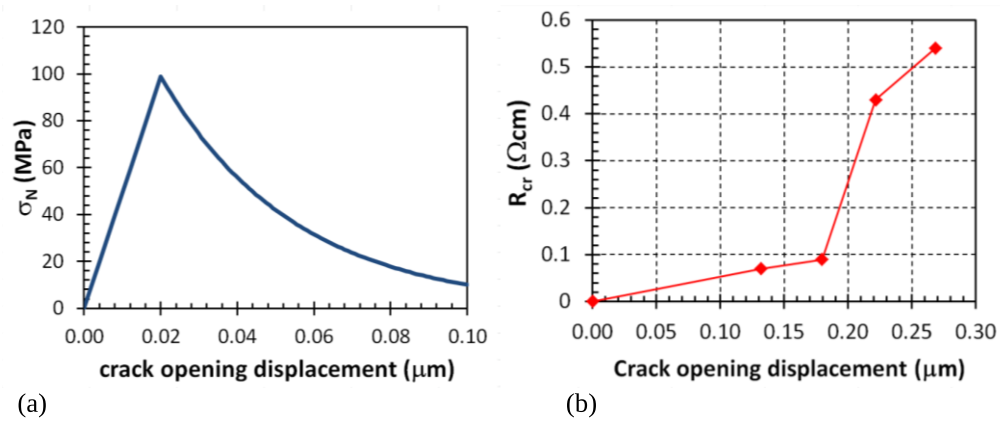
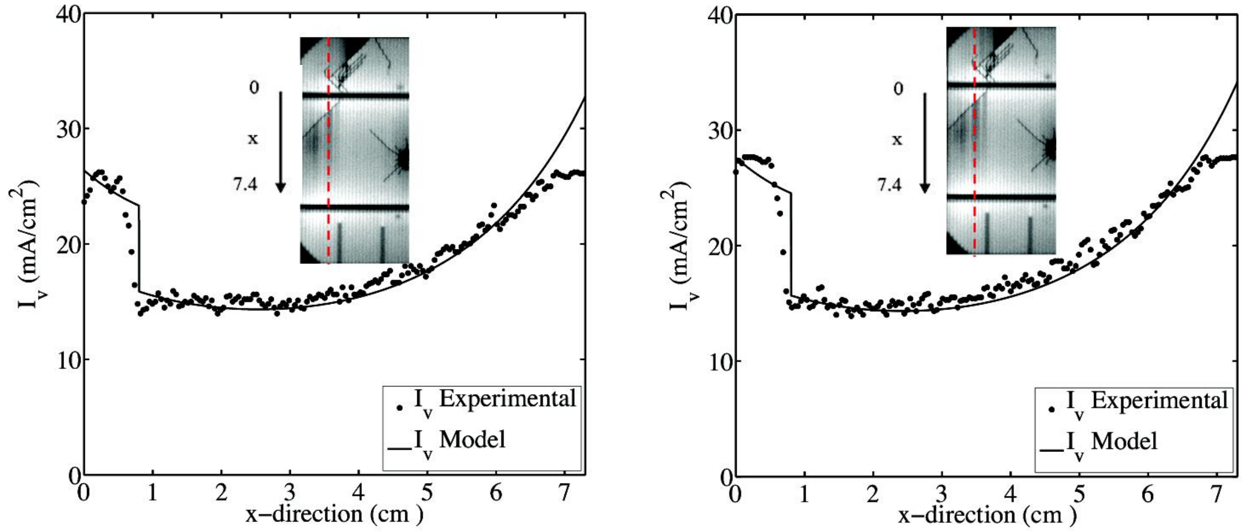


FIG. 2. (a) Cohesive traction-separation law. (b) Localized crack resistance vs. crack opening.

Comparison between experimental results and model predictions for a generic cross-section in red along a finger and intercepting a crack is shown in Fig. 3. The parameters for the electric model are: R_{loc}=0.2 Ωcm^2, V_T=25 mV, ρ_s=0.13Ω, I_{01}=1.48x10^{-12} mA/cm^2 and x_{cr}=0.8 cm. The values of R_{cr}, V_0 and the position x_0 are reported in the caption of Fig. 3.



(a) R_{cr}=0.43Ωcm, x_0=2.54 cm and V_0 =0.578 V (b) R_{cr}=0.54 Ωcm, x_0=2.43 cm and V_0 =0.578 V

FIG. 3. Vertical current in a monocrystalline Si cell along a finger crossed by a crack for imposed bending displacementsof 12 and 15 cm, respectively.

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References

[1] Köntges M, Kunze I, Kajari-Schröder S, Breitenmoser X, Bjrneklett B. The risk of power loss in crystalline silicon based photovoltaic modules due to microcracks (2011) Solar Energy Materials and Solar Cells; 95:1131-7.

[2] Kajari-Schröder S, Kunze I, Eitner U, Köntges M (2011) Spatial and orientational distribution of cracks in crystalline photovoltaic modules generated by mechanical load tests. Solar Energy Materials and Solar Cell ;95:3054-9.

[3] Kajari-Schröder S, Kunze I, Köntges M (2012) Criticality of cracks in PV modules. Energy Procedia;27:658-663.

[4] IEA PVPS Task 13, Performance and reliability of photovoltaic systems. Subtask 3.2: review of failures of photovoltaicmodules. ISBN 978-3-906042-16-9.

[5] Sander M, Dietrich S, Pander M, Ebert M, Bagdahn J (2013) Systematic investigation of cracks in encapsulated solar cells after mechanical loading. Solar Energy Materials and Solar Cells;111:82-89

[6] Paggi M, Corrado M, Rodriguez MA (2013) A multi-physics and multi-scale numerical approach to microcracking and power-loss in photovoltaic modules. Composite Structure, 95:630.638.

[7] Sapora A, Paggi M (2013) A coupled cohesive zone model for transient analysis of thermoelastic interface debonding. Computational Mechanics; 53:845-857.

[8] 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.

[9] Paggi M, Berardone I, Infuso A, Corrado M (2014) Fatigue degradation and electric recovery in Silicon solar cells embedded in photovoltaic modules. Scientific Reports 4:4506; DOI:10.1038/srep04506.