SPATIAL AND DIRECTIONAL DISTRIBUTION OF CRACKS IN SILICON PV MODULES AFTER UNIFORM MECHANICAL LOADS

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ABSTRACT

Crystalline silicon photovoltaic (PV) modules are prone to the formation of cracks in the solar cells when subjected to mechanical loads. In extreme cases these cracks lead to an electrical separation of cell parts, thus reducing the power output of the module. We present the analysis of crack distributions in PV modules after being subjected to a uniform mechanical load. A simplified numerical simulation of the strain distribution shows a good agreement with experimentally observed preferred cracking directions in PV modules. The simulation allows for the explanation of position-dependent cracking directions in terms of a principal strain analysis. Cracks parallel to the busbars may lead to exceptionally large cell parts being separated. Such cracks are predicted to occur more often than less critical cracks in other directions. Furthermore, we present a statistical analysis of the spatial and directional distribution of cracks from 27 PV modules with 60 cells each. The PV modules have aluminum frames and were loaded uniformly. In agreement with the numerical analysis we find, that the predominant crack orientation is parallel to the busbar with 50% of the cracked cells. However, cells in the corners of the modules are found to crack diagonally, which can be understood using the numerical strain analysis. We propose how to reduce the potential risk of cracks and thus to avoid the subsequent reduction of the module power.

INTRODUCTION

Within their lifetime photovoltaic modules are subjected to a variety of mechanical loads. During the manufacturing of the module, materials with different thermal expansion coefficients are bonded (e.g. soldering, lamination). This leads to mechanical stresses within the PV module depending on the process temperatures [1,2]. Additionally, the transport of the modules leads to vibrations and shocks [3], and in the field uniform static mechanical loads result from wind and snow loads [4]. Any of these mechanical loads may lead to cracks in the solar cells. This fact becomes even more relevant, as new solar cell types are thinner and in consequence more likely to break [5].

Cracks have been shown to considerably reduce the power stability of PV modules subjected to artificial aging if compared to crack-free modules [6]. Additionally the potential influence of a crack on the module power was found to be determined by the maximal cell area that can become electrically separated. It is therefore imperative to understand the formation of cracks due to different mechanical loads in order to develop crack-reducing module designs.

In this paper we focus on the formation and distribution of cell cracks resulting from an IEC 61215 uniform mechanical load test at 5400 Pa. The crystalline silicon PV modules have standard aluminum frames supporting the edges. Fig. 1 shows an electroluminescence (EL) image of a PV module after such a mechanical load test. Modules subjected to this kind of mechanical load repeatedly exhibit a common X breakage pattern, indicated in red. Individual modules, however, may according to their mechanical stability have very different numbers of cracks in the cells, or can even be crack free.

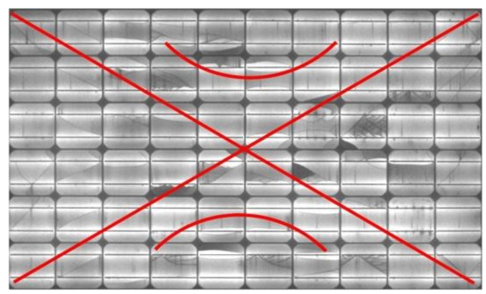

Figure 1: Electroluminescence image of a PV module after uniform mechanical loading. The red lines visualize the observed preferred cracking directions.

In order to understand this recurrent crack pattern and to gain insight into the potential criticality of the cracks, we use a simplified simulation of an edge-supported plate to calculate the strain distribution and the principal strain directions. Then we proceed to statistically analyze the cracking behavior found in experiments where 27 PV modules were subjected to the same uniform mechanical load. Each PV module consists of 60 mono or multi crystalline cells with 156 mm edge length. Finally we discuss the implications from this analysis for crack-reducing module designs.

NUMERICAL EVALUATION

The PV module thickness consists of 80% of glass. Therefore a PV module under a uniform mechanical load is dominated in its deflection by the glass plate. Additionally the glass is second in stiffness only to the silicon of the solar cells. Therefore it is possible to approximate the bending of the PV module with a glass plate. The frame is idealized as infinitely stiff, thus prohibiting a displacement of the glass plate at the edges. For a uniform load as discussed here, an analytical solution for the displacement of the plate is known as Navier plate solution [7]. The resulting strain distribution on the glass plate is shown in Fig. 2. The resulting strain is directly proportional to the load. Therefore a high uniform load can be chosen in experimental tests to assure that a statistically significant amount of breakage in the cells. Although the strain distribution and therefore the stress in the solar cells cannot be straight forwardly calculated from this calculation, we nevertheless consider this distribution a good measure for the relative loads on the center of cells at different positions.

The calculated first principal strain in Fig. 2 agrees qualitatively with the experimentally observed crack pattern in Fig. 1. A few features are particularly striking: the intensity of the strain extends with significant magnitude into the corners of the module, forming an X-pattern very much like the one observed experimentally. Within the corners, the principal strain is oriented in the diagonal directions. Such a strain leads to crack orientations following the corresponding module diagonals.

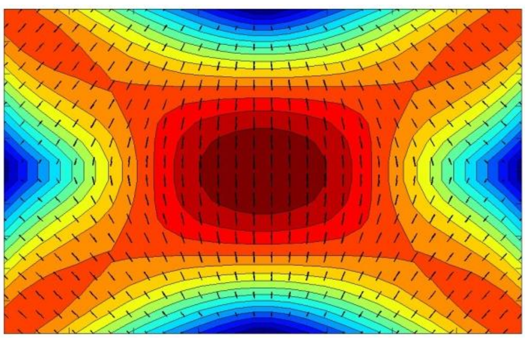

Figure 2: Strain distribution (dimensionless) and direction of first principal strain (black lines) on an edge supported glass plate subjected to a uniform mechanical load.

Additionally, with the exception of the corners the first principal strain is mostly oriented in the direction parallel to the short edges of the module. In consequence cracks parallel to the busbars are expected to be dominant.

The analytical model allows for an efficient evaluation of the stability of these features with respect to changes in the geometry of the module. Fig. 3 shows exemplarily the relative magnitude of the strains in x- and y-direction at the center of the module in dependence of the aspect ration l_x/l_y of the module. We find, that the strain in direction of the shorter edge of the module is always higher than the strain in the other direction. This can be understood by the fact, that the curvature in the shorter direction has to be higher than in the other direction in order to connect the point of highest displacement in the center of the module with the edge. As a consequence, cracks parallel to the longer side of a PV module are expected to be more frequent than perpendicular to the long side, independent of the precise geometrical parameters.

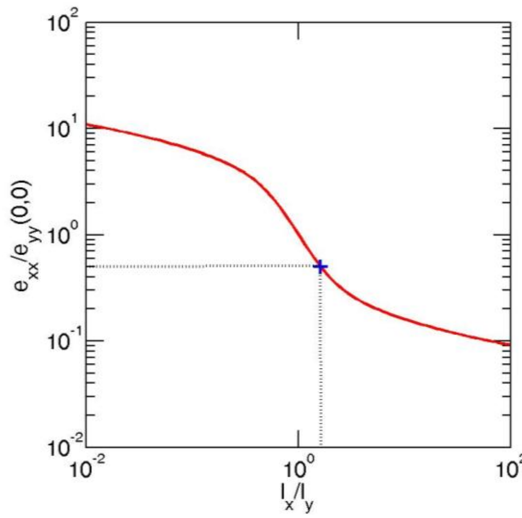

Figure 3: Relative magnitude of strains in x- and y-direction in dependence of the aspect ratio l_x/l_y. The aspect ratio of Fig. 2 is marked with a cross.

STATISTICAL DISTRIBUTION OF CRACKS

We statistically analyze the crack occurrence in 27 PV modules of 60 silicon solar cells each. The cracks are classified according to the orientation of a crack within the cell: dendritically cracked cells, cells with several cracking directions, cracks in either diagonal, cracks parallel and perpendicular to the busbars. These crack orientations are exemplified in Fig. 4. Both the classification of the orientation as well as the position of the respective cell in the cell matrix are evaluated. We first discuss the potential harmfulness of each crack class and then analyze the overall frequentness of cracked cells and crack orientations. Then we proceed to analyze the spatial characteristics of the cracking pattern. Finally, we analyze the worst case scenario of electrically separated cell parts resulting from the experimentally observed cracks.

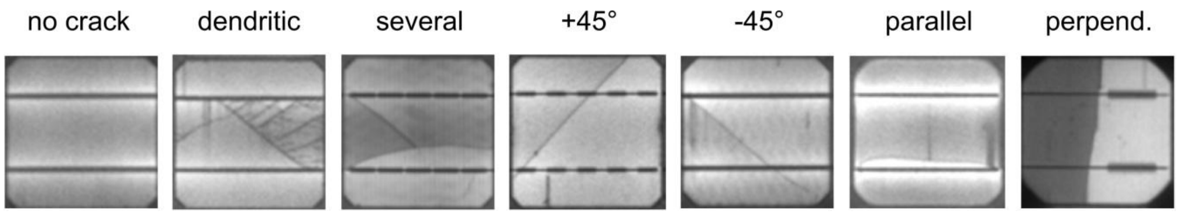

Figure 4: Strain distribution (dimensionless) and direction of first principal strain (black lines) on an edge supported glass plate subjected to a uniform mechanical load.

Statistics of crack orientations

The criticality of cracks for the power stability of the PV module is directly related to the maximal cell area that might become electrically separated [6]. The orientation of a crack in a cell leads to significantly different maximal disconnected cell areas. Fig. 5 shows the worst case separated cell areas for diagonal cracks, cracks parallel to the busbars and cracks perpendicular to the busbars. Within this single crack realizations the cracks parallel to the busbars have the highest potentially separated cell area.

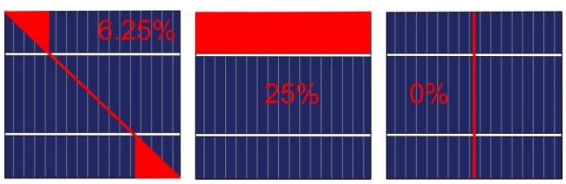

Figure 5: Worst case scenarios of separable cell area resulting from a single crack.

Dendritic cracks and cells with several cracks in different orientations are much more difficult to quantify in their cell area separation risk. Due to the high fragmentation in dentritically cracked cells it is reasonable to assume, that these cracks have a high risk for large separated cell areas as well.

In total 41% of the cells in the 27 PV modules with 60 cells were cracked after the mechanical load test. Fig. 6 shows the relative occurrence of the different crack orientations, with both diagonal orientations combined. By far the most prominent crack orientation with 50% of the cracks is parallel to the busbar. This is in agreement with the predictions of the analytical investigation, that these cracks are expected to be more frequent than cracks perpendicular to the busbars. Diagonal cracks appear in 20% of the cracked cells, cells with several cracking directions and dendritic cracks appear with 15% and 14%, respectively. Perpendicular to the busbars is by far the rarest crack orientation.

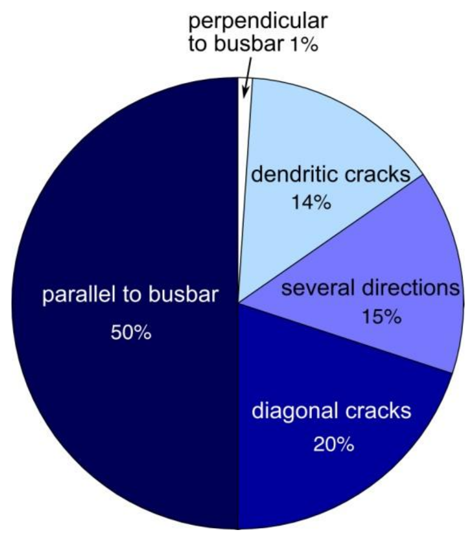

Figure 6: Relative occurrence of different crack orientations.

Considering the criticality of the different crack orientations this means, that the most critical crack orientations, cracks parallel to the busbar as well as dendritic cracks, appear in the majority of cracked cells. The comparatively uncritical cracks, in particular cracks perpendicular to the busbars, are much more rare. One consequence could be to reconsider the interconnection layout: the combined data from the numerical evaluation and the statistical data lead to the conclusion that a 90° rotation of the busbars within the module could reduce the ratio of critical to uncritical cracks considerably.

Spatial distribution of crack orientations

The cells within a PV module that is subjected to a uniform mechanical load experience different strains. This is illustrated by the numerical simulation in Fig. 2. It is therefore instructive to analyze the spatial distribution of crack orientations over the cell matrix. Fig. 7 exemplarily shows the distribution of cracks in the 45° direction, while Fig. 8 depicts the strain corresponding to such cracks.

Figure 7: Percentage of cells cracked in the 45° direction at each position in the cell matrix.

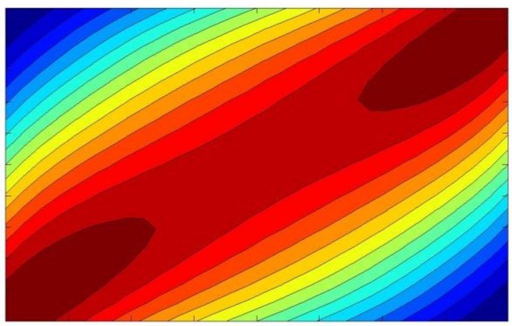

Figure 8: Calculated strain corresponding to cracks in the 45° direction.

We find an agreement in that diagonal cracks are expected from the simulation to appear predominantly in the corresponding corners, where the calculation gives the highest relevant strains. In the center of the module the statistical appearance of 45° cracks is much lower than would be naively inferred from Fig. 8. This is however to be expected, as cells in the center have an even higher probability to break parallel to the busbars, so that these cells do not appear in the 45° statistics.

Potentially separated cell area fractions

As the potential risk for a power degeneration in a PV module due to cracked cells is strongly influenced by electrically separated cell areas [6], we analyze the maximally separated cell area of the cracks generated by the mechanical load test. Here all cracks are considered to be electrically insulating resulting in an electrically separated cell area, compare Fig. 5. Note that this is a worst case scenario. This approach emphasizes the potential impact of a crack on the module power, not the likely impact, which is still unknown.
Fig. 9 shows the occurrence of potentially separated cell areas for cells with cracks. 10% of the cracked cells are entirely uncritical, as they do not lead to separated cell areas even in the worst case scenario. These are for example cracks perpendicular to the busbars, or cracks parallel to the busbars located between the busbars. Another 20% of the cracked cells can loose maximally 8% cell area. For a 230 W module with 60 cells this was found to be the threshold below which the power output of the PV module remains unchanged [6]. So nearly a third of the experimentally observed cracks can be considered uncritical even under worst case conditions.

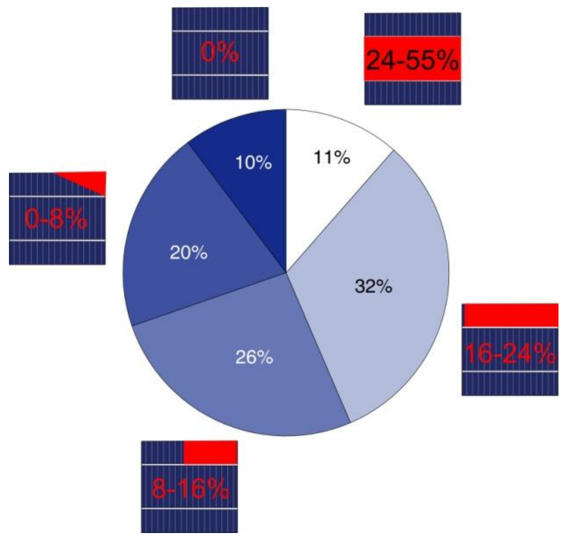

Figure 9: Occurrence of potentially separated cell area of cells with cracks.

The majority of the cracked cells have the potential to reduce the power output of the PV module. 11% of the cracked cells can potentially loose a quarter of the cell area or more, thus reducing the power output of the module drastically. However, up to now the probability of the cell part separation and the timescale in which it occurs in the field is still unknown.

CONCLUSIONS

We analyzed the distribution and impact of cracks with a simplified analytical calculation and a statistical analysis of 27 mechanically loaded PV modules. Cracks parallel to the busbar appear most frequently. The high potentially separated cell areas by these cracks can lead to a reduction of the module power output. We discussed, that the change of the orientation of the busbars has the potential to reduce the criticality of the generated cracks, albeit not the frequency of cracks.
In the corners of the modules we showed that the situation is different: the simulated principal strains are rotated by 45° and the predominant crack direction accordingly is along the module diagonals.
Following a worst case scenario we determined the maximally separated cell area of cracked cells. We found that 30% of the experimentally observed cracks have a potentially separated cell area below 8%. These cracked

cells can be considered uncritical for the power stability of the PV modules.

Modules that are less prone to crack formation, in particular of the critical classes, are desirable for their lower risk of power degradation. The insight gained by the presented experimental and analytical analysis can now be used to further explore suitable module designs.

REFERENCES

[1] A. M. Gabor, M. M. Ralli, L. Alegria, C. Brodonaro, J. Woods, L. Felton, "Soldering induced damage to thin Si solar cells and detection of cracked cells in modules", *Proc. of 21st EUPVSEC*, 2006, pp. 2042-2047

[2] J. Wendt, M. Träger, M. Mette, A. Pfennig, B. Jäckel, "The Link Between Mechanical Stress Induced by Soldering and Micro Damages in Silicon Solar Cells", *Proc. of 24th EUPVSEC*, 2009, pp. 3420-3423

[3] U. Jahn, F. Reil & T. Bernert, The Impact of Dynamic Loads on Crystalline PV Modules of Different Wafer Thickness Imaged by Electroluminescence, *Proc. of 23rd EUPVSEC*, 2009, 4CO.2.2

[4] *IEC 61215:2005*, "Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval", Section 10.16: Mechanical load test

[5] S. Dietrich, M. Pander, M. Ebert und J. Bagdahn, "Mechanical assessment of large photovoltaic modules by test and finite element analysis". *Proc. of 23rd European Solar Energy Conference,* 2008

[6] M. Köntges, I. Kunze, S. Kajari-Schröder, X. Breitenmoser, B. Bjørneklett, *Sol. Energy Mater. Sol. Cells (2011)*, doi:10.1016/ j.solmat.2010.10.034

[7] H. Altenbach, J. Altenbach, K. Naumenko, *Ebene Flächentragwerke*, Springer, 1998, p. 225