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Forecasting Environmental Degradation Power Loss in Solar Panels with a Predictive Crack Opening Test

Jason L. Lincoln[1], Andrew M. Gabor[2], Eric J. Schneller[1], Hubert Seigneur[1], Joseph Walters[1], Rob Janoch[2], Andrew Anselmo[2], Victor Huayamave[3] and Winston Schoenfeld[1].

[1]Florida Solar Energy Center, University of Central Florida, Cocoa FL, USA
[2]BrightSpot Automation LLC, Westford, MA, USA
[3]Department of Mechanical Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL, USA

Abstract — **Manufacturing, shipping & handling, installation, and in-field loading of photovoltaic solar panels are common contributors to the creation of cracks within the cells of a panel. Many cracks initially cause little or no power loss in the panel, but such tightly closed cracks may open over time due to environmental forces, and cause significant power loss and even failure of the module. We developed a method, using the *LoadSpot* tool, to apply a mechanical load to a panel to temporarily open pre-existing cracks while also allowing for electroluminescence (EL) imaging and flash IV testing. The change in the IV and EL measurements upon loading provides a quantifiable metric that can be used to evaluate reliability and durability. Such Predictive Crack Opening (PCO) tests have value in assessing preexisting damage as well as in the correlation with the degradation due to cracked cells opening upon environmental chamber and cyclic loading. We performed finite element modeling and simulation to illustrate the stresses applied at different load and mounting conditions. We demonstrate a wide range of mechanical loading and stress testing with accompanying EL and IV measurements which not only show the narrative of damage and power loss through static mechanical load, environmental chamber testing, and cyclic loading, but also suggests potential improvements which can be made to the order of chamber and cyclic load testing within the IEC 61215 standard. next.**

Index Terms — **accelerated aging, cell fracture, electroluminescence, finite element analysis, photovoltaic modules, silicon.**

I. INTRODUCTION

Cracked solar cells are commonplace in crystalline silicon based solar panels, and NREL has assigned “degradation related to fractured cells” as the 3rd most important degradation mechanism in newer generations of panels which have thin, easily fractured cells [1]. The 2nd most important mechanism is due to hot spots which may be linked to broken cells forced into reverse bias. Anecdotal evidence abounds concerning panels in the field that have been heavily damaged due to cracked cells, although the origin of the cracking is often not clear. The problem of assessing the risk posed by cracked cells is challenging since most cracks are tightly closed prior to field exposure, with continuity of the metallization across the cracks, and little or no power degradation. It can be quite challenging to even detect tightly closed cracks using the standard electroluminescence (EL) images of the panels taken with low-resolution (~1 Megapixels) scientific EL cameras.

Extended exposure of installed solar panels to environmental conditions, including wind and snow load and thermal cycling, is known to cause cracks in silicon solar cells, and such cracks have been shown to cause significant power loss [2].

To reduce the risk posed by cracked cells, the industry could 1) shift to cell/panel designs that are less sensitive to cracking [3], 2) develop quick, non-destructive tests that quantify how the cracks may affect power degradation in field, and 3) prove that such tests correlate well to actual degradation seen during accepted environmental chamber tests and/or actual field exposure. We previously suggested a predictive crack opening (PCO) test using the *LoadSpot* mechanical load testing tool [4], and discuss various consideration in other recent works [5]. In this work, we add a finite element modeling component to help inform the PCO test definition, delve deeper into the possibilities of predictive crack opening, present data on the power loss response of modules during and after stress testing, and investigate the impact of environmental chamber degradation before and after mechanical loading.

The *LoadSpot* tool is capable of using negative pressure (*e.g.* front side load) to induce a mechanical load on a solar module while allowing the module to undergo electroluminescence (EL) and I-V characterization. A unique image can then be taken showing the previously closed cracks, now more open to varying degrees, without stressing the module to the point of creating new cracks. Additionally, a snapshot of the degradation in the I-V curve can be extracted while loaded, to show the predicted power loss due to the eventual opening of these cracks. Furthermore, we can use these snapshots to capture the narrative of power loss due to cracking through various load conditions and stress testing.

By applying a static mechanical load of 2400 Pa, as is done in the IEC 61215 standard, we may generate new cracks which might be caused in-field via snow/wind load on the front surface of the panel. Then, we subject these modules to a series of thermal cycling and humidity-freeze tests, followed by cyclic loading tests, which can permanently open those cracks which were created via mechanical load. Additionally, we can show what impact cyclic loading can have on solar panels which were weakened by environmental chamber testing. The loaded and unloaded EL and IV measurements at each major step are then compared to describe the predictive qualities of the *LoadSpot* tool, as well as its ability to assist in the optimization of module technologies by amplifying the changes in the IV and EL signals used for the characterization of mechanical reliability.

II. MODELING OF LOADSPOT TEST

The *LoadSpot* tool is capable of loading panels while clamping at the usual two points along the long edges (four points total) as is required for IEC static and cyclic load testing. Although four-point support is more representative of field conditions, the industry may be better served by a PCO test that is applicable to a simpler tool design. Multiple groups [6] have explored full perimeter support for loading under vacuum from the rear side, and we model this approach here.

We consider four loading conditions for stress modeling in the Abaqus software. The simulations are split into two categories, perimeter support and four-point support. Each category shows a load of 800Pa, the load at which cracks are opened, but not formed if not weakened by environmental chamber testing [6], and 2400Pa, the IEC standard, known to cause cracks.

The simulations all use a uniform distributed load on the front surface of the panel. Panel dimensions are 1.5 m x 1 m. A sheet of silicon is used to simulate the layer of solar cells in the panel in order to simplify the simulation as well as to allow for analysis of the stresses at this layer. The encapsulation structure includes a 3.2 mm thick soda-lime float glass sheet followed by 0.2 mm of EVA, the 0.2 mm silicon sheet, another 0.2 mm layer of EVA and finally enclosed by a 0.325 mm backsheet. The encapsulation is surrounded by a standard aluminum frame. An encastre constraint, allowing for zero degrees of freedom, is used at four points, following typical clamp locations, for group 1, and surrounding the perimeter of the frame for group 2. These setup configurations can be seen in Fig. 1.

Because of the brittle nature of silicon, it is most relevant to consider the first principal stress as an indicator for crack creation and propagation. We generate the first principal stress profile at the silicon layer of the panel where the solar cells lie for each configuration. The results can be seen in Fig. 2.

Comparing each configuration shows an interesting narrative as load conditions are changed. At the lower load level in Fig. 2 a) and b) the differences in first principal stress area, magnitude, and shape are small. At 2400 Pa, the differences are quite large, as can be seen in Fig. 2 c) and d). This is caused by deformation of the aluminum frame at higher load levels, which is restricted in a full perimeter support.

Therefore, in performing the predictive crack test at 800 Pa, perimeter support will be used in order to more closely conform with other pressure induced loading tests on simpler equipment, such that results in this test might contribute to a formal testing standard. Note however, when performing static loading at higher pressures with the aim of creating new cracks, it is important to use the four-point support configuration so that the stresses are representative of what may be experienced by the module in the field.

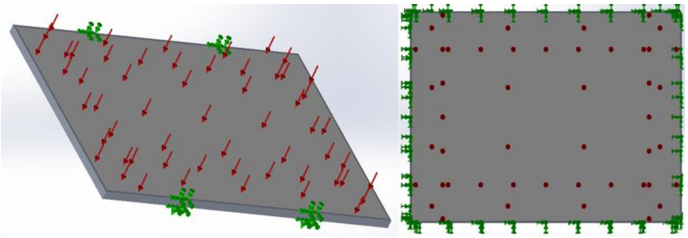

Fig. 1. Simulation setup display for both groups. Red arrows represent the uniform load, whereas green arrows represent encastre constraints. The left image shows the four-point constraint at clamp locations, while the right shows full perimeter support.

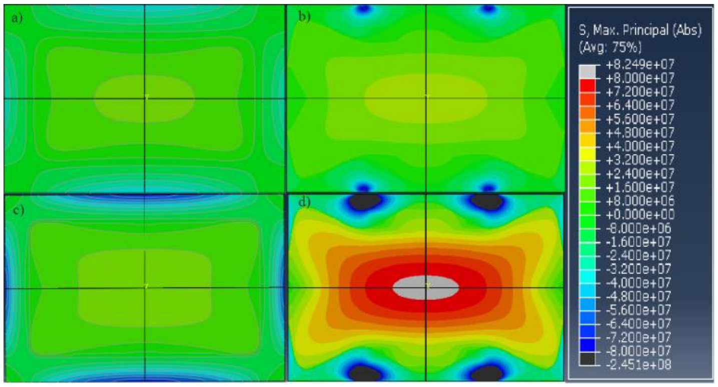

Fig. 2. First principal stress profile at the silicon layer for a) Perimeter supported panel loaded at 800 Pa, b) Four-point supported panel loaded at 800 Pa, c) Perimeter supported panel loaded at 2400 Pa, and d) Four-point supported panel loaded at 2400 Pa. Black and grey regions indicate areas of very high compressive and tensile stress, respectively.

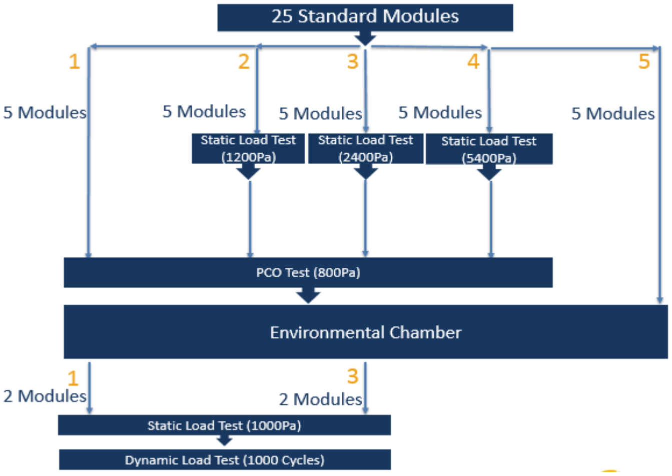

Fig. 3.. Experimental Plan – Five groups of five modules, which underwent various loading conditions prior to an environmental chamber test. Additional modules from groups 1 and 3 were subjected to additional static and cyclic loading after environmental chamber testing.

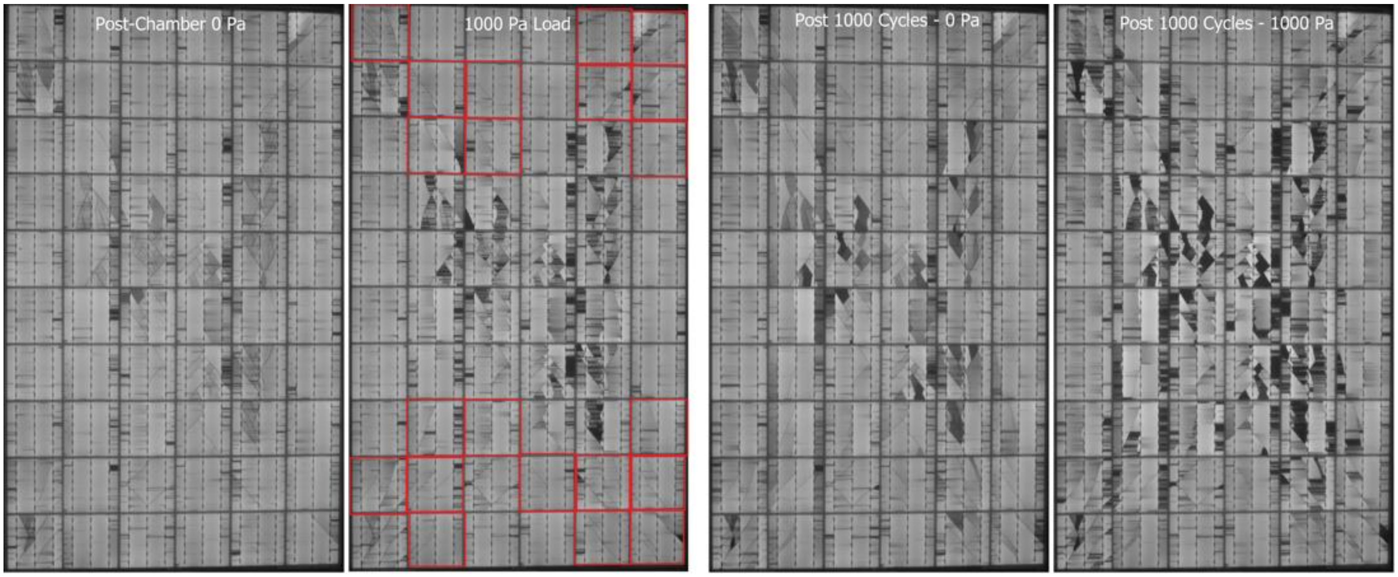

Fig. 4. Electroluminescence images of a module from group 3 (2400 Pa Static Load), which underwent further static loading and cyclic loading after environmental chamber testing. From left to right: 1) Unloaded module post environmental chamber. 2) Module after chamber testing, with a 1000 Pa load applied. Cells which had new cracks form during the 1000 Pa static load test have been highlighted. 3) Module image after 1000 cyclic load cycles, taken at 0 Pa. 4) Module after 1000 cyclic load cycles, taken at 1000 Pa.

III. EXPERIMENT

The full experiment includes the testing of twenty-five standard mono-silicon 60-cell panels, shown in Fig. 3. The panels are split into five groups, which each include five panels. Initial IV and EL measurements are taken of each panel before any further testing. Group 1 undergoes an 800 Pa predictive crack opening test, with EL and IV measurements taken both during and after loading. Groups 2, 3, and 4 are subject to static mechanical loading on the *LoadSpot* to create varying levels of cracks using standard 4-point support at 1200 Pa, 2400 Pa, and 5400 Pa, respectively, before receiving the PCO test, which shows how newly formed cracks from mechanical loading can be detected at lower load levels. Group 5 is kept as the control and does not undergo any mechanical loading. Each group is then subject to fifty thermal cycles and ten humidity-freeze cycles (TC/HF) as has been recommended by PVQAT [7] in an environmental chamber to further open the cracks. Subsequently, four modules, two from Groups 1 and 3, were subjected to further mechanical loading in the form of a 1000 Pa load, followed by a cyclic load sequence of 1000 cycles, from 1000 to -1000 Pa. EL and IV measurements were taken at 0 and 1000 Pa for each step.

IV. RESULTS AND DISCUSSION

A. Crack generation and damage to modules

The snapshots of electroluminescence and IV characteristics throughout the experiment tell a story which is uniquely enhanced by the *LoadSpot* tool. Imaging the modules as we increase the static mechanical load shows that cracks can generate or propagate as early as 800 Pa. This cracking gradually gets worse as you increase mechanical load, up to the complete shattering of cells, seen at 5400 Pa. Additionally, EL images provide clear imagery which show how previously created cracks can be re-opened at lower load levels than was used to create those same cracks [6]. However, before chamber testing, the opening of cracks at lighter loads, as in the PCO test, does not provide a large signal of power loss, such that alternative failure modes may overshadow those results and obscure the role of cracking in module degradation. For instance, in this experiment, most modules tested were influenced by a disconnection of fingers, which created large sums of dark areas over the surface of the cells. This proved to show the PCO test before environmental degradation as a situational tool for module characterization when other modes of degradation are lesser in their role of power loss, and it is inconclusive how well it may perform in other circumstances as a predictive tool in this stage.

Fig. 5. shows the change in max power as four modules traversed the various stages of the experiment. Compared to just static loading, with the measurement taken at 2400 Pa, environmental chamber testing proved to cause significantly more power loss. However, those modules which saw higher mechanical load did not see much greater power loss after chamber testing than those which only underwent the PCO test.

Furthermore, it is the mechanical loading after chamber testing which has the greatest implications to our understanding of module reliability testing and power loss due to cracking. Fig. 4. shows the EL images taken at each major step after chamber testing. We can see many new cracks forming on the cells after only a load of 1000 Pa, far below the load applied in the original static mechanical load test, prior to chamber testing.

This implies that TC/HF sequence causes a mode of weakening in the solar panel, which degrades the mechanical reliability of the encapsulated cells. As the common testing procedure stands, mechanical loading is frequently performed only before chamber testing, with the expectation of the environmental degradation to open the cracks created via mechanical load. The implication follows that because of the nature of in-field conditions, which would apply mechanical loading before, during, and after thermal cycling, it may be wise to implement tests that address this new mode of failure.

Finally, in Fig. 5, the power loss seen at 1000 Pa is near identical to that seen at 0 Pa after 1000 cycles. Although this investigation was rather limited in its scope, this data suggests that a PCO test taken to 1000 Pa may serve as a quick replacement to the slower standard cyclic load test. This result can be further reinforced when reviewing the second and third module images in Fig. 4, which have remarkably similar crack opening patterns, as illustrated by the dark regions.

B. *The LoadSpot as a tool for module optimization*

By taking a measurement of the power at each step in the cyclic load test, both at 0 and 1000 Pa, we can not only get an idea of how power degrades over the course of the test, but we also get a glimpse into how else the *LoadSpot* might be used for module design and optimization. Seen in Fig. 6, the measurement of power at 1000 Pa is much less than the measurement taken at the same number of cycles at 0 Pa. In addition, the difference between the measurements taken at 0 and 1000 Pa gets larger as the number of load cycles increases. As shown previously, the signal from cracking due to mechanical load can be smaller and difficult to differentiate from other degradation mechanisms. Therefore, the *LoadSpot* test offers an opportunity to greatly increase this signal, which can lead to finer tuning of module design to improve the reliability of modules with respect to cracking in solar cells.

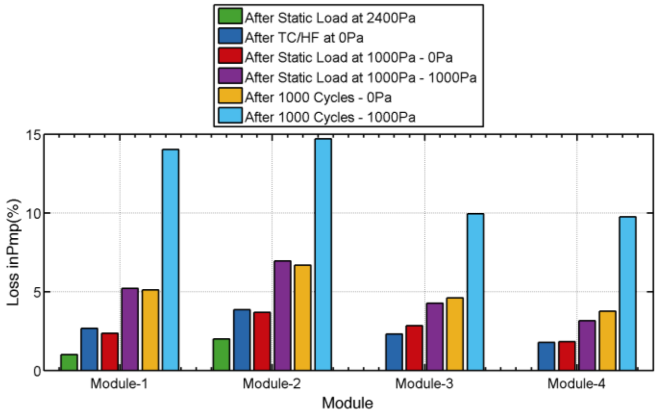

Fig. 5. Comparison of the loss in P_{mp}, in terms of loss percentage from initial performance, for four modules which underwent additional mechanical loading after environmental chamber testing. Module 1-2 are from Group 3 (2400 Pa static load test group), and Module 3-4 are from Group 1 (PCO only group). Each bar shows the change in P_{mp} from each major IV snapshot, compared to the original P_{mp}.

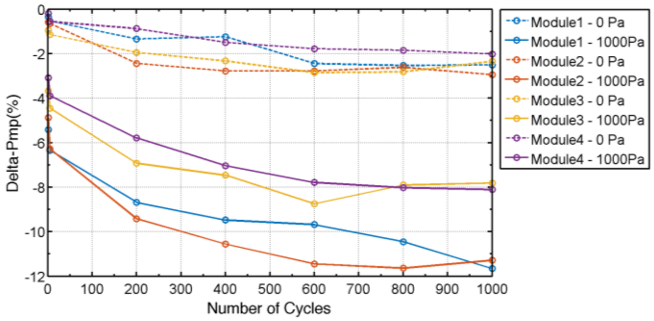

Fig. 6. Plot showing the change in $P_{mp,}$, in terms of loss percentage from the initial unloaded state, over the course of the cyclic load test for four modules. Data is presented from measurements taken in the unloaded state (0Pa) and unloaded state(1000Pa) for each interval. The first data point shows the change in P_{mp} after one cycle.

V. CONCLUSION

The momentum within the PV durability testing community entails a shift to a testing sequence involving cyclic loading to generate cracks, followed by environmental chamber testing to "open up" these cracks. The data we presented here on a single module type questions this approach as the environmental chamber exposure appears to have weakened these modules such that subsequent cyclic loading caused extensive damage and power loss. Such a sequence represents real world conditions where wind and snow loading occur after years of climate exposure, and is thus of concern. Future work will attempt to understand the root causes of the climate-chamber induced sensitivity to load testing, and explore whether this sensitivity extends to other module designs from different manufacturers. If this sensitivity is seen to be commonplace and result in more damage than the reverse sequence, then modification of the testing standards may be prudent.

We have demonstrated both cyclic and static loading of solar panels with the *LoadSpot* tool where IV and EL data can be collected in both the unloaded and loaded states to clearly show crack formation and the evolution of cracks from closed to open states. In general, the solar panels tested are remarkably resilient to power loss even after extensive cell cracking. With such small changes in module power, it is difficult to optimize module designs, materials, and processing based on the changes in IV data after accelerated testing, and instead must usually lean more heavily on the EL data. The measurement of module power during application of small loads to prop open otherwise closed cracks amplifies the change in IV data to allow better optimization using the IV data. We found such a predictive crack opening test to correlate well to the degradation seen after subsequent cyclic loading of the modules weakened by chamber testing.

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