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Fatigue crack growth in Silicon solar cells and hysteretic behaviour of busbars

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ABSTRACT

Photovoltaic modules are subject to cyclic deformation during their lifetime as a result of vibration, applied loads, and thermal effects. Vibration and applied loads induce cyclic bending on the modules, while operating temperature excursions during the day lead mostly to cyclic axial deformation. In both cases, the region between two solar cells is severely stressed. For cyclic bending, cracks can nucleate near the points where busbars are soldered onto Silicon and might propagate due to fatigue. For cyclic axial deformation, on the other hand, busbars are stressed above the elastic regime and may experience plasticity and hysteretic energy dissipation. The present study focuses on the experimental characterization of such material degradation phenomena related to the above two types of cyclic deformation. For the former, fatigue crack growth in Silicon and its evolution have been quantified by using two independent nondestructive monitoring techniques based on electroluminescence and thermal infrared imaging. For the latter, plasticity and degradation of the material response of busbars has been assessed in relation to different applied cyclic strain levels. The obtained results shed light onto the cyclic response of materials used in photovoltaics, and pinpoint features that should be taken into account in the development of refined standard qualification tests for photovoltaics including cyclic deformation.

1. Introduction

The increase of the lifetime of photovoltaic (PV) modules is an important concern for a sustainable development of PV technologies. According to the IEC 61215 qualification standards [1], PV modules are subject to severe monotonic mechanical loads to assess their pass or fail criteria, mostly with the intent to simulate the effect of uniform snow pressures. However, if the focus is the understanding of slow degradation of the PV materials which affects their lifetime, then cylic loading is the major type of action onto PV modules that should be investigated. For example, it is known that vibrations during transportation can lead to crack propagation in Silicon from the existing defects or from the points where busbars are soldered onto the solar cells. Similarly, wind oscillations induce cyclic bending and the effect of their continuous action over million of cycles is not fully understood, although a revision of the IEC 61215 standards has been put forward by including cyclic uniform pressure loads before performing accelerated ageing tests, as prescribed in the recent IEC 62782 standards [2]. On the other hand, from the pioneering experimental results reported in [3], we know that, due to the encapsulation of Silicon into EVA layers in the PV module, cracks can propagate during cyclic bending with a phenomenon analogous to fatigue, which is not possible for Silicon as a stand alone material due to its high brittleness. Temperature excursions of the module experienced during a day can also promote cyclic loading. In this case, the gap between solar cells, usually 2 mm wide at the room temperature, can be increased of 60 μm due to thermo-elastic deformation of the materials at the maximum temperature of about 80 °C, as experimentally and theoretically shown in [4,5].

In the present study, cyclic bending on the modules and cyclic axial deformation tests are experimentally performed and characterized in relation to their effect onto the region between two solar cells, which is one of the most critical positions. For cyclic bending, cracks can nucleate near the points where busbars are soldered onto Silicon and might propagate due to fatigue. For cyclic axial deformation, busbars can be stressed above the elastic regime and may experience plasticity and hysteretic energy dissipation. For the former problem, fatigue crack growth in Silicon and its evolution are quantified by using two independent nondestructive monitoring techniques based on electroluminescence and thermal infrared imaging. For the latter, plasticity and degradation of the material response of busbars are assessed in relation to different applied strain levels.

The obtained results shed light onto the cyclic response of materials used in photovoltaics, and pinpoint important features that should be taken into account in the development of refined standard qualification

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Table 1
PV module's layers and their corresponding elastic modulus (E). PET = polyethylene terephthalate, EVA = poly(ethylene-*co*-vinyl acetate) [4].

Layer	Material	E (MPa)
Backsheet	PET	2800
Encapsulant	EVA	10
Cell	Silicon	130,000
Encapsulant	EVA	10
Frontsheet	PET	2800

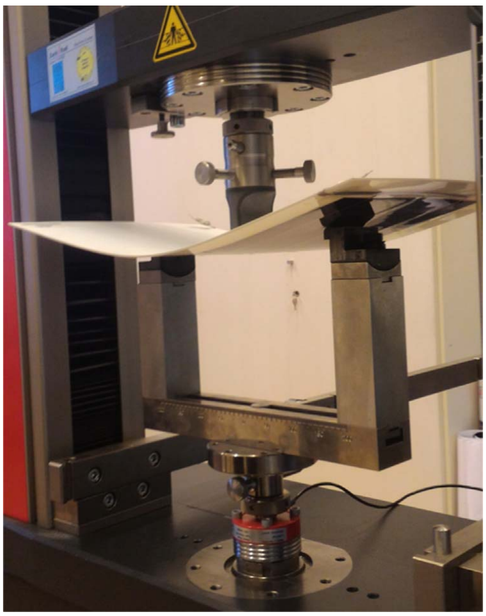


Fig. 1. Picture of the experimental setup for the bending tests.

tests for photovoltaics accounting for cyclic loading.

2. Description of the experimental setups

The present section provides a synthetic description of the experimental setup used to conduct cyclic three-point bending tests on photovoltaic (PV) mini-modules to assess the phenomena of crack nucleation and their sub-critical propagation in solar-grade polycrystalline Silicon (Si) near the critical points where the busbars are soldered. Moreover, cyclic tensile tests are performed on the busbars, which may also fail since they are axially elongated and stretched by repeated loadings, in order to characterize their nonlinear constitutive response and energy dissipation under cyclic tests.

2.1. Experimental setup for cyclic three-point bending on PV mini-modules

The tested sample was a semi-flexible photovoltaic (PV) mini-module composed of two squared Silicon (Si) solar cells 155 mm wide with a three busbar architecture aligned parallel to the longest module side. The PV module was manufactured for the purpose of the present study and it is composed of the following sequence of layers: a polymeric backsheet 0.345 mm thick, an EVA layer 0.4 mm thick, polycrystalline Si solar cells 0.166 mm thick, another EVA layer 0.6 mm thick, and finally a PET cover 0.265 mm thick (see Table 1 for more details concerning also the Young's modulus of each material).

The mini-module was subjected to cyclic three-point bending by supporting it above two steel hinges at a distance of 180 mm between each other, and by applying the line load in the mid-span position with another pin. The mini-module is placed downwards, with its backsheet directly loaded by the central pin (see Fig. 1).

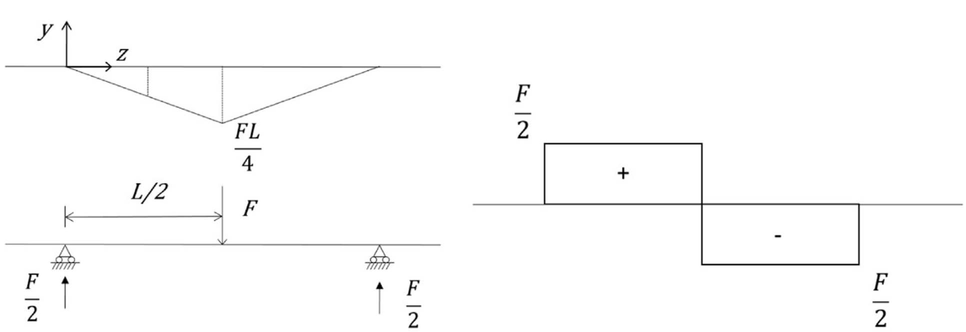
Such a loading configuration, which induces a linear bending moment diagram with maximum value in the mid-span position, was selected in order to induce the maximum axial stress in the busbars at the point where they connect the two solar cells in series. As a result, axial stresses concentrate in the neighboring portion of Silicon, allowing us to investigate crack nucleation and propagation caused by tiny microcracks generated by the soldering of the busbars onto Silicon. Cyclic loading is achieved by displacement control of the central pin and imposing two linear ramps, one ascending up to a maximum displacement of 20 mm in 120 s, followed by another descending ramp down to a minimum displacement corresponding to a pre-load of 5 N, again performed in 120 s. A sequence of 3500 cycles was made using the Zwick Universal testing machine (Zwick/Roell, Z010TH) equipped with a 1 kN load cell. The imposed maximum displacement was selected to induce a maximum applied force F of about 64 N. A straightforward application of stress analysis formulae provides the distribution of the axial stress σ_z function of the position y in the mid-span cross-section. By modelling the mini-module as an Euler-Bernoulli beam with perfectly bonded layers as in [4,6], the mid-span cross-section is subject to a bending moment $M = FL/4$, where $L = 180$ mm, and to a vanishing axial force $N = 0$. By assuming the conservation of plane cross-sections, the axial strain $\epsilon_z(y)$, which physically represents the gradient of the axial displacement with respect to the axial coordinate z, is a function of the coordinate y along the PV module cross-section (see Fig. 2 for the reference system, where $y = 0$ is set at the intrados of the laminate), is given by:

$$\epsilon_z = \frac{\sigma_{z,i}}{E_i} = \epsilon_0 + \chi y, \tag{1}$$

where ϵ_0 is the longitudinal strain at $y = 0$ and the χ is the beam curvature, unknowns of the problem.

The axial stress σ_z can be determined from ϵ_z as:

$$\sigma_{z,i} = E_i \epsilon_z = E_i \epsilon_0 + E_i \chi y. \tag{2}$$



(a) Bending moment (b) Shearing force

Fig. 2. Bending moment and shearing force diagrams in the module during fatigue tests.