Power Loss of Crystalline Solar Cell under Cyclic Loadings

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Abstract. In application of building attached photovoltaic in China, the solar cells in the modules are mono-crystalline or polycrystalline cells. In some applications where the wind load is at higher level, a large deflection of the modules will occur. Due to the fluctuation of the wind load, the initial damages inside the cells will develop under this cyclic loading, as a result, the power loss of the solar cell can be observed due to the development of the fatigue damage. In this paper, the fatigue damage evolution of crystalline solar cell in module is investigated experimentally. The damage evolution with the cyclic number was obtained via the measurement of the power loss of the cell. The damage evolution equation was derived based on the continuum damage mechanics and the fatigue life of the cell was predicted.

1. Introduction
In recent years, the applications of the photovoltaics (PV) increase dramatically in China. There are considerable PV modules mounted on the roofs or integrated in the buildings for abundant sun light. In order to avoid the shelter from surrounding buildings, photovoltaic modules are always installed on the roof of high-rise buildings. The most common external load for photovoltaic modules installed in this position is wind load. For some large-size modules, the deflection of the modules is relatively large under high wind pressure and results in the rising of the stress in the crystalline solar cells. Due to the fluctuation of wind load, the long-term effect results in the development of the initial damage in the crystalline solar cells, which leads to the partial electrical performance degradation or overall failure of the modules.

Compared to the great applications of photovoltaic power generation on buildings in recent years, the related research work is relatively limited and the investigations mainly focus on the following aspects: (1) the research of the wind load effect on solar photovoltaic modules (Cosoiu et al, 2008; Weiss et al, 2009); (2) the investigation of the strength and failure behavior of crystalline solar cells (Rozigonyi et al., 2011; Schonfelder et al, 2008; Pingel et al, 2008); (3) the thermal stress of crystalline solar cells under thermal cycles (Cao et al., 2008; Eitner et al, 2011). In those studies the cell layer was considered as a continue one instead of the separated cells and the damage evolution of the cells and its impact on the overall electrical output performance are not considered.

Despite the fact that some efforts on measurement and calculation of the stress and strain of the cells in modules brought us the information, the investigations on the development of fatigue damage resulting from the cyclic loading and the corresponding power loss of the cells are, however, not available in literature so far. In this paper, the experiment for the fatigue property of the crystalline solar cell under cyclic loading was performed. The damage of the cell was obtained by measuring the power loss of the cell under fixed light intensity and the constant temperature. The fatigue life of the cell was predicted by the damage evolution equation derived from the continuum damage mechanics.
2. Measurement of the Damage in the Solar Cell

The photovoltaic module is a laminated structure as shown in Fig. 1. The laminated configurations from the top to the bottom of the module are 3.2mm glass panel, 0.5mm EVA (Ethylene-Vinyl Acetate) layer, 0.19mm cell layer, 0.5mm EVA layer and 0.35mm TPT (Tedlar/Pet/Tedlar), respectively, and the crystalline solar cells are embedded in the EVA layer. When the module is deformed due to the load, the surfaces of the cell are loaded not only by the normal surface forces, but also by the tangential shear forces resulted from the shear deformation of EVA layers.

In general, the damage of materials can be obtained by measuring the residual stiffness or residual strength of the structures. This method is often used to measure the damage of a single material component. For laminated photovoltaic modules, the cells with thickness of only 0.19mm are embedded in the soft EVA layers and separated from each other by small gaps. There are only two metal strips with width of about 3mm and thickness of about 0.1mm between cells as the electrical connection. In this manner, the cell layer has little contribution to the overall stiffness of the modules, which makes it is difficult to obtain the damage evolution of the cells by measuring the stiffness change of the module. On the other hand, the decrease of the stiffness for a laminated structure represents the sum of the damage from each layer, which is not corresponding to the damage of cell layer.

Considering a small cell element, the effective volume (i.e., the volume of undamaged material) in the initial state is \(dV_0\). After \(n\) cyclic loading, the damage occurs in the element and the effective volume is reduced to \(dV\). The damage of the cell element is defined as

\[
D^* = 1 - \frac{dV}{dV_0}
\]

Eq. (1) is integrated in the whole cell, we have

\[
\frac{1}{V_0} \int D^* dV_0 = 1 - \frac{V}{V_0}
\]

where \(V_0\) is the total effective volume of the cell in the initial state, and \(V\) denotes the total effective volume of the cell after damaged, we define

\[
D = \frac{1}{V_0} \int D^* dV_0
\]

The variable \(D\) represents the average damage of the cell, then

\[
D = 1 - \frac{V}{V_0}
\]

The solar cell is the basic unit of the power generation. The performance of the solar cell is characterized by the \(I-U\) curve that is expressed as (Bashahu and Nkundabakura, 2007)
in which $I_i$ is the photocurrent generated by the cell, $I_0$ is the reverse saturation current of the diode, $q$ represents the electric quantity of the electron, $q = 1.602 \times 10^{-19}$, $n_0$ is the ideal factor of the diode and its value is between 1 and 2, $k$ denotes the Boltzmann constant and $k = 1.3807 \times 10^{-23}J/K$, $T$ is the absolute temperature, $R_s$ is series resistance which includes the effects of the metal grid wire, bulk resistance of semiconductor material and metal/silicon junction resistance, etc, $R_{Sh}$ is parallel resistance due to the effects of the electric leakage caused by semiconductor defect at the cell edges. Under the certain ambient temperature and the light intensity, the magnitude of the photocurrent produced by the cell is directly proportional to the effective volume of the cell material. At initial state, the photocurrent generated by the cell under certain ambient temperature and light intensity is $I_{L0}$, then $I_{L0} = \lambda V_0$, and $\lambda$ is a constant related to the cell material. When the damage occurs in cell, the damaged material no longer generates photocurrent and the corresponding photocurrent generated by the cell under the same ambient temperature and light intensity is $I_L$, then $I_L = \lambda V$, Eq. (4) becomes

$$D = 1 - \frac{V}{V_0} = 1 - \frac{I_L}{I_{L0}}$$

Eq. (6) shows that the average damage of the cell caused by the cyclic loading can be obtained by measuring the photocurrent variation of the cell under the certain ambient temperature and light intensity.

3. Experiment

The 195w standard module with the size of 1580mm×808mm was used in experiment, the module has 72 pieces of 125mm×125mm mono-crystalline solar cells. The experimental set up to simulate the uniform wind pressure on the upper surface of the module is shown in Fig. 2. The module was simply supported on four sides and the glass panel of the module was upward. The flexible enclosure adhered to the periphery of the glass panel was used to contain the water. The experiment was performed as following, at first, the water was injected into the container formed by flexible enclosure and the glass panel to load the module, the pump was turned off when the water depth reached the pre-setting value. Next, the valve on the water outlet was opened to drain off the water. After drainage, the water was re-injected again to achieve the cyclic loading, in this manner, the stress ratio of the cells is $R = 0$. The period of the one cycle is about 3 minutes ($f \approx 0.0056$Hz).

The independent electric output ends were set for the cell at the center of the module. The lamp fixed above the module was used to test the electric parameters of the cell at the center of the module after finished the preset cycles. The light intensity achieved at the center of the module glass panel was 304W/m². The pre-setting depth of the water in experiment was 65mm that was corresponding to the

![Figure 2. The experiment set up](image-url)
wind pressure of 0.65kN/m². The measurement of the cell damage evolution with the cyclic number was performed as following:

1. Firstly, the initial $I-U$ data of the cell were measured at the light intensity of 304W/m² and the ambient temperature of $T = 306k$.

2. After the completion of the initial test, the cycle loading process was performed and the $I-U$ data of the cell under the same light intensity and ambient temperature were measured at the cycles of $N = 100$.

3. The $I-U$ data of the cell under the same light intensity and ambient temperature were measured again at the cycles of $N = 200, 300, 400, 600, 800$ and $1000$, respectively.

The experiments were performed in a dark room to avoid the ambient stray light, it is important for the measurement of $I-U$ data.

![Figure 3. The measured data at $N = 0$, $N = 1000$ and the corresponding fitted $I-U$ curves of the cell under the light intensity of 304W/m² and the ambient temperature of $T = 306k$.](image)

The parameters $n_0$, photocurrent $I_L$, reverse saturation current $I_0$, series resistance $R_S$ and parallel resistance $R_{SH}$ in (5) are fitted to the measured $I-U$ data for corresponding cyclic number. The fitted results are shown in table 1 where the damage variable $D$ is evaluated by (6). The fitted curves for $N = 0$ and $N = 1000$, for example, are plotted in Fig. 3.

| $N$ (cycles) | 0   | 100 | 200 | 300 | 400 | 600 | 800 | 1000 |
|-------------|-----|-----|-----|-----|-----|-----|-----|------|
| $R_S$ (Ω)   | 0.0122 | 0.0126 | 0.0124 | 0.0124 | 0.0127 | 0.0125 | 0.0122 | 0.0129 |
| $R_{SH}$ (Ω) | 21.021 | 22.203 | 22.853 | 23.405 | 22.974 | 23.103 | 22.974 | 23.103 |
| $n_0$ (nA)  | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| $I_L$ (A)   | 0.2762 | 0.2709 | 0.2669 | 0.2651 | 0.2624 | 0.2592 | 0.2579 | 0.2557 |
| $D$         | 0   | 0.0192 | 0.0337 | 0.0402 | 0.0499 | 0.0616 | 0.0663 | 0.0742 |

For the case where the amplitude of the cyclic loading is constant, the damage accumulation is nonlinear. The general form of the damage evolution equation can be expressed as (Lemaitre and Desmorat, 2005)

$$\frac{\partial D}{\partial N} = D^\alpha \left[ \frac{\sigma_m - \overline{\sigma}}{M(\overline{\sigma})} \right]^\beta$$  

(7)
where $\alpha$ is the parameter related to the maximum stress $\sigma_M$, the average stress $\bar{\sigma}$ and temperature $T$, and $M(\bar{\sigma})$ is the function of the average stress $\bar{\sigma}$, by integrating (7) we have

$$D = \left\{ (1-\alpha) \left[ \frac{\sigma_M - \bar{\sigma}}{M(\bar{\sigma})} \right]^{\beta} \right\}^{\frac{1}{1-\alpha}} \quad (8)$$

If $D_{CR}$ represents the critical fatigue damage, then the fatigue life of the cell is obtained from (8) as

$$N_F = \frac{D_{CR}^{1-\alpha}}{(1-\alpha)} \left[ \frac{\sigma_M - \bar{\sigma}}{M(\bar{\sigma})} \right]^{-\beta} \quad (9)$$

With inserting of (9) into (8), yields

$$D = D_{CR} \left( \frac{N}{N_F} \right)^{\frac{1}{1-\alpha}} \quad (10)$$

There are only two unknown parameters, $\alpha$ and $N_F$, in (10) when the critical fatigue damage $D_{CR}$ is pre-appointed.

The performance decay of the crystalline cells is in two aspects: photoinduced decay and the degradation caused by the damage development inside the solar cells. The former is due to the formation of boron-oxygen complex in crystalline silicon, which reduces the life of a few carriers and leads to the power loss of solar cells. In general, the photoinduced decay of crystalline cells can reach about 10% and then in stable state. The latter is mainly due to the external load such as wind load.

According to the relevant codes in China, the total performance decay of crystalline silicon cells during the service life (25 years) should be less than 20%, and thus the decay due to the damage development in the cells should be less than 10%, and then critical fatigue damage is taken as $D_{CR} = 0.1$. The parameters $\alpha$ and $N_F$ in (10) are obtained by fitting the experiment data in table 1 and the results are $N_F = 1645$, $\alpha = -0.919$. The fitted curve is shown in Fig. 4.

![Figure 4. The measured damage and the fitted curve](image)
4. Conclusion
In this paper, the fatigue damage evolution of crystalline solar cell under constant amplitude of the cyclic loading was studied experimentally. The damage of the cell was obtained from the measurement of the power loss of the cell. The damage evolution law of the cell was derived based on continuum damage mechanics. The results show that the damage accumulation in the cell is non-linear. For the building photovoltaic systems applied in some areas with high wind pressure, the damage development of the cells may result in the performance decay of crystalline silicon cells quickly. Therefore, the damage development in the cells caused by external load should be considered in the design.

5. Acknowledgements
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6. Reference
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