Fatigue Damage of Crystalline Solar Cell under Cyclic Loadings

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Abstract. In application of building attached photovoltaic (PV) in China, the wind loads are the main mechanical loading for the modules of the PV system installed on the roofs of the buildings. 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 damage evolution equation for solar cell was derived based on the continuum damage mechanics, the fatigue damage evolution in the solar cell was simulated by FE and the results are in good agreement with that of experiment.

1. Introduction
In recent years, photovoltaic has been widely used in China. A considerable numbers of PV modules are installed on roofs or integrated in buildings for sufficient sunlight. In this case, wind pressure is the main load of modules. For PV modules installed at this position, wind load is the most common external load besides gravity. Due to the fluctuation of wind load, the long-term effect leads to the development of the initial damage in the crystalline solar cells of photovoltaic modules and the decay of some electrical properties or overall failure.

It is one of the effective methods to predict the fatigue life of the structures by applying the continuous damage mechanics in the fatigue problem to derive the reasonable fatigue damage evolution equation. Chaboche and Lesne (1988) first applied the continuous damage mechanics (CDM) method to the fatigue problems. Lemaitre (1996) proposed the fatigue damage evolution equation based on the CDM method and the model was improved for the low cycle fatigue damage prediction (Yang et al, 1997) and the high cycle problem (Xiao et al, 1998). Later, this model was extended to the anisotropic damage problem (Lemaitre et al, 2000). During past years, some models in CDM framework were developed and applied for brittle or quasi-brittle materials (Richard et al, 2010; Richard and Ragueneau, 2013; Yadav and Thapa, 2020; Yang and Liu, 2020).

Despite the fact that some efforts on calculation of the stress and strain of the solar 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 is, however, not available in literature so far. In this paper, the damage accumulation and the development in the solar cell were calculation based on the Lemaitre’s model, then the ANSYS was used to simulate the evaluation of the fatigue damage evolution in the solar cell under cyclic loading and the results were compared to experiment.

2. Damage Evolution in Crystalline Solar Cell
Monocrystalline and polycrystalline silicon cells are mainly two types of the crystal solar cells in applications. In general, monocrystalline silicon is an anisotropic material (Li et al, 2008), its elastic
modulus in (111) crystal surface (about 140GPa) is lower than that of other two crystal surfaces (about 180GPa) while the anisotropy of polycrystalline silicon is much less than that of monocrystalline silicon. In the present analysis, for simplicity, the solar cell is assumed to be isotropic material and the damage variable $D$ is independent on the direction of cross section. For isotropic damage, the effective stress tensor of the cell is expressed as

$$\tilde{\sigma}_{ij} = \frac{\sigma_{ij}}{1-D}$$  \hspace{1cm} (1)$$

where $\sigma_{ij}$ represents the Cauchy stress tensor. When the isotropic damage is considered, the damage evolution law reads (Lemaitre and Desmorat, 2005)

$$\dot{D} = \dot{\lambda} \frac{\partial \psi_D}{\partial Y}$$ \hspace{1cm} (2)$$

where $\dot{\lambda}$ is the plastic multiplier, $\psi_D$ denotes the dissipative damage potential, $Y$ represents the strain energy density release rate

$$Y = \frac{\tilde{\sigma}^2_{eq}}{2E}$$ \hspace{1cm} (3)$$

$$\tilde{\sigma}_{eq} = \frac{\sigma_{eq}}{1-D}$$ \hspace{1cm} (4)$$

$$R_v = \frac{2}{3}(1+\mu) + 3(1-2\mu) \left( \frac{\sigma_H}{\sigma_{eq}} \right)^2$$ \hspace{1cm} (5)$$

in which $E$ and $\mu$ are the Young’s modulus and Poison ratio of the material, respectively, $R_v$ is the triaxiality function, $\tilde{\sigma}_{eq}$ is effective equivalent stress, $\sigma_{eq}$ and $\sigma_H$ are von Mises stress and hydrostatic stress, respectively:

$$\sigma_{eq} = \left( \frac{3}{2} s_{ij} s_{ij} \right)^{\frac{1}{2}}$$ \hspace{1cm} (6)$$

$$s_{ij} = \sigma_{ij} - \sigma_H \delta_{ij}$$ \hspace{1cm} (7)$$

$$\sigma_H = \frac{1}{3} \sigma_{kk}$$ \hspace{1cm} (8)$$

where $s_{ij}$ denotes the stress deviator, $\delta_{ij}$ is Kronecker symbol. Based on the experimental observations, Lemaitre and Desmorat (2005) suggested that the dissipative damage potential function $\psi_D$ can be expressed in a simple form as

$$\psi_D = \frac{s_0}{(s_1 + 1)(1-D)} \left( \frac{Y}{s_0} \right)^{s_1 + 1}$$ \hspace{1cm} (9)$$

where $s_0$ and $s_1$ are material parameters.

Crystalline silicon is a brittle material and the plastic deformation in macroscopic level or even in mesoscopic level can not be observed in the range of working temperature of the module, however, the micro-scale plastic strains always exist at the microcrack tips and the micro-scale defects. If $\pi$ denotes the microplastic equivalent strain, the plastic multiplier $\dot{\lambda}$ can be expressed in terms of the accumulated plastic strain rate $\dot{\pi}$ and the damage variable $D$ as
Assuming that the microplastic equivalent strain, \( \dot{\lambda} \), for the cyclic loading can be expressed in the form of the Ramberg–Osgood relation

\[
\dot{\lambda} = (1 - D) \dot{\lambda}
\]  

(10)

in which \( K \) is the cyclic strength coefficient, and \( n \) represents the cyclic strain hardening component. Substituting (3), (4), (5), (9), (10) and (11) into (2), yields

\[
\dot{D} = \frac{1}{nK^{1/n}} \left( \frac{R_s}{2Es_0} \right)^{s_1} \left( \frac{\sigma_{eq}}{\sigma_{eq}} \right)^{s_1} \sigma_{eq}
\]  

(13)

in which \( \alpha = 2s_1 + 1/n - 1 \). If \( \sigma_{eqM} \) and \( \sigma_{eqm} \) represent the maximum and minimum equivalent effective stress in the cycle number \( N \), respectively. The increment of damage per cycle can be obtained by integrating (13) in one cycle, we have

\[
\frac{\partial D}{\partial N} = \frac{1}{nK^{1/n}} \left( \frac{R_s}{2Es_0} \right)^{s_1} \int_{\sigma_{eqm}}^{\sigma_{eqM}} \left( \frac{\sigma_{eq}}{\sigma_{eq}} \right)^{s_1} \sigma_{eq} \, d\sigma_{eq} + \frac{1}{nK^{1/n}} \left( \frac{R_s}{2Es_0} \right)^{s_1} \int_{\sigma_{eqm}}^{\sigma_{eqM}} \left( \frac{\sigma_{eq}}{\sigma_{eq}} \right)^{s_1} \sigma_{eq} \, d\sigma_{eq}
\]  

(14)

At the constant temperature, the cyclic strength coefficient \( K \), the cyclic strain hardening component \( n \), and the parameters \( s_0 \) and \( s_1 \) are the material constants. The unknown parameters in (14) can be summarized as an undetermined parameter

\[
C = \frac{2}{(\alpha + 1)nK^{1/n}(2Es_0)^{s_1}}
\]  

(15)

and then the increment of the damage per cycle is rewritten as

\[
\frac{\partial D}{\partial N} = C[(\sigma_{eqM})^{s_1} - (\sigma_{eqm})^{s_1}] \frac{R_s^{s_1}}{(1 - D)^{s_1}}
\]  

(16)

3. FE Simulation

In this section, the cell damage evolution in the module of 1580mm×808mm is simulated via the finite element method. The laminated configurations of the module from the top to the bottom are 3.2mm glass panel, 0.5mm Ethylene-Vinyl Acetate (EVA) layer, 0.19mm cell layer, 0.5mm EVA layer and 0.35mm Tedlar/Pet/Tedlar (TPT) layer, respectively. Since the cells are separated by small gaps in the module, the calculation unit is cut down at the middle of the module with the size of 129mm×129mm which contains one 125mm×125mm cell only as shown in Figure 1(a).

The loads acting on the calculation unit are shown in Figure 1(b). The corresponding material parameters and the geometry of the layers are shown in Table 1 where \( E \) is young's modulus, \( t \) is the thickness of each layer, \( \mu \) is Poisson's ratio, and \( a \) is the side length. According to the experimental results (Eitner et al, 2010), the shear storage modulus of the EVA layer used in calculation is about 6MPa at the temperature of \( T = 306K \).

Since the size of the cell is about one order smaller compared to that of the glass panel of the module, it is reasonable to assume that the bending moment of the module within the calculation unit range is uniform. The \( x \)-axis of the cell is along the short side direction of the module while the \( y \)-axis is along the long side direction of the module in calculation. Under the wind pressure of 0.65kN/m², the
corresponding bending moments at the middle of the module are $M_x = 55.88 \text{Nm}$ and $M_y = 37.45 \text{Nm}$, respectively (Li and Yang, 2016).

**Table 1.** The parameters for the layers.

|                  | $E$(GPa) | $t$(mm) | $\mu$ | $a$(mm) |
|------------------|----------|---------|-------|---------|
| Glass panel      | 72       | 3.2     | 0.20  | 129     |
| Cell             | 180      | 0.19    | 0.27  | 125     |
| TPT layer        | 1.5      | 0.35    | 0.30  | 129     |
| EVA layer        | $G_{EVA} = 6\text{MPa}$ | 0.5 | 0.2 | 129 |

It should be noted that the uniform bending moment $M_x$ and $M_y$ in Figure 1(b) are applied to the glass panel, the upper and lower EVA layers, and the TPT layer, leave the cell free from the bending moment. In this manner, the loads of the cell are from the shear deformation of the upper and lower EVA layers, which is closed to the real situation for a separated cell layer.

![Figure 1](image1.png)

**Figure 1.** (a) The calculation unit of the cell; (b) The coordinates and the loads of the unit.

The upper and lower surfaces of the calculation unit are divided into $80 \times 80$ meshes, and in the thickness direction it is divided according to the material of each layer. The established and meshed finite element model is shown in Figure 2. In order to avoid rigid body movement and rotation during the analysis, the nodes located on the $x$-axis of the unit are constrained to move in $y$-direction while those located on $y$-axis of the unit are restrained from moving in $x$-direction.

The commercial software ANSYS is used to establish the fatigue damage model. The cycle-by-cycle method to calculate the damage accumulation is used in analysis. For each cycle, the material properties are considered as the constants to simplify the problem. The effect of the damage for each element in the cell is introduced by the reduction of the Young’s modulus. The module is subjected to pulsation load, i.e., $\sigma_{eqm} = 0$, in this case, the increment of the damage per cycle (16) reduces to
\[
\Delta D = C(\sigma_{eqM})^{\alpha+1} \frac{R^b}{(1-D)^{\alpha+1}}
\]  

(17)

For /th element at the /th cycle, the steps to evaluate the damage accumulation for each element in the cell as follow:

1. For /th element, the initial damage of the /th cycle is given by
\[
D_j(i) = D_j(i-1) + \Delta D_j(i-1)
\]  

(18)

2. The effective Young’s modulus of the element is replaced by \(E'_j = [1 - D_j(i)]E\) in calculation of the stress \(\sigma_{eqM}\).

3. The damage increment \(\Delta D_j(i)\) produced by this cycle is then evaluated by
\[
\Delta D_j(i) = C(\sigma_{eqM})^{\alpha+1} \frac{R^b}{[1-D_j(i)]^{\alpha+1}}
\]  

(19)

In this manner, the damage evolution for each element in the cell can be calculated cycle by cycle. After finished the /th cycle, the damage of the /th element in the cell is expressed as
\[
D_j = D_j(i) + C(\sigma_{eqM})^{\alpha+1} \frac{R^b}{[1-D_j(i)]^{\alpha+1}}
\]  

(20)

in which \(\alpha = 2s_k + 1/n - 1\). The average damage \(D\) of the cell is calculated by
\[
D = \frac{1}{V_0} \sum_{j=1}^{m} D_j V_j
\]  

(21)

where \(V_j\) and \(D_j\) are the volume and damage variable of the /th element, respectively, and \(V_0\) is the total volume of the cell.

**Figure 3.** The average damage from the FE simulation and compared to experiment.

The parameters \(C\), \(\alpha\), \(n\) and \(s_k\) in (21) are obtained by fitting the experimental data in Li (2013) and the results are shown in table 2.

| \(C\)       | \(\alpha\) | \(n\)  | \(s_k\)  |
|------------|------------|-------|----------|
| \(3.7 \times 10^{-10}\) | \(-0.5\)    | 0.034 | \(-14.456\) |

Table 2. The fitted parameters of the cell.
The comparison of the average damage evolution of the cell evaluated from FE and the experimental results in Li (2014) are plotted in Figure 3. It can be seen that the results from the FE simulation are in good agreement with those of the experiment.

4. Conclusion

The damage evolution equation based on the Lemaitre’s model for solar cell was derived. The damage accumulation formula for cycle-by-cycle calculation was established and the ANSYS was employed to simulate the damage evaluation in the cell. The numerical results are in good agreement to those of the experiment.

Acknowledgements

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