THERMOMECHANICAL DESIGN RULES FOR PV MODULES

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ABSTRACT: We present a set of thermomechanical design rules to support and accelerate future PV module developments. The design rules are derived from a comprehensive parameter sensitivity study of different PV module layers and material properties by finite element method simulations. We develop a three-dimensional FEM model, which models the PV module geometry in detail from busbar and ribbons up to the frame including the adhesive. The FEM simulation covers soldering, lamination and mechanical load at various temperatures. The FEM model is validated by mechanical load tests on three 60-cell PV modules. Here, for the first time, stress within a solar cell is measured directly using stress sensors integrated in solar cells (SenSoCells®). The results show good accordance with the simulations.

The parameter sensitivity study reveals that there are two critical interactions within a PV module: (1) Between ribbon and solar cell. (2) Between front/back cover and interconnected solar cells. Here, the encapsulant plays a crucial role in how the single layers interact with each other. Therefore, its mechanical properties are essential and four design rules are derived regarding the encapsulant. Also, four design rules concern front and back side and three address the solar cells. Finally, two design rules each deal with module size and frame, respectively. Altogether we derive a set of 15 thermomechanical design rules.

As a rule of thumb of how well a bill of material will work from a thermomechanical point of view, we introduce the concept of specific thermal expansion stiffness $\hat{E}_\alpha = E \cdot \alpha \cdot A_\mathrm{j} \cdot h$ as the product of Young's modulus E, coefficient of thermal expansion α, joint area A_j and materials height h. The difference between two materials is a measure of how much thermal strain one material can induce in another. A strong difference means that the material with the larger value will induce thermal strain in the other.

Keywords: PV Module, Design, Module Manufacturing, Modelling, FEM Simulation, Durability, Reliability

1 INTRODUCTION

Stress in solar cells plays a crucial role in the reliability of photovoltaic (PV) modules. Influences on stress are as diverse as the number of different materials in a PV module and become more and more complex with growing variety of PV modules for different applications. Nevertheless, the bill of materials development for new PV modules is often a try and error, which is very time and cost consuming. The finite element method (FEM) in combination with material characterization offers an approach for digital prototyping, which has the potential to reduce the amount of needed physical prototypes significantly. Accordingly, FEM simulations are frequently used in research as the review from Nivelle *et al.* [1] shows. The aim of this work, which is conducted within a dissertation [2], is to derive general thermomechanical design rules for PV modules on the base of a parameter sensitivity study performed with a detailed 3D FEM model of a 60-cell PV module, including ribbons and frame. Additionally, a factor for the quick and straight forward thermomechanical assessment of materials, called specific thermal expansion stiffness $\hat{E}_\alpha$ is introduced. The full version of this paper is published in Progess on Photovoltaics [3].

2 METHOD

The basis of the design rules is a comprehensive parameter sensitivity study conducted with a detailed 3D FEM model of a 60-cell PV module using COMSOL Multiphysics. Intermediate versions of this FEM model have been published previously [4–6]. It covers a simplified soldering process (cooling from 179 ° to 25 °C), lamination (cooling from 150 °C to 25 °C) and homogeneous surface load of 2400 Pa at different temperatures. The stress tensor from each study is transferred to the subsequent study at the temperature at which the subsequent study starts. For more details, we refer to [2].

The parameter sensitivity study consists of 72 parameter combinations covering the material properties shown in Table 1, different frame materials (aluminum, steel, wood), solar cell dimensions and formats as well as module sizes for glass-foil and glass-glass modules. The results of the size variation have been published previously [6]. The results are evaluated according to stress, cell fracture probability P_f and deflection d. For a detailed description of used parameters as well as simulation results, we refer to the authors open access dissertation [2]. In this article, we focus on the design rules themselves.

Table 1: Variation of PV module layer material properties.

	Front/back cover	Encapsulant	Solar cells
Young's modulus E	x	x	
CTE α	x		
Height h	x	x	x

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We find two major stress causes:

1. The mismatch of thermal expansion when exposed to temperature differences.
2. The curvature of PV module and solar cells when exposed to mechanical loads.

Table 2: Derived Thermomechanical design rules clustered by component. The magnitude of the influence on the stress within the solar cells is given in the last column, with increasing magnitude from + to +++.

Component	Design Rule	Influ-ence
Encapsulant	Sharp melting point with a sudden increase of the Young's modulus E_e.	+
	Sharp glass transition with a sudden increase of the Young's modulus E_e.	+
	The encapsulants specific thermal expansion stiffness $\hat{E}_{\alpha,\mathrm{e}}$ should be between the ribbon $\hat{E}_{\alpha,\mathrm{r}}$ and solar cell $\hat{E}_{\alpha,\mathrm{c}}$ value: $\hat{E}_{\alpha,\mathrm{r}} < \hat{E}_{\alpha,\mathrm{e}} < \hat{E}_{\alpha,\mathrm{c}}$.	++
	Low thickness, given that there is sufficient material between ribbon and front- and backsheet and that the critical stress originates from the solar cell-ribbon interaction.	+
Front/Back Cover	At least one stiff layer is needed with a minimum thickness. For soda-lime glass around 3 mm.	++
	The CTE of stiff layers should have a value between the one of the solar cell and ribbon: $\alpha_\mathrm{c} < \alpha < \alpha_\mathrm{r}$. In symmetric module designs more critical.	+++
	A larger CTE of the backsheet is advantageous for push loads: $\alpha_\mathrm{bs} > \alpha_\mathrm{fs}$.	+
	For minimal bending stress: Place the solar cells in the neutral axis, e.g. by a symmetrical module design.	++
Solar Cells	High solar cell thickness.	++
	Small solar cell edge length.	+
	Split cells: Alignment of the shorter side along the higher curvature.	+
PV Module Size	Smaller module area decreases stress.	+
	Module aspect ratio: Longer modules instead of wider modules (for mounting on long side and non-extreme ratios).	+
Frame	The higher the frames stiffness, the better.	+
	Frame design has to be adapted to specific module design.	+

The first one is responsible for compressive stress of solar cells after lamination as well as high tensile stress at the end of the ribbon, which dominates the cell fracture probability P_f.

The second one is responsible that corner solar cells show tensile stress although the deflection from mechanical load is minimal (see Figure 1). For different mounting solutions, like frameless modulus with laminate clamps it could be shown that the highest tensile stress even occurs at the position of the largest curvature instead of the largest deflection [5].

Both causes interact with each other and should not be analyzed separately. Regarding the layer interfaces, we have identified two critical interactions:

1. Between ribbon and solar cell.
2. Between front/back cover and interconnected solar cells.

The thermomechanical design rules reflect these influences. They are summarized in Table 2. For more details we refer to the full paper version [3] as well as the authors open access dissertation [2].

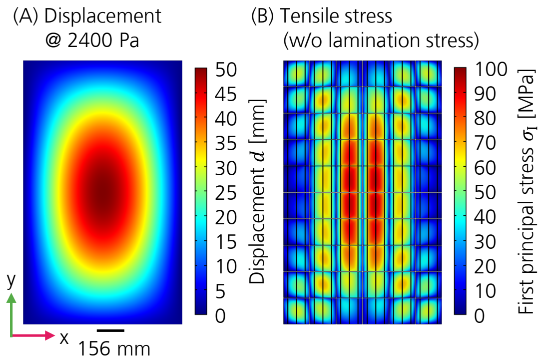

Figure 1: Displacement d at 2400 Pa mechanical load (A) with corresponding first principal stress σ_I in solar cells, neglecting stress after lamination (B). Modified after [2].

4 CONCLUSION

There are many and often entangled influences on stress within solar cells, which we summarize in the derived 15 Thermomechanical Design Rules. Additionally, we introduce the specific thermal expansion stiffness $\hat{E}_\alpha = E \cdot \alpha \cdot A_\mathrm{j} \cdot h$ to characterize PV module materials easily and straightforwardly according to their influence on the thermomechanics.

We derive the design rules from a comprehensive parameter sensitivity study using a manifold approach: FEM simulations complemented by solar cell integrated sensors as validation. The developed FEM model covers the PV modules geometry in detail, from the busbar metallization until the frame. The analysis of the parameter sensitivity study results show that some phenomena are only revealed by this multi-scale approach.

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