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Influence of Material Models on the Numerical Predictions of Thermomechanical Behavior of Silicon Photovoltaic Modules

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Abstract. Silicon photovoltaic (PV) modules are made using different materials, namely glass, EVA, silicon, and a backsheet material such as PET. To develop a numerical thermomechanical PV module model capable of providing accurate predictions, the influence of the material models on the predictions must be analyzed. A two-dimensional, thermomechanical, finite-element (FE) model of PV modules was created, and it was able to reproduce some experimental measurements. It was then used to study the influence of the material models on the numerical predictions. Attention was given to the material models of EVA and silicon. Firstly, the material model of EVA was considered, and the predictions of the following models were compared: linear elastic, temperature-dependent linear elastic, and viscoelastic. Secondly, as the coefficient of thermal expansion (CTE) plays a major role in the thermomechanical behavior, the influence of its temperature dependence on the predictions was compared. The numerical results show that it is necessary to use a viscoelastic EVA model to reproduce the experimental data of the change in cells gap. It was also found that the temperature dependence of the CTE of EVA and silicon has significant influence on the module deflection and stress, hence it should be taken into consideration in future numerical studies.

Keywords: Photovoltaic Modules, Thermomechanics, Numerical Simulation, FEM

1. Introduction

Throughout their lifetimes operating outdoors, silicon PV modules experience a variety of environmental factors, such as temperature changes, UV light, and humidity. These environmental factors can lead to the degradation of the module's materials [1] and the subsequent appearance of failure modes that affect the performance of PV modules and might lead to their complete failure [2]. Examples of failure (or degradation) modes are the delamination of the layers, cell cracking, corrosion, hotspots, and glass soiling.

PV modules are made of five main layers; a front transparent panel, two encapsulant layers that surrounds the PV cells, a matrix of PV cells, and a backsheet. Commonly, the front panel is made of glass, the encapsulant layers of EVA, the cells of silicon, and the backsheet of polymers such as PET [3]. The typical structure of a PV module is shown in Fig. 1.

The materials that constitute a PV module have different CTEs, and since PV modules' layers are adhered together, a temperature change results in internal stresses. These internal stresses can drive some of the failure modes as they strain PV modules' materials and the adhesion between the layers [5]. Hence, to increase the reliability of PV modules and their operational lifetime, and to decrease the severity of the degradation modes, it is necessary to have a better understanding of the internal thermomechanical stresses that arise during operation. One approach to this end is to model and simulate the thermomechanical behavior of PV modules using the finite-element method (FEM), which is the approach used in this work. Furthermore, different material models can be used to describe a material's behavior. In this work, the influence of the choice of material models implemented in a finite-element PV module model on the numerical predictions will be explored.

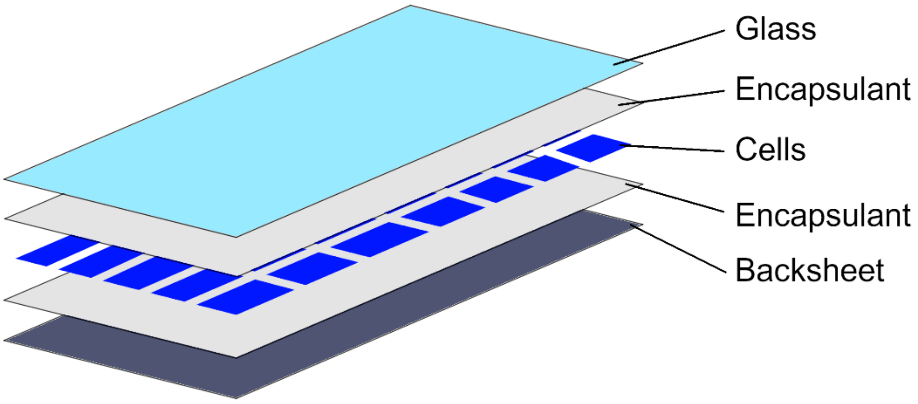

Figure 1. The main five layers of PV modules (adapted from [4]).

2. Thermomechanical modeling and simulation

The mechanical behavior of the materials that constitute a PV module can be described, or modeled, using different constitutive equations (material models). One of the challenges in creating a numerical model that provides accurate predictions is the choice of material models. In this work, different material models will be considered, and their predictions will be compared to better understand their influence on the numerical predictions.

The mechanical behavior of glass can be considered as being linear elastic, with a constant CTE. This is due to the fact that PV modules operate at temperatures well below the glass transition temperature of glass (550°C) [5], [6]. PET is considered as a backsheet material in this work, and its behavior can be considered as linear elastic with a constant CTE [7]. EVA is commonly modeled as a linear elastic or temperature-dependent linear elastic material in literature despite having a strong time-dependent behavior which can be modeled by viscoelasticity [5], [8]. Therefore, the three material models will be considered.

Material CTEs play a major role in the thermomechanical behavior of PV modules. The CTE of EVA varies greatly with temperature [8], hence the influence of its temperature dependence on the mechanical behavior of a module is of interest. Silicon, which can be modeled based on its bulk behavior [9], can be approximated as a linear elastic material, but its CTE varies significantly across different temperatures [10], [11], hence it also is also of interest. The temperature dependence of the CTEs is not always considered in the literature [7], [12], this emphasizes the importance of understanding their influence. Therefore, the influence of the temperature dependence of the CTEs of EVA and silicon on the thermomechanical behavior will be considered.

An important aspect of creating an accurate numerical model is the model validation using experimental data. In the literature, different experimental measurements were used to validate numerical models, such as: module deflection [13], micro-Raman spectroscopy measurement [14], and the change in the gap between the cells [9].

In this work, the change in the gap between the cells measurements will be used to validate the numerical model [9]. In the experiment, a module made of three cells, as shown in

Fig. 2, was laminated, left at room temperature for 24 hours, and then the temperature was increased then decreased. The temperature profile is shown in Fig. 3. While the module temperature was measured, the change of gap (distance) between the cells was measured using high resolution cameras. The change in the gap between the cells was recorded right before the temperature increase from room temperature (22°C), at which the change in cells gap was considered to be equal to zero (reference). All the details of the experimental set-up including the geometry, temperature profile, and measurements can be found in [9]. The experimental data allows the validation of the numerical PV module model and the comparison of the accuracy of the predictions of different material models.

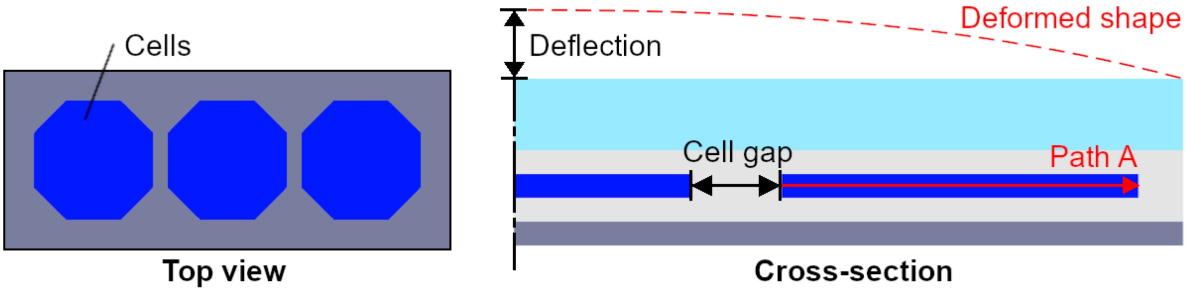

Figure 2. A schematic diagram of the three-cell module, showing the locations of the cells gap, the deflection, and path A along the cell.

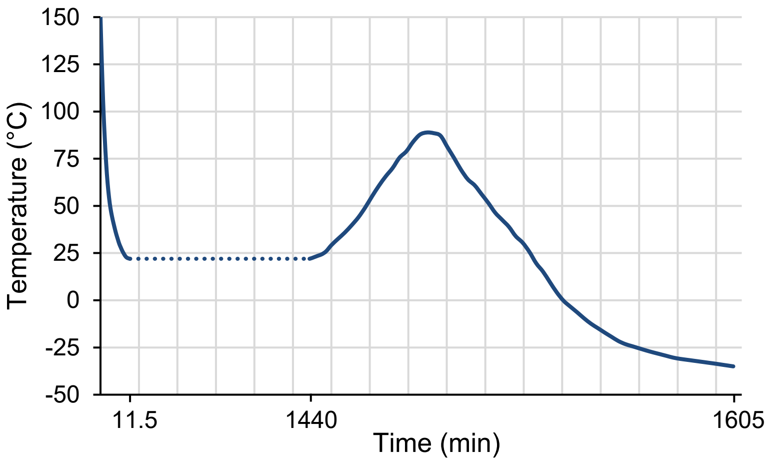

Figure 3. Temperature profile of the cells gap experiment as a function of time [9].

A two-dimensional (2D), FE thermomechanical model of the experimental PV module was created using the commercial software ABAQUS/Standard. Due to the high aspect ratio of the geometry of PV modules, that is the ratio of the length or width to the thickness, a very large mesh is required to model them. To reduce the computational cost, a 2D plain-strain assumption is considered. Convergence studies on the element type, element size, and time step size were done to arrive at a model that is independent of the mesh and time step size. Quadrilateral, full integration elements with linear basis functions (CPE4) were chosen, and the mesh had 46,000 elements in total. As PV modules are manufactured at around 150°C, which is the temperature at which EVA cures, it is considered to be the stress-free temperature [9]. In order to accurately simulate the internal stresses, the cooling of the PV module from the manufacturing temperature and the associated internal stresses were simulated.

After considering several combinations of material models, the simplest set of models whose predictions were able to follow the experimental data closely were taken as the reference models. The reference material models are: linear elastic model for the glass, silicon, and PET, linear viscoelastic model for EVA, and constant CTEs for all materials. The values of the parameters of the reference material models are listed in Table I. Any variation from the set of reference models will be explicitly mentioned. The temperature-dependent Young's modulus of EVA was taken from [15] at the lowest strain rate, and the value of a constant Young's modulus was taken at 22°C and is equal to 6.91 MPa. The temperature dependence of the CTE of EVA can be found in [8], and for the silicon in [10], [11], they are plotted in Fig. 4.

Table 1. Reference material parameters.

Material	**Young's Modulus (GPa)**	**Poisson's Ratio**	**CTE (10^{-6} 1/K)**
Glass [9]	73	0.24	8
EVA [8]	Viscoelastic	0.49	310
Silicon [9]	130	0.28	2.49
PET [9]	3.5	0.29	50.4

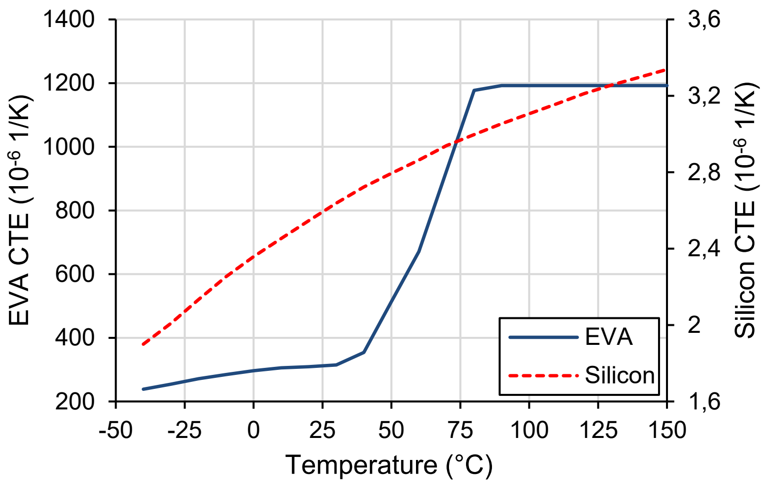

Figure 4. Temperature-dependent CTE curves of silicon and EVA [8], [10], [11].

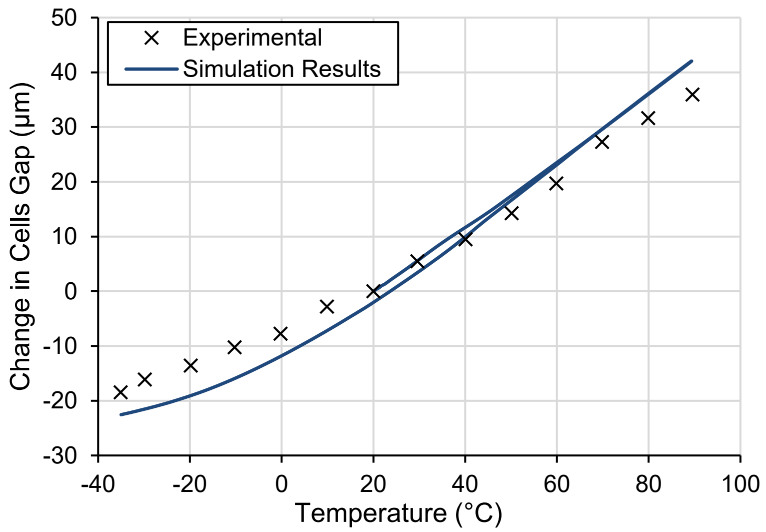

Figure 5. The numerical predictions of the change in cells gap using the reference material models. (Experimental data taken from [9]).

Fig. 5 shows the numerical predictions using the reference material models of the change in the cells gap against the experimental measurements. The numerical predictions are in good agreement with the experimental data and they follow the curved appearance of the experimental points. The developed FE model can now be used as a platform to understand the influence of the material models on the numerical predictions.

3. Numerical results

Various material models are used in the literature to simulate the thermomechanical behavior of PV modules. To highlight the influence of the choice of material models on the numerical thermomechanical predictions in PV modules, the predictions of several models will be compared in this section. Three material models of EVA and the temperature dependence of the CTE of EVA and silicon will be considered.

The numerical predictions of the change in cells gap will be compared to the experimental data. To further compare the predictions of the different material models, the predictions of the deflection of the module are compared for the full simulation time. The deflection used in this work is marked on the schematic in Fig. 2, which is the vertical displacement of the center of the glass's free surface relative to its edges. This particular choice of deflection is independent of the change in the module's thickness due to temperature change, and allows the study of the influence of the different material models on the numerical global bending behavior of the module. The influence on the stress levels in the cells will also be compared at two temperatures: 22°C after the initial cooling, and -35°C. While no experimental data of the deflection and stress exists to compare against, these comparisons give insight into the influence of the material models on the numerical predictions of a PV module's thermomechanical behavior.

3.1 Influence of EVA material model

The influence of three material models on the numerical predictions will be considered in this section: viscoelastic model, linear elastic model, and the temperature-dependent linear elastic model. Regarding the change in cells gap, the numerical predictions of the three material models of EVA are shown in Fig. 6(a). Only the predictions of the viscoelastic model are in good agreement with the experimental data, in addition to following its curved shape. The predictions of the temperature-dependent linear elastic model, surprisingly, greatly deviate from the measurements. The temperature considered as the reference temperature, that is where the change in the gap is considered to be zero, is 22°C. If the curves in Fig. 6(a) were shifted such that the reference temperature is 90°C, then a better agreement between the temperature-dependent linear elastic model and the experimental data is achieved until 60°C. At temperatures below 60°C, the time-dependent behavior of EVA becomes significant [15], which is not taken into account in the temperature-dependent linear elastic model. The viscoelastic model, on the other hand, accounts for both the temperature and time-dependent behavior of EVA. The predictions of the linear elastic model are close to the measurements above 20°C, but this model is unable to reproduce the measurements on the full temperature range. These results are in agreement with the results of [9].

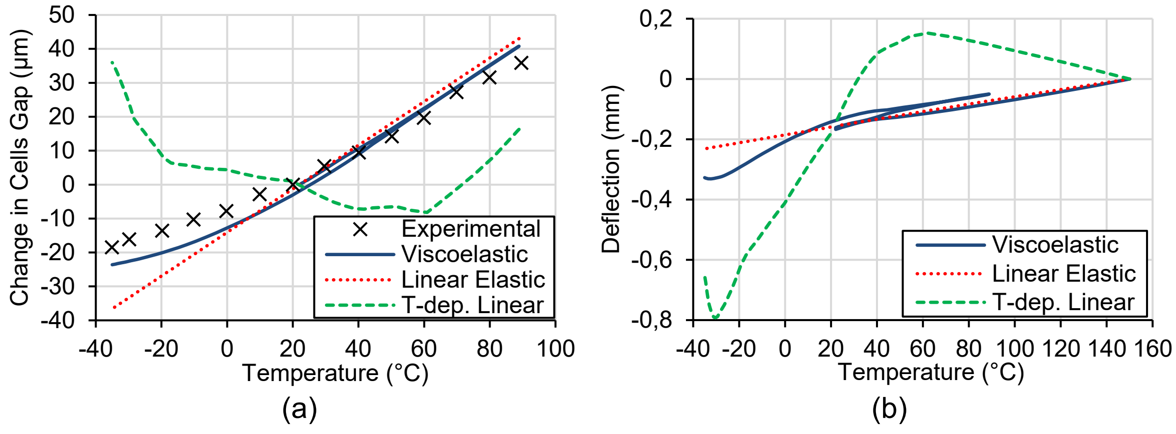

Figure 6. Numerical predictions of different EVA models: (a) change in cells gap, and (b) module deflection (experimental data taken from [9]).

The deflection predictions of the three models are shown in Fig. 6(b), and their significant differences emphasize the importance of the choice of EVA material model. Furthermore, the time-dependent behavior of EVA has a significant influence on the module's behavior, this is demonstrated by the deflection predictions of the viscoelastic model showing hysteresis. Fig. 7 shows the stress along the cell's length (path A, shown in Fig. 2) at two temperatures. Significant differences in the predictions of the three models were also found. In Fig. 7b, the temperature-dependent linear model of EVA seems to overestimate the stress levels in PV cells, whereas the linear elastic model seems to underestimate the stress levels. The stress predictions are in agreement with the deflection predictions, Fig. 6b.

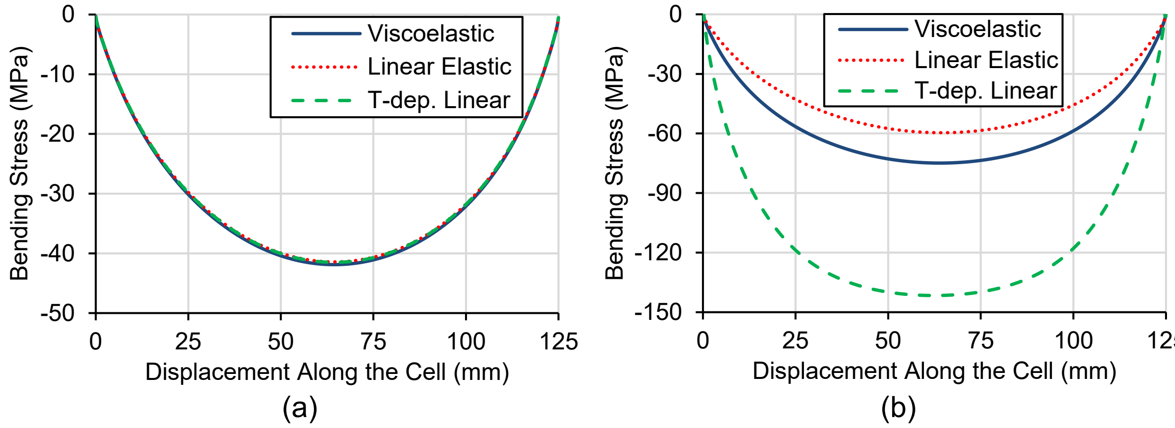

Figure 7. Numerical predictions of different EVA models of the cell stress: (a) at 22°C, and (b) at -35°C.

3.2 Influence of CTE temperature dependence

The influence of the temperature-dependance of the CTEs of silicon and EVA on the numerical predictions will be considered in this section. For constant CTEs, a "C" abbreviation is used, and for temperature-dependent CTEs, a "D" abbreviation. Four cases are established by combining the two CTE types of both materials; silicon and EVA.

Regarding the change in cells gap, the numerical predictions of the four cases are shown in Fig. 8(a). The four cases provide very similar predictions. But when considering module deflection, the numerical predictions have significant differences. Fig. 8(b) shows the numerical prediction of the deflection. The use of the temperature-dependent CTE for either the EVA or silicon results in a significant change in the predictions, and combining both results in even greater change.

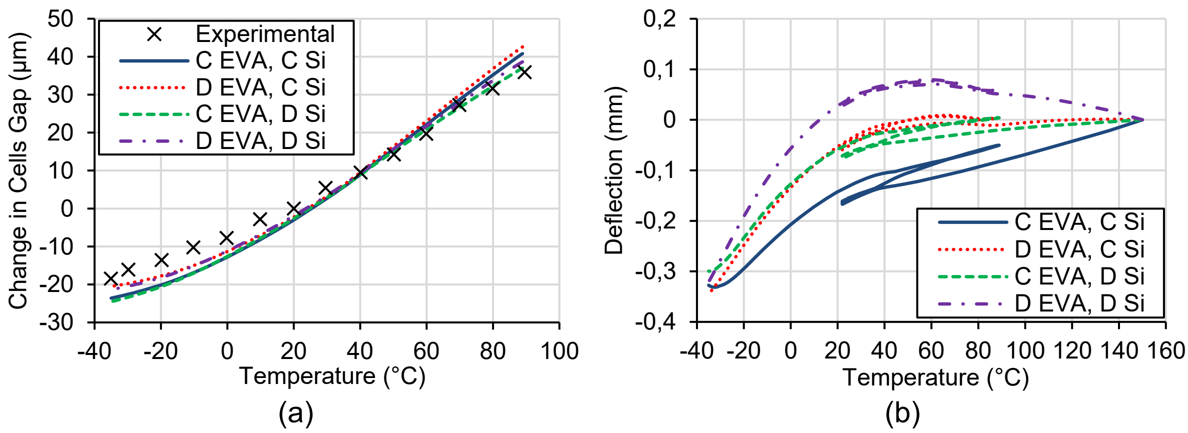

Figure 8. Numerical predictions of different CTE models of EVA and silicon: (a) change in cells gap, and (b) module deflection (Experimental data taken from [9]).

It's clear that the temperature dependence of the CTEs of EVA and silicon has a significant impact on the numerical predictions and should be considered in numerical PV module models. Since the four cases give similar predictions of the change in cells gap and varying predictions of the deflection, it can be concluded that the change in cells gap measurements are not sufficient to fully validate a PV module model. Fig. 9 shows the stress along the cell's length (path A shown in Fig. 2) at two temperatures. Similar to the comparison of EVA models, significant differences in the predictions of the CTE models were found. While the temperature dependence of the CTE of EVA doesn't have a significant influence on the stress levels in the cells, the temperature dependence of the CTE of silicon does. Hence, when conducting a numerical study of the thermomechanical stresses in PV modules' cells, it's necessary to at least consider the temperature dependence of the CTE of silicon.

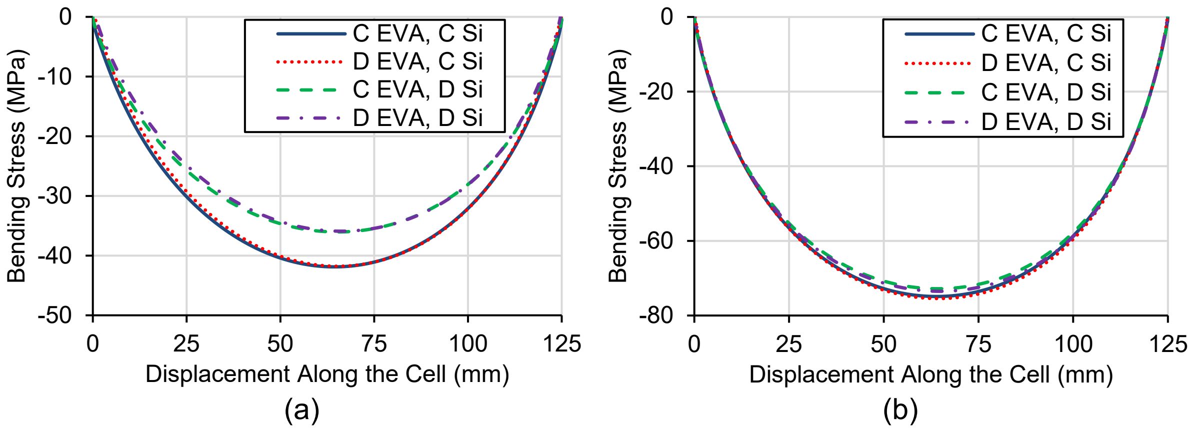

Figure 9. Numerical predictions of different CTE models of the cell stress: (a) at 22°C, and (b) at -35°C.

4. Conclusion

A 2D FE model of a silicon PV module has been created and was able to reproduce some experimental measurements available in the literature, and the numerical predictions of different material models have been compared. It was found that it is necessary to account for the viscoelastic effects of the EVA behavior to validate the numerical model. Furthermore, the choice of material model of EVA has a significant influence on the numerical predictions of the change in cells gap, the deflection and stress levels in the cells. It was also found that the numerical predictions of the PV module's deflection and stress in the cells vary greatly when considering the temperature dependence of the CTEs of EVA and silicon. This emphasizes the importance of considering them, and they should be included in future simulations. Finally, it was concluded that the change in cells gap measurements are not sufficient to fully validate a numerical PV module model.

Data availability statement

Data will be made available on request.

Author contributions

S. Al-Manaseer was responsible for designing and writing the study. S. Touchal and J.P.M. Correia contributed to providing critical revisions to this article. All authors read the final manuscript and approved that it was true.

Competing interests

The authors declare no competing interests.

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