

Thermo-Mechanical Stresses of Silicon Photovoltaic Modules

Michael Owen-Bellini*, Jiang Zhu, Thomas R. Betts, Ralph Gottschalg

Centre for Renewable Energy Systems Technology, Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU

* Corresponding Author: M.Owen-Bellini@lboro.ac.uk

Abstract

Modelling and analysis of the thermo-mechanical behaviour of silicon photovoltaic (PV) modules has been conducted using finite-element numerical methods (FEM). Experimentally determined material properties have been implemented in the model to represent the 6-cell mini-modules fabricated at the Centre for Renewable Energy Systems Technology (CREST). The stresses generated during indoor accelerated ageing tests and real outdoor conditions have been compared. It is found that the thermo-mechanical stresses are highest at the extreme temperatures during indoor testing. The outdoor accumulated stress generated within the interconnecting ribbons is greater than the stress generated during indoor thermal cycling programs for the same amount of temperature travelled. The results shed light on the relevance of indoor accelerated ageing programs to real outdoor conditions.

Introduction

Solder bond failures, cell cracks and encapsulant delamination are mechanisms which contribute significantly to the degradation of modules. Such mechanisms can be attributed to the unavoidable thermo-mechanical strains which are induced during normal operation of the devices [1-2]. Mismatches in material properties, most notably the coefficient of thermal expansion, results in the generation of compressive and shear stresses within the module components. Thermo-mechanical degradation mechanisms have previously been identified as critical. They are tested for in type approval tests [3]. The tests are largely empirical in nature and whilst they are useful in identifying critical issues with module designs, they are no predictor of service life. The complexities of the outdoor environments and a lack of understanding of the mechanical behaviour of modules

are some of the reasons why such tests have not been improved upon.

The complex nature of PV module assemblies makes it difficult to measure the internal stresses. In this work, the finite-element method is employed to estimate the stresses and strains which are generated during indoor accelerated test conditions and in outdoor conditions at Loughborough. The results presented highlights the relevance of indoor accelerated ageing to long-term fatigue and service life estimations for field deployed modules.

Finite-Element Model

Geometry

A finite-element model has been developed to reflect the mini modules which are produced at CREST. The modules contain six mono crystalline silicon cells connected in series via solder-coated copper-based ribbons. The active circuit is encapsulated in ethylene vinyl-acetate (EVA) which binds together a float glass front cover and polymeric backsheet. The dimensions for each component have been summarised in Table 1.

Component	Length	Width	Height
Cell	156	156	0.22
Glass	538	359	2.9
EVA	538	359	0.62
Backsheet	538	359	0.41
Ribbons	Var.	1.5	0.13
Solder	Var.	1.5	0.02

Table 1: Dimensions of the elements in the modules, mm

Symmetry boundary conditions have been applied which effectively halves the model and reduces the computational requirements without compromising the accuracy of the results. The screen capture

in Figure 1 demonstrates a cross-sectional view of the model, focusing on the interconnection between two cells.

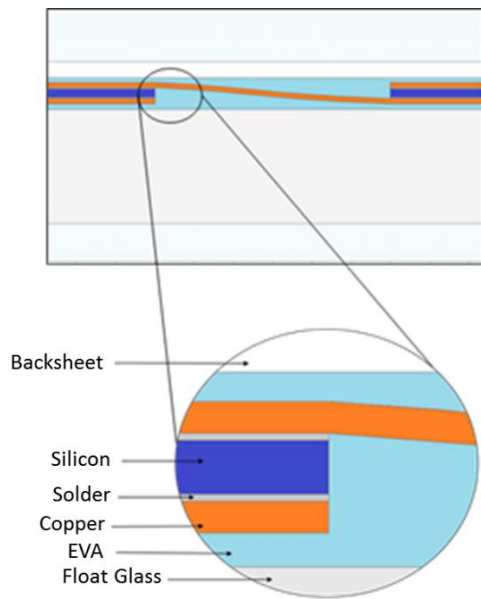


Figure 1: Cross-sectional screen capture for the FEM model

Material Properties

User-inputted material properties are required for FEM simulations. The relevant properties in this model are the coefficient of thermal expansion (CTE), Young's Modulus (or Shear Modulus) and Poisson's ratio. To get the most accurate results, it is important to provide the model with accurate material property values. These have been obtained experimentally for the materials used in the modules produced at CREST. The glass, ribbons and backsheet all exhibit linear material properties, such that determining their values is relatively simple. For CTE and Young's modulus, a TA Instruments Q400 thermomechanical analyser is used. EVA is a complex polymer with viscoelastic properties and as such requires a more complex modelling approach to capture its behaviour.

Viscoelasticity of EVA

Viscoelasticity describes materials which exhibit both elastic and viscous characteristics. For an applied strain, the generated stress is dependent on both temperature and time. This kind of behaviour can be significant when considering the range of operating temperatures and the rate of change of temperature experienced by PV modules.

According to the Generalised Maxwell Model, the viscoelastic behaviour of a material can be represented as a number of spring-dashpot elements combined in parallel. The springs and dashpots represent the elastic and viscous portions of a single Maxwell element, respectively. The model requires that the elasticity and viscosity of each Maxwell branch be quantified. The necessary values can be determined experimentally using a TA Hybrid-2 rheometer. Storage (or shear) modulus is measured over a range of oscillatory frequencies at multiple isotherms ranging from -40 to 150°C in steps of 10°C. The measurements can then be fit to the Generalised Maxwell model to determine the number of Maxwell elements required, and the Maxwell element parameter values.

Stress relaxation is indicative of viscoelastic behaviour and can be used to validate the model. A rapid step deformation is applied to a small sample of EVA, and the stress required to hold that deformation is measured over time such that relaxation can be observed. The experiment is conducted with the same rheometer at isotherms of -20, 0, 40 and 80°C. The same experiment is then modelled in COMSOL Multiphysics, with the Generalised Maxwell Model parameters applied to the material properties of EVA. Figure 2 below demonstrates the models suitability to capturing the relaxation behaviour (and therefore viscoelastic behaviour) of the EVA, with an observed root mean squared error of 0.12.

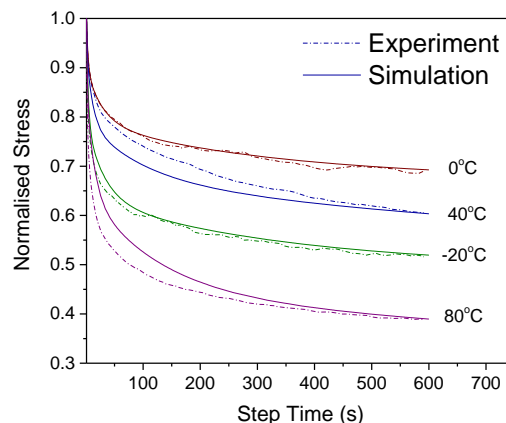


Figure 2: Simulated and measured stress relaxation test used as a means of validating viscoelastic model

The material properties for all components have been summarised in Table 2.

Component	CTE ($10^{-6}/K$)	Young's Modulus (GPa)	Poisson Ratio
Cell	2.6	170	0.28
Glass	9	73.1	0.17
EVA	Viscoelastic		0.49
Backsheet	150	3.2	0.4
Ribbons	17	110	0.35
Solder	10	10	0.4

Table II: Summary of material properties used in the simulations

Loading Conditions

Loading conditions are required to simulate the effect that external forces have on the model. In this case, module operating temperatures are applied to simulate the thermally-induced mechanical strains. Two thermal profiles are used. Case A is the indoor accelerated temperature profile which are applied during accelerated ageing testing procedures. Case B is module temperature measurement data taken directly from the rear surface of modules installed at the outdoor monitoring facility at CREST for a typical day in June. For simplicity, module temperature is assumed to be homogenous through all components. Total temperature travelled is the absolute sum of the temperature changes during a period of time. Here it is used as a means of normalising the thermal profiles used. One cycle from Case A is equivalent to 250°C travelled. For 1 day of real data in case B, the total temperature travelled is 501°C, approximately equivalent to 2 thermal cycles.

Mechanical Behaviour

Applying case A allows the mechanical behaviour to be observed at the extreme temperatures. The stresses observed in the glass and backsheet (Figure 3) reveals more about the behaviour at low temperatures and the reasons for mechanical deformation. The colour bar represents the Von Mises stresses which are highest in the backsheet and inner surface of the glass. The arrows represent the 3rd principal stresses, and are effectively a representation of the type of stress, with red and blue arrows

representing tensile and compressive stresses, respectively.

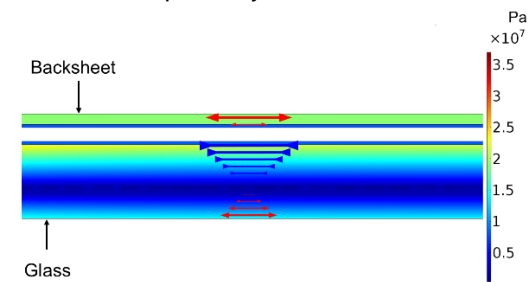


Figure 3: Stresses on the backsheet and glass at -40°C. Colour bar represents Von Mises stress and arrows indicate 3rd Principal Stress

The 3rd principal stress indicates that the backsheet and front surface of the glass are in high tension, whereas the inner surface of the glass is in compression. This behaviour can be attributed to the mismatch in coefficient of thermal expansion, which is much greater in the backsheet than the glass. As the module temperature decreases, the backsheet tries to shrink faster than the other components. Without the freedom to shrink as required, the backsheet is pulled in tension. The contraction of the backsheet and EVA pulls on the glass, which does not contract as rapidly. This causes the module to bend and applies stresses on the cells and interconnects. The negative values for 3rd principal stresses on the cells, as shown in Figure 4, reveals that they are under high compressive stress due to the contraction and deformation of the other components. Such stresses can be responsible for the initiation and propagation of cracks. The maximum compressive stress on the cell for case A was found to be 145MPa, whereas for case B it was found to be much less at 94.7MPa.

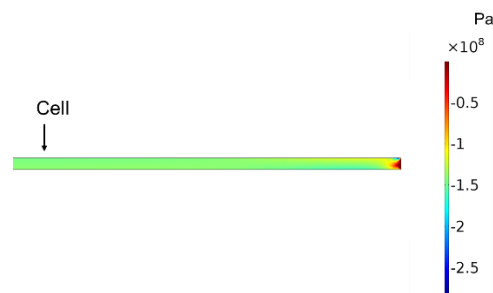


Figure 4: 3rd Principal stress observed on the silicon cells

Contraction of the assembly forces the cells to move closer together. This displacement generates shear stresses on the interconnecting ribbons and solder bonds.

The stress tensor in the x-direction for the interconnections are shown in Figure 5. It is seen that the stress is lower on the ribbon bend between the cells due to its flexibility and freedom to move as the cells move closer.

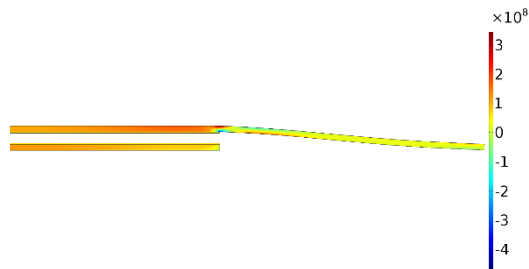


Figure 5: Stress tensor in the x-direction on the interconnecting ribbon and solder

Stress Accumulation of Solder Bonds

Degradation of solder bonds is the critical failure mechanism attributed to thermomechanical degradation. For each thermal profile case, the accumulated stress on the solder bonds is calculated. It is shown in Figure 6 that the accumulated stress on the solder bonds is highest in the outdoor environment.

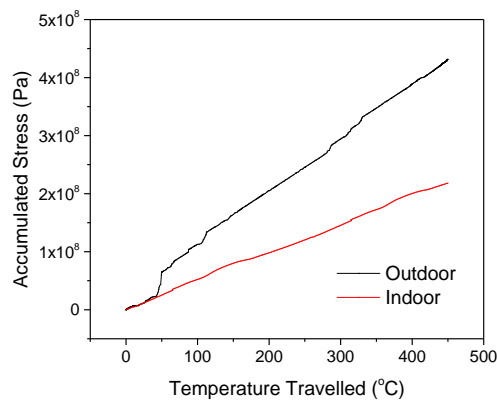


Figure 6: Accumulated stresses on solder bonds for indoor and typical outdoor conditions in June over the same temperature travelled

Even though the maximum stress observed during indoor thermal cycling is higher, the continual fluctuation and cycling of temperatures in the outdoors results in an increased accumulation of stress on the solder bonds. It is this accumulation of stresses and continuous cycling that results in the fatiguing and degradation of the solder bonds, leading to increased series resistance and power loss until the bonds

become completely disconnected and total failure of the device occurs.

Conclusions

Simulations of the thermomechanical behaviour of monocrystalline silicon mini modules during indoor and outdoor thermal cycling have been conducted. It is found that mismatched material properties cause the backsheet and glass front cover to experience high tensile stress as the components contract at low temperatures resulting in a deformation of the module assembly. Because of the deformation, the cells are under high compressive stresses, whilst the displacement of the cells causes the interconnecting ribbons and solder bonds to experience shear stresses. Whilst the maximum observed stress is highest during indoor accelerated testing, the accumulation of stresses on the solder bonds are greater in outdoor conditions. This is likely a result of the continual fluctuation of temperature experienced in outdoor climates. These results could indicate that the stresses which are generated during accelerated testing are too extreme, and whilst they are useful for testing modules for their susceptibility to high levels of stress, they may not be so useful in quantifying long-term fatigue mechanisms and effective service life.

References

- [1] J.-S. Jeong, N. Park, and C. Han, "Field failure mechanism study of solder interconnection for crystalline silicon photovoltaic module," *Microelectron. Reliab.*, vol. 52, no. 9–10, pp. 2326–2330, Sep. 2012.
- [2] W. Herrmann, N. Bogdanski, F. Reil, M. Köhl, K. – Weiss, M. Assmus, and M. Heck, "PV module degradation caused by thermomechanical stress: real impacts of outdoor weathering versus accelerated testing in the laboratory," *Proc. SPIE*, vol. 7773, no. 1, p. 77730I–77730I–9, 2010.
- [3] "61215. Crystalline Silicon Terrestrial Photovoltaic (PV) Modules—Design Qualification and Type Approval," *International Electrotechnical Committee*, vol. 3, 2005