SIMULATION ASSISTED DESIGN OF A PV MODULE INCORPORATING ELECTRICALLY CONDUCTIVE ADHESIVE INTERCONNECTS

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ABSTRACT: Crystalline cells used in PV modules are becoming thinner, while at the same time the surface area increases. This trend is mainly driven by cost efficiency. Due to the higher fragility of thin solar cells, the admissible limits on mechanical stresses during assembly and during field operation are lower.

Nowadays, solar modules are typically assembled using soldered interconnects. The soldering process induces a combination of thermal and mechanical loads on the cell. For thin cells, these loads are expected to lead to unacceptably high breakage levels during module production. By applying conductive adhesives, the thermo-mechanical loads are reduced. The back-contacted cell concept [1][2] allows for a relatively straightforward introduction of adhesive interconnects into a PV module.

An important issue in the design of PV modules is its long term thermo-mechanical reliability. The paper presents the application of computer simulation techniques in addressing this issue. It highlights critical aspects for performing accurate simulations of thermo-mechanical PV module behaviour. The simulation techniques are demonstrated on the design of a suitable adhesive interconnect size in a PV laminate that is subjected to temperature cycling.

Keywords: PV Module, Modelling, Reliability

1 INTRODUCTION

The common way for assessing the (thermo-)mechanical reliability of a PV module is to build prototypes that are subjected to relevant thermal and mechanical loadings. Well-known tests are the temperature cycling test, the high temperature humidity storage test, and the impact test. Depending on the outcome of such a test program, the laminate design is adjusted and the cycle of building and testing is repeated until it meets the demands. This process is time consuming and expensive as the tests may take several months to complete.

The work described in the current paper is aimed at shortening the design time of a PV module. Part of the physical building and testing of prototypes is replaced by computer simulations which take considerably less time, effort, and materials to be performed.

For performing successful computer simulations, accurate input is required in the form of (*i*) the geometry and dimensions of the module, (*ii*) interaction of the module with its environment, and (*iii*) properties of each material in the module. In particular the latter aspect proves to be a serious bottleneck in many cases. Sufficiently accurate models describing the behaviour of materials are frequently lacking.

This paper describes the application of simulation techniques to predict the mechanical stresses that develop in a PV module during temperature changes as, for example, encountered during assembly and field operation. In addition, characterisation experiments are carried out to determine the thermo-mechanical properties of the conductive adhesive used in the module.

The layout of the module is schematically shown in Figure 1. The silicon cells in this module are electrically interconnected by a so-called backside foil consisting of electrically conductive tracks supported by a layer of Polyethylene Terephthalate (PET) and Polyvinyl Fluoride (PVF). The PET/PVF layers also act as a barrier layer to the environment. The backside foil is connected to the cells using an electrically conductive adhesive. The cavities between the backside foil and the cells that are not occupied by the adhesive are filled with Ethylene Vinyl Acetate (EVA). The front side of the cells is also covered by a layer of EVA which is attached to a glass plate.

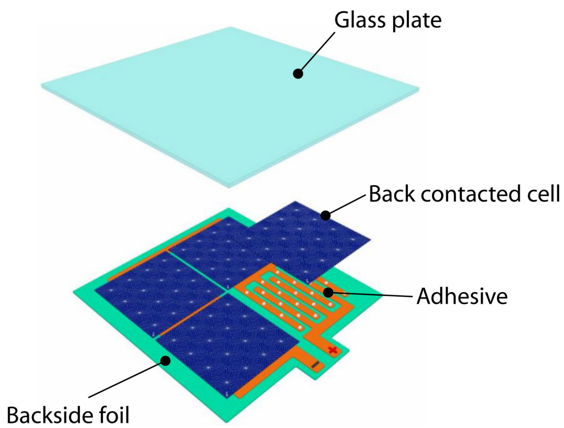

Figure 1: Layout of a PV module incorporating electrically conductive adhesive interconnects.

The next section describes the experiments carried out to arrive at an accurate description of the behaviour of the electrically conductive epoxy adhesive used in the module. Section 3 illustrates the application of simulation techniques in the design of the adhesive interconnect in the module. The final section gives some conclusions on the applied approach.

2 EXPERIMENTS

From a simulation point of view, the materials used in a module can be divided in two categories: those for which the properties are well-known and those for which the properties are more difficult to obtain. Materials in the former category are the glass plate, the electrically conductive tracks and the silicon cells. The materials in the latter class exhibit significantly more complex behaviour: the EVA, the adhesive and the PET/PVF foil.

This section illustrates the experiments carried out to characterise the behaviour of the electrically conductive adhesive material. The other materials are characterised in a similar manner.

2.1 Characterisation experiments for adhesive material

Test samples of the adhesive are prepared by pouring uncured material in beam-shaped cavities machined in a Teflon block. These samples are subsequently cured in an oven for 1 hour at a nominal temperature setting of 150°C. The curing time is longer than advised on the datasheet to ensure that the material is fully cured. The dimensions of the samples are $30\times2\times5 mm^3$.

The sample is mounted in a TA Instruments DMA 2980 as shown in Figure 2.

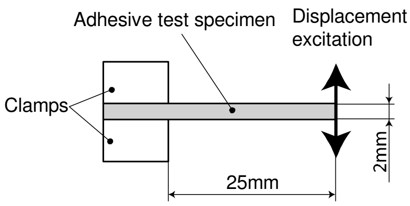

Figure 2: Set-up of the characterisation experiments.

The sample is clamped on one end and a harmonically varying lateral displacement is applied on the free end. The required force as a function of time is monitored and this information is used to determine the modulus of the material. Many polymeric materials – such as the adhesive tested here – exhibit so-called temperature dependent visco-elastic behaviour, *i.e.* the modulus varies as a function of time and temperature. For certain classes of materials, this behaviour is conveniently determined by measuring the modulus using the experiment described above and varying the temperature of the sample and the frequency of the displacement excitation over certain ranges [3].

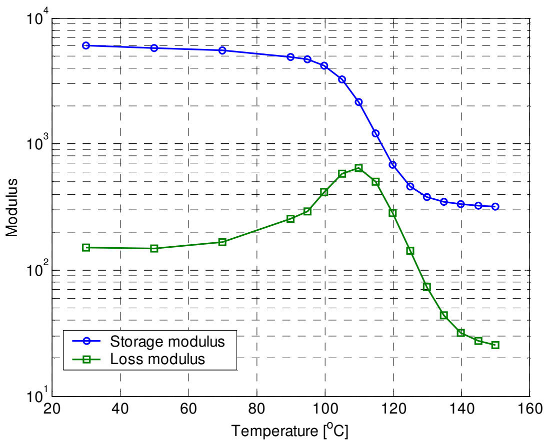

Figure 3: Storage and loss modulus as a function of temperature for a 1 Hz excitation frequency.

The modulus as measured in such an experiment can be decomposed into a part associated with the elastic behaviour of the adhesive and a part associated with the viscous behaviour. These parts of the modulus are termed the storage modulus and loss modulus respectively. Typical results of the experiment are shown in Figure 3 and Figure 4.

Figure 3 shows the storage and loss modulus of the adhesive as a function of temperature for an excitation frequency equal to 1 Hz. In the range from 100°C to 120°C the storage modulus drops more than one order of magnitude. The material transforms from its glassy phase to its rubbery phase and the temperature at which this occurs is called the glass transition temperature. There are several definitions in literature for this temperature [4][5]. Using the peak in the loss modulus curve as a definition, the glass transition temperature is found at 110°C, which agrees well with the value specified on the datasheet.

Figure 4 shows the storage and loss modulus at 110°C as a function of excitation frequency. These curves are constructed from the curves measured at all other temperatures (ranging from –30°C to 150°C) using the time-temperature superposition principle [3][6].

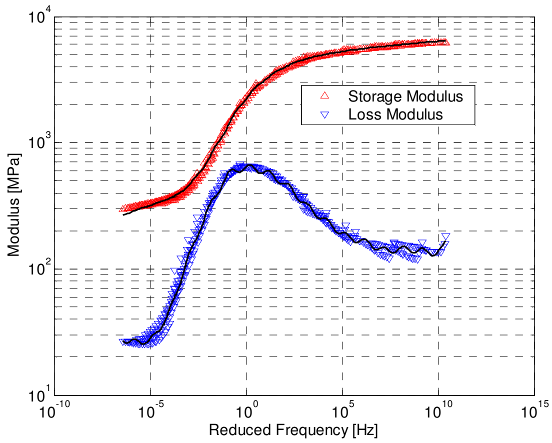

Figure 4: Comparison between model fit (solid lines) and measurements for storage and loss modulus at 110°C for different frequencies.

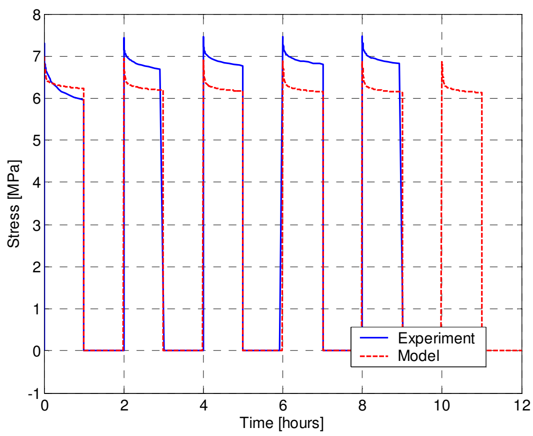

Figure 5: Comparison between model predictions and experiments for a repetitive relaxation experiment at -20°C.

A linear visco-elastic model is fitted on the data as shown in Figure 4. A multi-mode Maxwell model [6] is used here. The model fit (solid lines in Figure 4) agrees well with the measurement data.

As a first validation of the model, additional experiments are carried out that differ slightly from the previous experiments. The same test setup is used as before (see Figure 2), but instead of applying a harmonic excitation, relaxation experiments are carried out at different temperatures. The sample is subjected to a 0.1% bending strain and this strain is maintained for 1 hour while the development of the stress in monitored. Next, the stress on the sample is released. This situation is maintained for an hour as well. This cycle is repeated several times.

The results are shown in Figure 5 and Figure 6 for two temperatures: -20°C and 120°C. In addition, these figures show the prediction of the visco-elastic model as fitted on the data of the previous experiment.

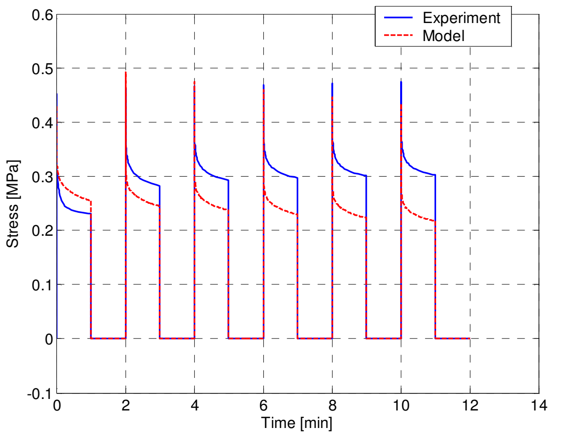

Figure 6: Comparison between model predictions and experiments for a repetitive relaxation experiment at 120°C.

The model predictions show a reasonable agreement with the measurements. There is a difference in absolute stress levels of about 10-15%. Stress relaxation is observed in the experiment which is also predicted by the model.

2.2 Validation experiments

An additional validation was carried out using an adhesive-on-strip experiment. In this experiment a thin steel strip is used on which an adhesive layer is applied which is subsequently cured at 150°C. After curing, the sample allowed to cool down to room temperature.

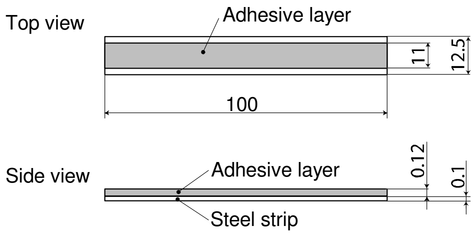

Figure 7: Dimensions of the adhesive on strip sample after curing of the adhesive layer. All dimensions are in mm.

The final sample is schematically shown in Figure 7 in top and side view. The steel strip is 0.1mm thick and the thickness of the adhesive layer is approximately 0.12mm.

The sample is mounted in an oven as shown in Figure 8. The temperature in the oven is varied over time. This will lead to lateral deflection of the sample due to the difference in coefficient of thermal expansion of the adhesive and the steel strip. The amount of lateral deflection is – among other factors – dependent on the properties of the adhesive layer.

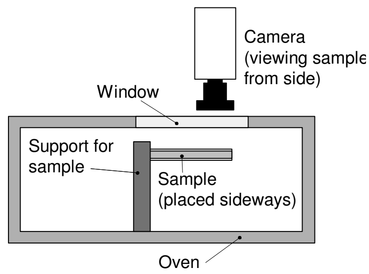

Figure 8: Set-up for measuring the deflection during temperature changes.

One end of the strip is clamped by a support. The strip is mounted sideways in order to cancel out the influence of gravity. Deflection of the sample takes place perpendicular to the plane of drawing in Figure 8. The deflection is measured optically using a digital camera placed outside the oven and viewing the side of the sample through a window. The images of the sample are processed digitally to determine changes in lateral deflection of the sample's free end. The temperature in the oven is monitored using a thermo-couple.

Experiments are carried out for two oven temperature profiles as shown in Figure 9. For the first temperature profile, the maximal temperature in the oven is about 100°C and for the second profile, the maximal temperature is nearly 150°C. Additional experiments have been carried out with thermo-couples placed on the samples as well. The sample temperature turns out to be a few degrees below the measured oven temperature. In the actual experiments, no thermo couples were placed on the samples, in order to avoid disturbances.

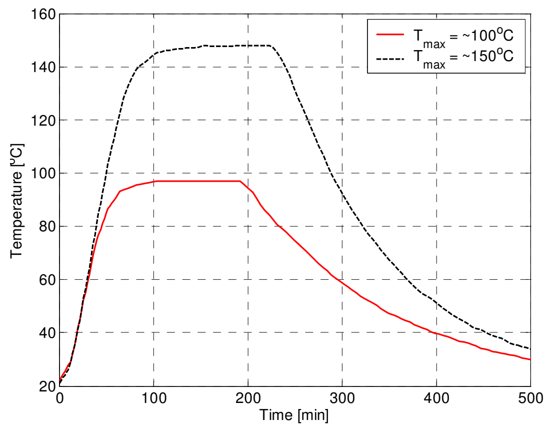

Figure 9: Measured temperature profiles in the oven for the strip bending experiments.

The deflection of the strip was predicted using a generalised plane strain (2D) finite element model implemented in the finite element code MSC.Marc [7].

This model incorporates the visco-elastic model of the adhesive as determined in the previous section. For the steel strip a linear elastic material model is adopted with parameters taken from literature.

A comparison between the measured deflection of the free end of the strip and calculated deflection for the first temperature profile ($T_{max} \approx 100°C$) is shown in Figure 10. The measurements are compared with two model predictions. In the first prediction, the stresses that developed during cool down from curing temperature to room temperature were neglected and in the second prediction these stresses were taken into account. The same comparison is made for the second temperature profile ($T_{max} \approx 150°C$) in Figure 11.

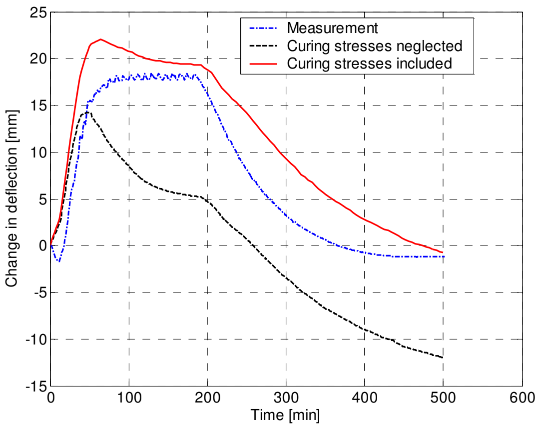

Figure 10: Comparison between measured and calculated lateral deflection change of the sample during temperature changes. Maximal oven temperature is nearly 100°C.

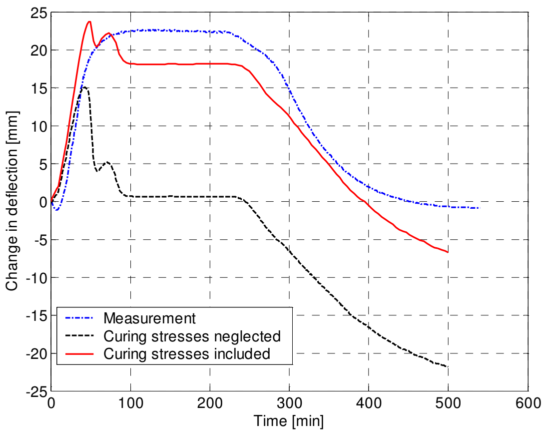

Figure 11: Comparison between measured and calculated lateral deflection change of the sample during temperature changes. Maximal oven temperature is nearly 150°C.

For both temperature profiles, the inclusion of curing stresses clearly results in more accurate predictions of the observed deflections. Nevertheless, even for the simulations with curing stresses included, there are still remarkable differences between the experiments and the models. The relaxation of the adhesive at higher temperatures is clearly more pronounced in the model predictions than in the experiment. The precise reasons for these deviations are not fully understood, but some causes for the differences can readily be identified:

- The curing profile used in the characterisation experiments (for determining the model parameters) is different from the profile used for curing the adhesive on the strip material. This will influence the mechanical properties of the cured adhesive.
- In the model, the stress build-up due to curing is only approximately taken into account. No full analysis of the stress-development during adhesive cure is made.
- The sample temperature used as input in the simulations is the measured oven temperature. It has been observed from additional experiments that the sample temperature is a few degrees below the oven temperature and not uniform over the strip.
- The thickness of the adhesive layer is measured at a few discrete points and these values are used in the model for defining the adhesive layer thickness. The deflection of the free strip end is strongly dependent on this parameter.
- The model neglects possible chemical and physical ageing processes that might be developing in the adhesive.

3 SIMULATIONS

The effect of the adhesive thickness and the presence of EVA material on the stresses in the adhesive interconnects is investigated by means of numerical simulations. A single cell laminate is considered.

Previous numerical studies have shown that the stresses in such a laminate are similar to the stress development in a full (for example 9×4 cell) laminate. The general construction of a PV laminate was already shown in Figure 1. Additional characteristics of the single cell laminate considered here are shown in Figure 12 and Figure 13.

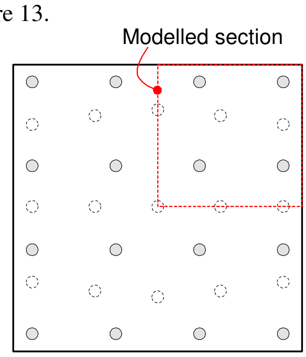

Figure 12: Top view of the single cell laminate as studied by means of numerical simulations. Circles denote the location of adhesive interconnects.

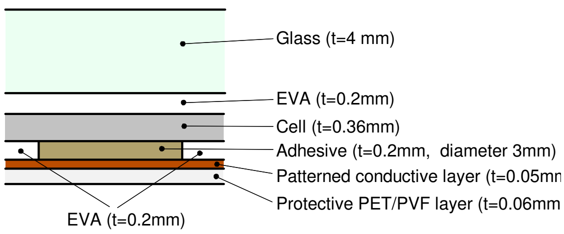

Figure 13: Cross-section of a part of the single cell laminate. The symbol t denotes the thickness of a layer.

A 3D model of a quarter of the laminate is implemented in the finite element package MSC.Marc [7]. The mesh is shown in Figure 14. Because of symmetry reasons, only a quarter of the actual laminate is modelled. The locations of adhesive interconnects are indicated by arrows in Figure 14. The adhesive interconnect furthest away from the centre of the laminate (denoted by 'A' in the Figure) is meshed more densely in order to capture the deformation patterns there as accurately as possible. This interconnect experiences the highest stress and strain levels during temperature changes and is thus most susceptible to failure.

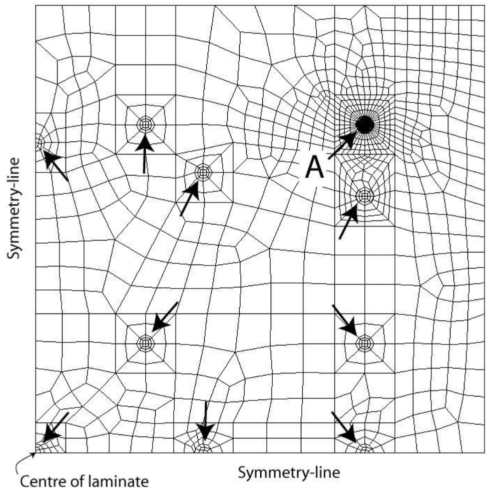

Figure 14: Top view of the 3D finite element mesh. The locations of the adhesive interconnects are indicated with arrows.

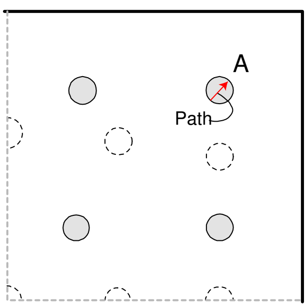

Figure 15: Path along the centre of the adhesive interconnect A (see Figure 14) for which stresses are plotted in subsequent figures. Perpendicular to the plane of drawing, the path is located in the mid-plane of the interconnect.

In the first simulation run, the influence of the thickness of the adhesive interconnect (and EVA layer) on the stress build-up is investigated. For this, the temperature of the laminate is uniformly decreased from 150°C (assumed to be the stress free temperature) down to 20°C. Figure 16 and Figure 17 show the normal and shear stresses along the path indicated in Figure 15.

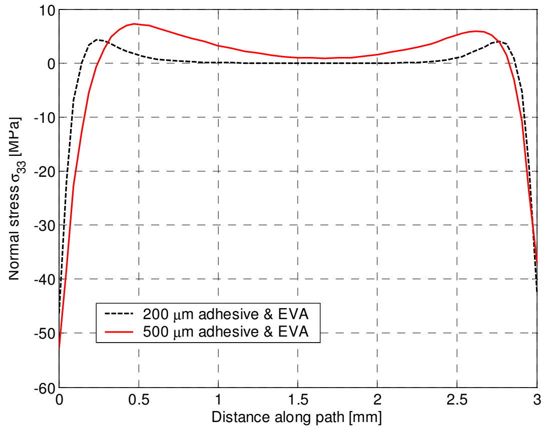

Figure 16: Normal stress in the adhesive along the path shown in Figure 15 after cooling down from 150°C to 20°C.

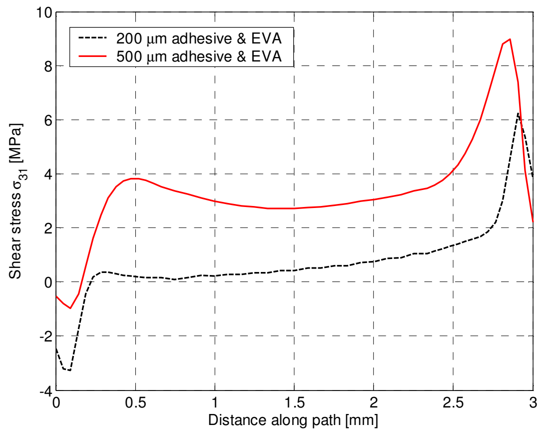

Figure 17: Shear stress in the adhesive along the path shown in Figure 15 after cooling down from 150°C to 20°C.

These results predict higher normal and shear stress levels for thicker interconnects. The stresses along the path as shown in Figure 16 and Figure 17 are only indicative for the stress distribution in the interconnect. The stress distribution is highly inhomogeneous as Figure 18 and Figure 19 show.

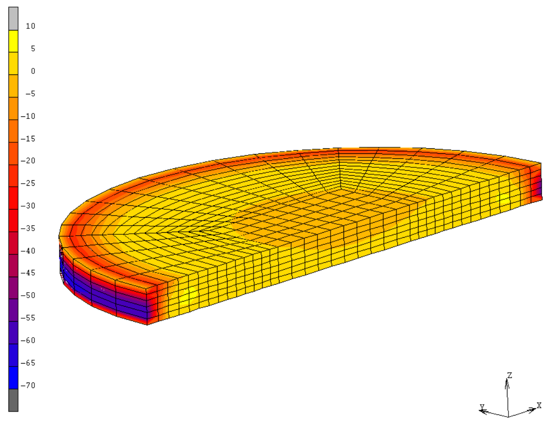

Figure 18: Normal stress distribution in a 200μm thick adhesive interconnect after cooling down from 150°C.

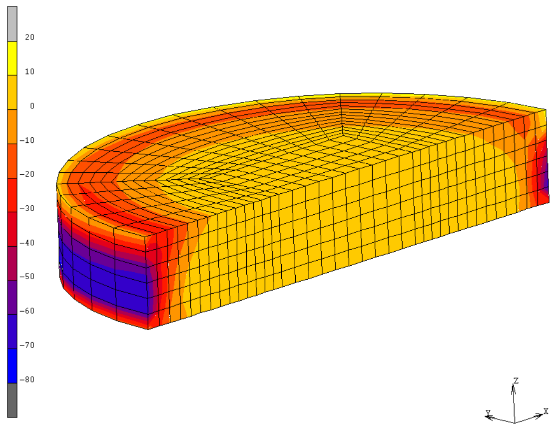

Figure 19: Normal stress distribution in a 500µm thick adhesive interconnect after cooling down from 150°C.

The presence of the EVA layer results in a net reduction of stresses in the adhesive interconnects. As an illustration, Figure 20 and Figure 21 show the normal and shear stresses along the path indicated in Figure 15 after heating up the single cell laminate from 80°C to 150°C for situations with and without EVA.

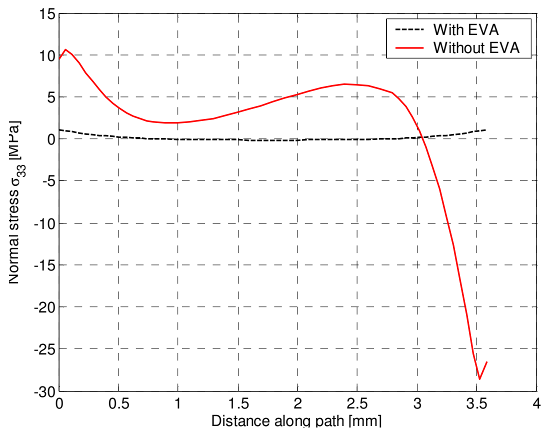

Figure 20: Normal stress in the adhesive interconnect after a temperature increase from 80°C to 150°C for a situation with and without EVA.

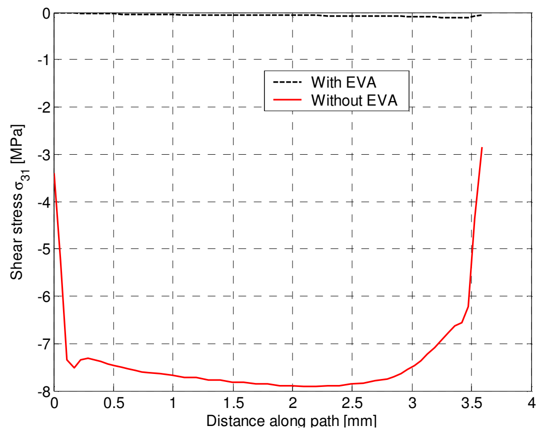

Figure 21: Shear stress in the adhesive interconnect after a temperature raise from 80°C to 150°C for a situation with and without EVA.

In the situation without EVA, the adhesive interconnect would probably fail due to the high forces exerted caused by the difference in thermal expansion between the other materials in the assembly.

4 CONCLUSIONS

The paper described the use of numerical simulations in the design of a PV laminate incorporating adhesive interconnects. Crucial for a successful application of numerical simulation techniques is the quality of the input in the form of accurate material models.

The determination of materials parameters has been demonstrated for an electrically conductive adhesive. An initial validation of the materials model showed a reasonable agreement between measured and predicted relaxation curves. A strip bending experiment was used for further validation. It turned out that the stress build-up during adhesive curing and subsequent cooling down to room temperature could not be neglected for an accurate prediction of the deflection of the strip during temperature cycling.

Numerical techniques were applied for investigating the influence of adhesive layer thickness and the presence of and EVA layer on the stress levels in the adhesive during temperature changes. The stress distribution in the adhesive turned out to be strongly inhomogeneous. The stress levels were higher for thicker adhesive layers. Furthermore, the exclusion of the EVA material resulted in unacceptably high stresses in the adhesive interconnects.

5 ACKNOWLEDGEMENTS

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