Improving Computational Efficiency of Mechanical Finite Element Method Simulations for PV Modules

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IMPROVING COMPUTATIONAL EFFICIENCY OF MECHANICAL FINITE ELEMENT METHOD SIMULATIONS FOR PV MODULES

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ABSTRACT: In this work we have elucidated the tradeoff between structural mechanics FEM model accuracy and computation time by employing lower fidelity viscoelastic models for a module's encapsulant. Results indicate that computation time can easily be cut in half while only expecting a potential maximum error of 10 % by considering lower fidelity models.

1 INTRODUCTION

As the photovoltaic (PV) industry matures, structural mechanics modeling using the Finite Element Method (FEM) is becoming a more popular tool with which to design and evaluate PV modules for their long-term reliability. These FEM models require material specific models as input to describe each material's mechanical response to loading. While the mechanical behavior of some module materials, such as silicon and glass, may be accurately described with simple linear elastic models, the polymer-based materials (encapsulant, backsheet and electrically conductive adhesive (ECA)) require more complex viscoelastic material models. Recently, a high fidelity set of viscoelastic materials models were published for popular PV module encapsulants, backsheets and ECAs [1, 2]. While these models provide for an accurate description of these material's time– and temperature–dependent mechanical response, their incorporation significantly increases the size (degrees of freedom (DOF)) of the FEM model and consequently the requisite memory and computation time. When coupled with the already DOF expensive geometry of a PV module, these models often become too big to run even simple simulations on powerful desktop computers. Most studies have avoided this obstacle by only considering linear elastic approximations for their viscoelastic materials. This compromise, however, yields unpredictably inaccurate results and sets up the conundrum between an accurate model which is too slow or cannot be solved and an efficient model that yields incorrect results.

The purpose of this work is to study the tradeoff in FEM simulation accuracy with computation time. We effect computation time by considering lower fidelity viscoelastic materials models for the encapsulant within the structural mechanics model of a PV module. Preliminary results indicate that computation time can be halved while only anticipating a maximum inaccuracy of 10 %.

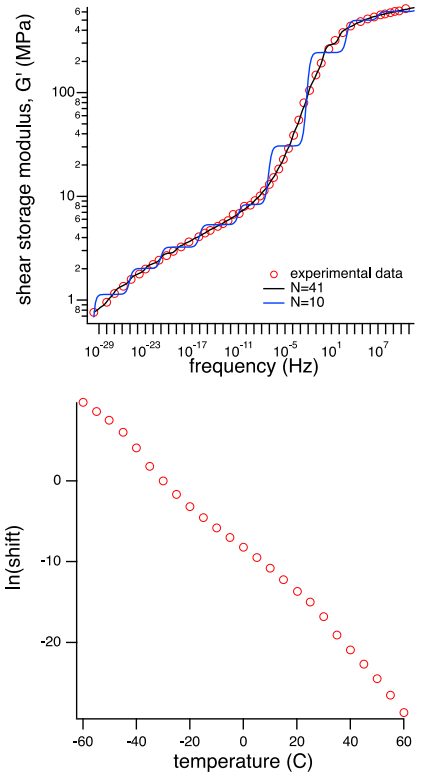

Figure 1: Master (top) and shift function (bottom) curves for EVA. The Master curve includes a 41 and 10 term Prony Series fit to the experimental data.

2 MODELING

2.1 Viscoelastic Materials Model

We chose to evaluate the accuracy and computing time of a FEM model by considering a viscoelastic material model for an encapsulant of varying levels of fidelity. The experimental time–temperature superposition master curve evaluated at -30 C and temperature shift function curve for a commercially available ethylene-vinyl acetate (EVA) examined in this work is presented in Fig. 1 [1]. A description of the physics and how these curves are

produced are outside the scope of this work but can be found here [3]. We employ a Generalized Maxwell Model to mathematically describe the viscoelastic material behavior of this material. In this model, Maxwell Figure 1. Master (left) and shift function (right) curves for EVA. The Master curve includes a 41 and 10 term Prony Series fit to the experimental data. In this model, Maxwell elements are described as pairs of series connected springs of relaxation moduli G_n and dashpots with relaxation times, t_n, that are connected in parallel to describe the varying time distribution of relaxation. The Generalized Maxwell Model conveniently takes the form of a Prony Series:

$$G(t) = G_\infty + \sum_{n=1}^{N} G_n exp\left(-t/\tau_n\right) \qquad (1)$$

which describes the relaxation modulus at time t when n pairs of Maxwell elements are connected in parallel. By making use of Fourier transformation, Eq. (1) can be converted to the frequency domain to describe the time–temperature master curve:

$$G(\omega) = G_o\left[1 - \sum_{n=1}^{N} \frac{g_n}{1+(\tau_n \omega)^2}\right] \qquad (2)$$

Where $G(\omega)$ is the shear modulus at frequency w, G_o is the instantaneous shear modulus and $g_n = G_n/G_o$. When Eq. (2) is fit to the experimental Master curve it produces pairs of (g_n, t_n) which are directly input into the FEM modeling software. To produce the fit, first the number of pairs N is chosen. For the high–fidelity fit N is chosen to be the number of decades that span the Master curve, 41. For the lower fidelity fits considered in this work, N=35, 30, 25, 20, 15, 10, 5 and 0 (N=0 is the linear elastic approximation). The corresponding relaxation times, t_n, are calculated according to

$$\tau_n = \frac{1}{max(\omega)} 10^{N-n} \qquad (3)$$

Which yields an even spacing across the Master curve frequency range. The Prony Series is then constructed and the corresponding g_n values solved for via a linear regression to the experimental data. The result of the high-fidelity N=41, and lower fidelity N=10, are included in Fig. 1(left).

2.2 Structural Mechanics Model

A 2D cross-sectional model of a crystalline silicon PV module was generated using COMSOL. The module was modeled to contain six cells and be simply supported at its ends. To evaluate the accuracy and computation time of the model with an encapsulant viscoelastic material model of varying levels of fidelity, a simple loading simulation was run that applied a uniform load of 1 kPa to the front side of the module for 24 hours. A WLF fit to the experimental temperature shift function curve was used to repeat this simulation for temperatures from -40 to 60°C, in 10°C increments to probe the entire Master Curve. The cell to cell gap, between the cells at the center of the module, was the metric chosen to evaluate model accuracy. Linear elastic material models were used for the remainder of the materials.

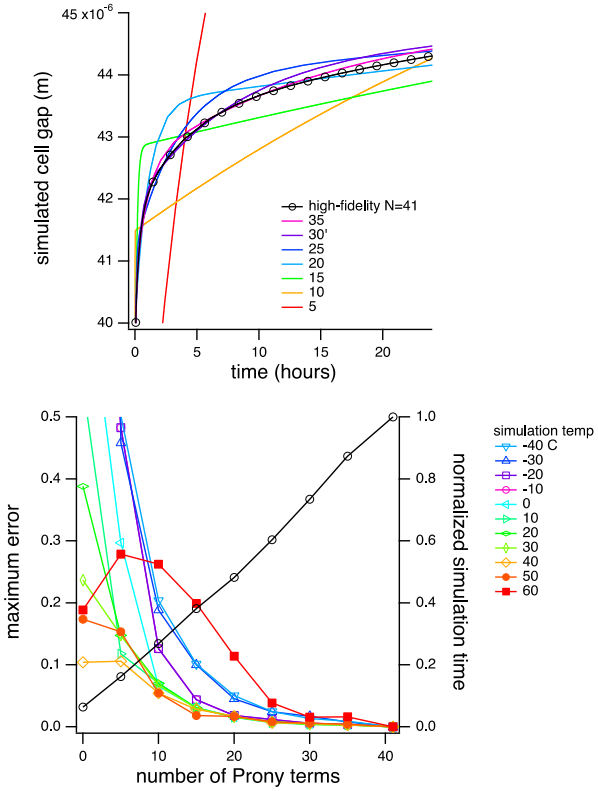

Figure 2: Simulation results (top) of cell gap for of varying level of model fidelity. Maximum error of cell gap (bottom) and corresponding computation time for isothermal models of varying fidelity. Error of the 0-term model is > 90 %.

3 RESULTS AND ANALYSIS

Simulation results for the single temperature of 25°C are presented in Fig. 2 (top). The 0-term linear elastic approximation yielded a simulated cell gap ~ 51 µm and was therefore omitted from the graph. As the number of terms increases, the resulting simulated cell gap converges to the high-fidelity model. To simultaneous examine all simulation results, we report the maximum error between each lower fidelity simulation and the high-fidelity simulation for each temperature, Fig. 2 (bottom). This analysis yields the most conservative estimate of model error since it does not consider the time in the simulation at which the error exists. In this form, we can easily visualize the tradeoff between computation time and worst-case error. For instance, by instead choosing a 20-term model, our computing time is cut in half while only anticipating a maximum error of ~10 %. What also emerges from this analysis is that the error also depends on simulation temperature. This manifests from how the lower fidelity fits periodically intersect the master curve, Fig. 1. As the master curve is shift in frequency to represent the different simulation temperatures, an evaluation of lower-fidelity fit may become either more or less accurate depending on the evaluated frequency (strain rate). For isothermal simulations between 0 and 50°C, for instance, 10-term models become adequate to keep the maximum error ~5 %, while the maximum error for the -30 and -40°C models jump to 20 % and the 60°C model to 27 %.

4 CONCLUSIONS

In this work we have elucidated the tradeoff between structural mechanics FEM model accuracy and computation time by employing lower fidelity viscoelastic models. Results indicate that computation time can easily be cut in half while only expecting a potential maximum error of 10 % by considering lower fidelity models.

6 ACKNOWLEGEMENT

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7 REFERENCES

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