Multi-scale, multi-physics modeling capabilities towards improving PV reliability

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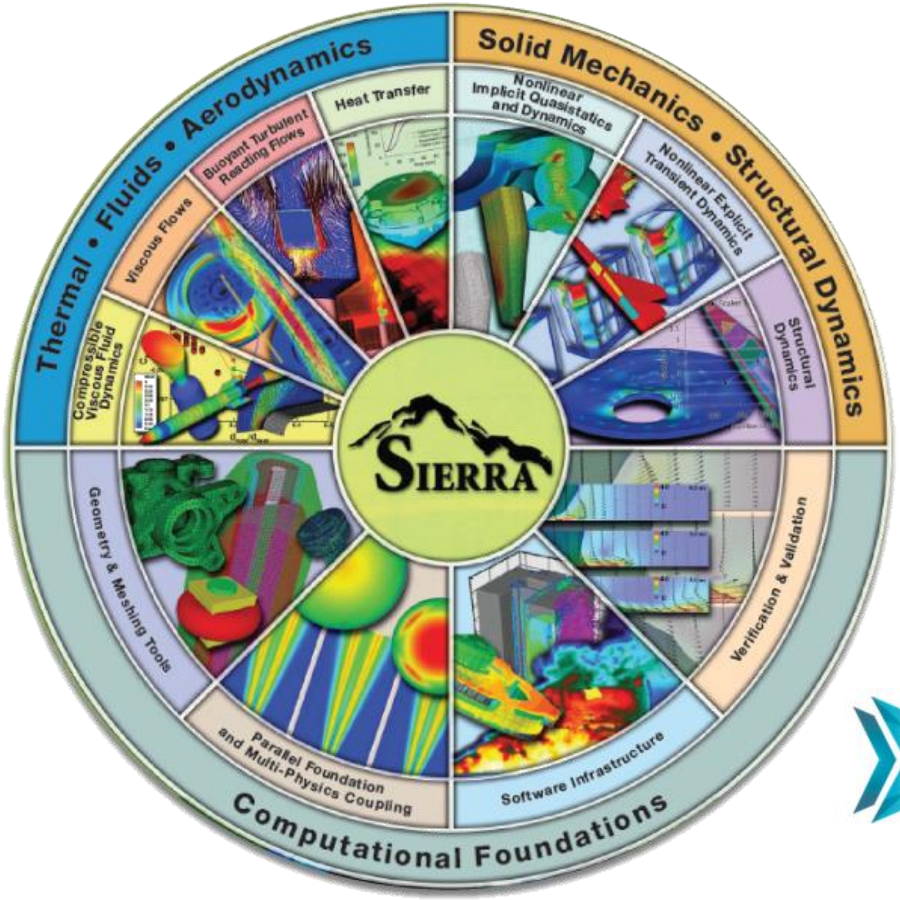
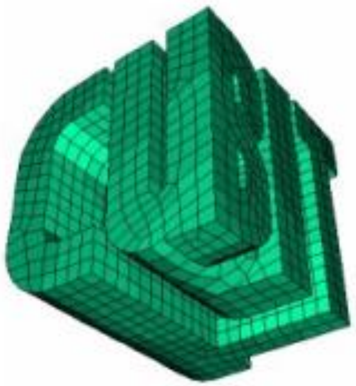
Introduction

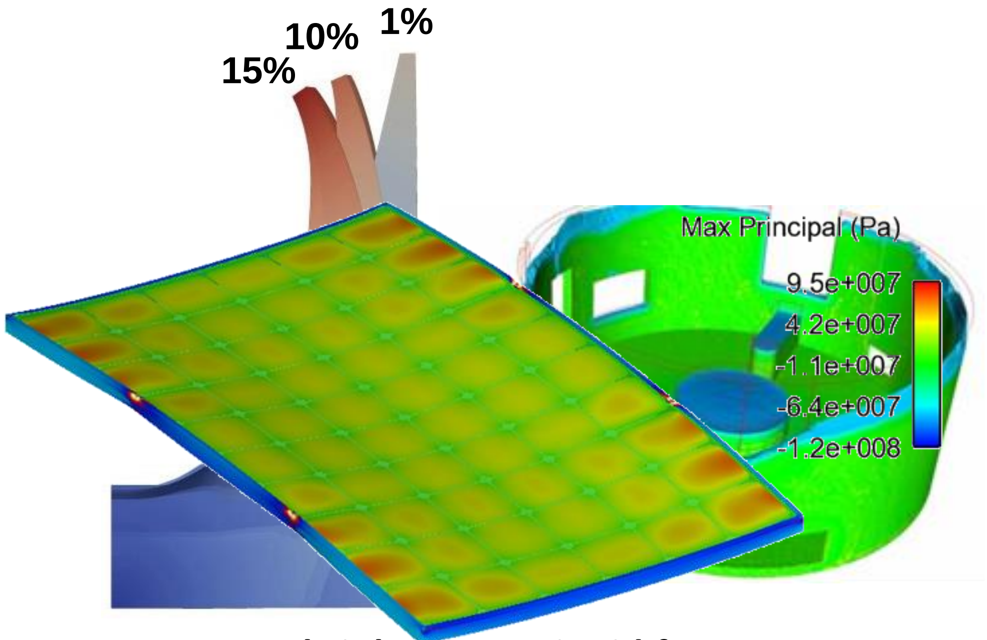
- Advanced computational capabilities at Sandia have been developed to predict behavior in many complex systems





DAKOTA

Explore and predict with confidence.



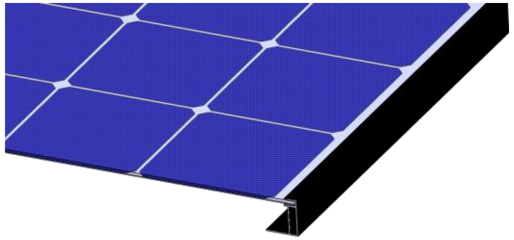
Cure shrinkage causes warpage of a solid part

Liquid foam reacts, expands, solidifies to fill a mold

Let's apply these tools to PV modules in their operating and testing environments

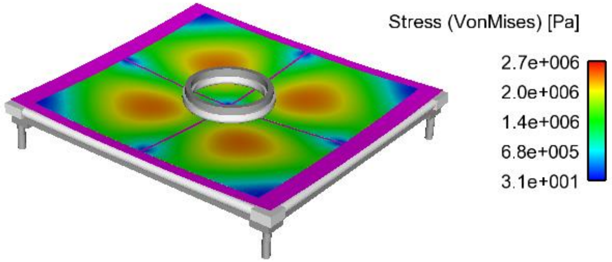
Multi-Scale Models for PV Reliability

- Modeling capabilities to predict stresses at various scales of a PV module:

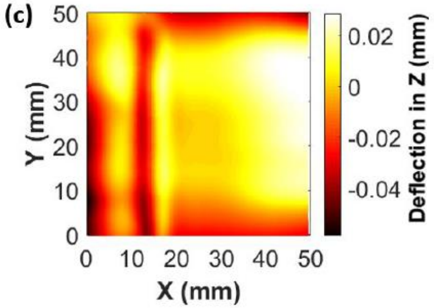


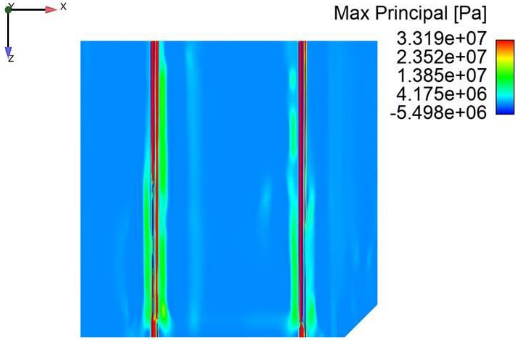
Full Modules
[Hartley; SNL]

Combined-Accelerated Stress Testing Chamber (C-AST)

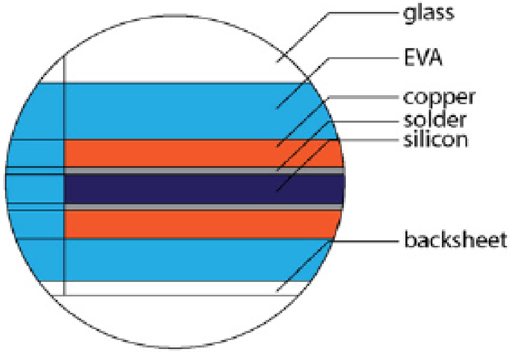


Mini-Modules
[SNL with Owen-Bellini, Hacke; NREL]





Tabbed cells
[SNL with Bertoni; ASU]

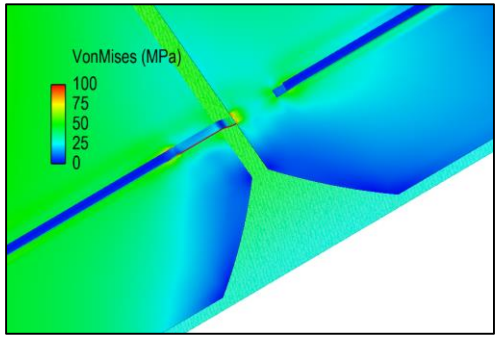


Interconnect damage
[Bosco; NREL]

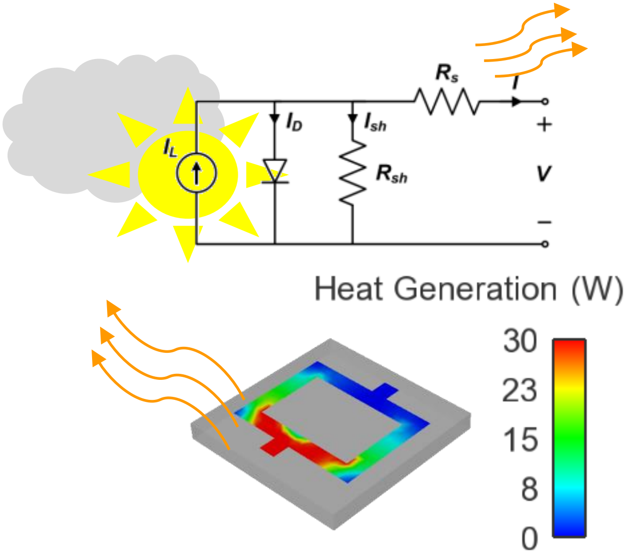
Multi-Physics Models

- Modeling capabilities incorporate various physics causing or related to degradation:

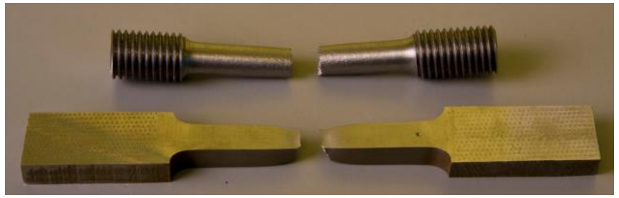
Mechanical stress
[Hartley, SNL]



Thermal stress
[Hartley, SNL]



Electrical-thermal coupling [SNL]



Material responses:

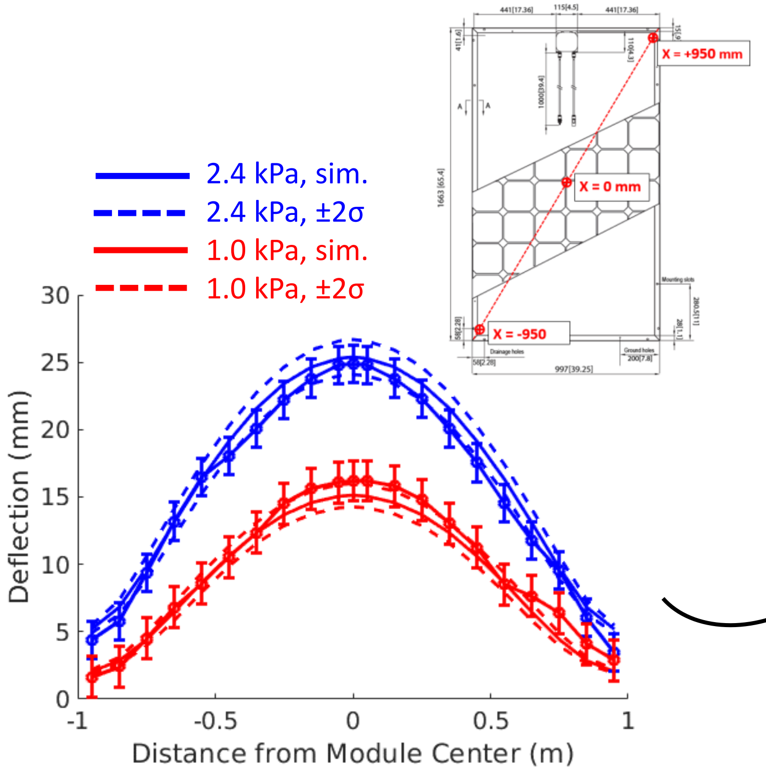
- **Encapsulant viscoelasticity [Maes, SNL]**
- Electrically Conductive Adhesive viscoelasticity and damage [Bosco, NREL]
- Backsheet aging [Owen-Bellini, NREL; Schelas, SLAC]

Additional physics could include moisture transport, corrosion chemistry, and many others

Sensitivity Analysis for Module Deflection

- Modeling capability was demonstrated for a 60-cell c-Si module and a large format glass-glass module, and validated against experimental deflection vs. load data at room temperature
- Input parameters (materials properties & dimensions) were varied parametrically to generate uncertainty estimates and analyze sensitivities

Parametric inputs: Materials, dimensions
120 total samples



Predicted deflection vs. load with parametric uncertainty

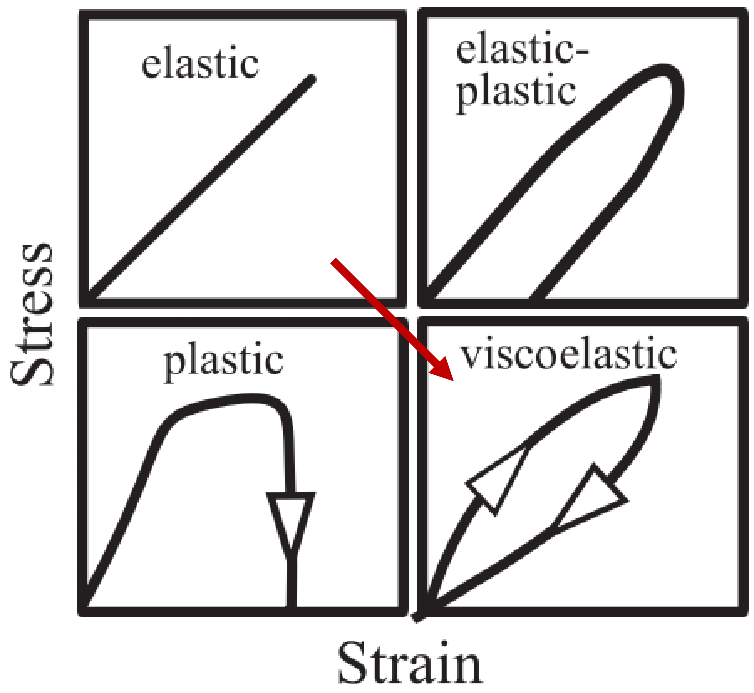
Parameters highly correlated to module deflection

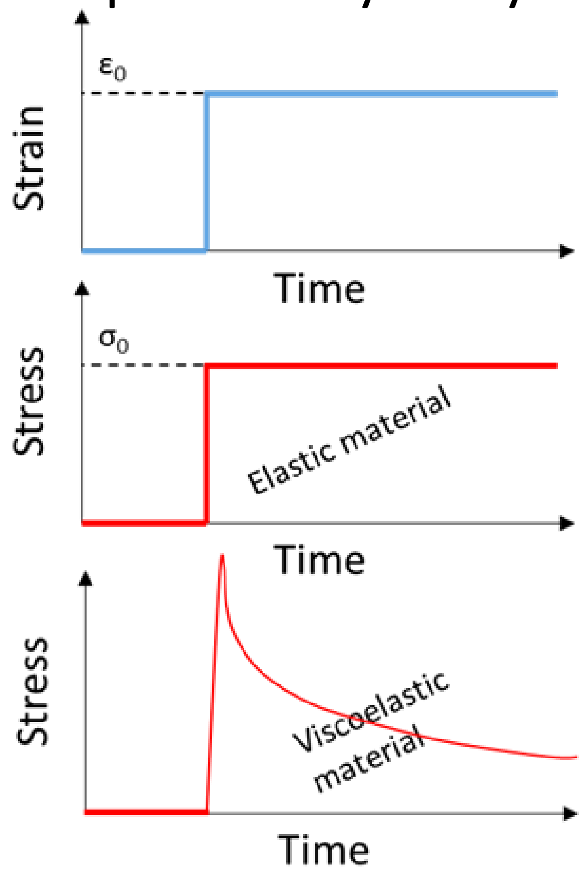
1.0 kPa		2.4 kPa	
Parameter	|R|	Parameter	|R|
Edge tape modulus	0.630	Glass modulus	0.561
Glass modulus	0.532	Edge tape modulus	0.553
Edge tape Poisson's	0.336	Edge tape Poisson's	0.361
Glass thickness	0.286	Glass thickness	0.321
Encap. thickness	0.132	Encap. thickness	0.111

J. Y. Hartley, et al., PVSC, 2019

Adding Time and Temperature Dependency of Polymer Materials

- The viscoelastic nature of polymer encapsulants is potentially a key factor affecting component stress states





- The polymeric layers of modules are known to have higher thermal expansion coefficients than surrounding materials, leading to stress during thermal cycling

Adding Time and Temperature Dependency of Polymer Materials

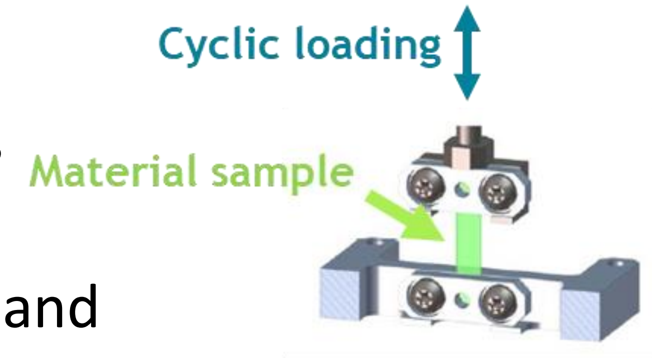
- This presentation summarizes the **steps taken to populate a material model** for two encapsulant polymers

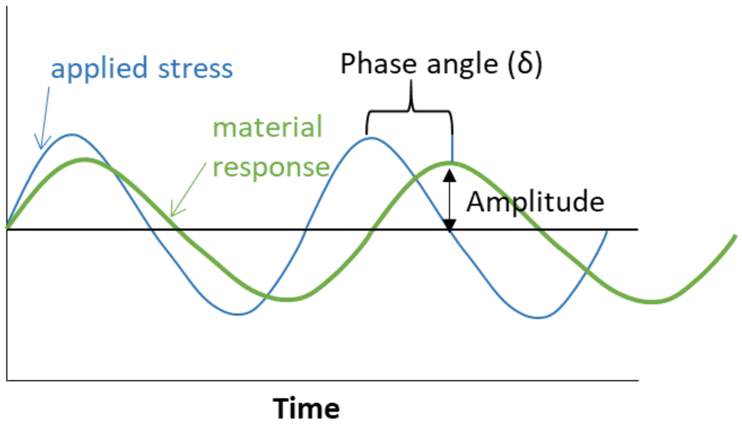
- EVA is the most common encapsulant material used in PV modules
- We characterized crosslinked samples of a fast-curing commercial EVA

- Polyolefin films are a common alternative encapsulant with several improved characteristics that are especially valued in thin-film PV modules
- We characterized commercial POE samples that were heated and pressed to mimic manufacturing lamination conditions

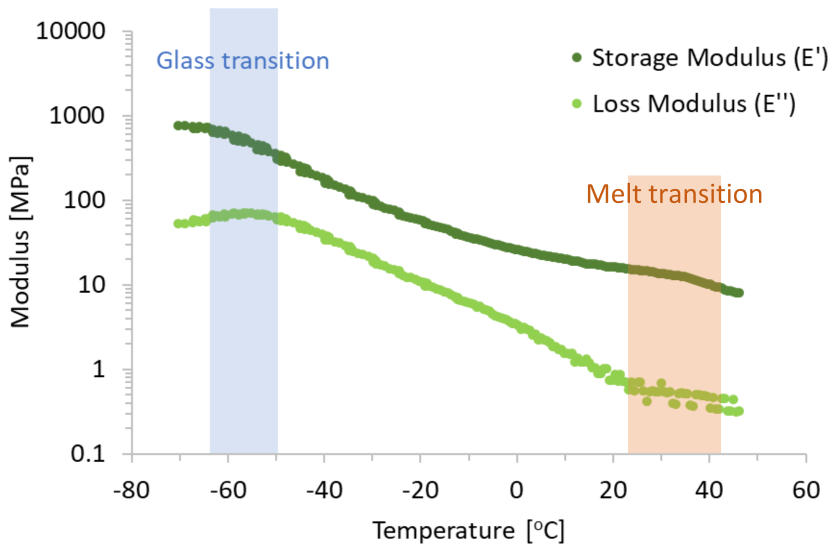
Dynamic Mechanical Analysis (DMA) to Measure Viscoelastic Behavior

- Viscoelastic materials have mechanical responses between those of elastic solids and viscous fluids
- DMA applies an oscillatory stress and measures the material response

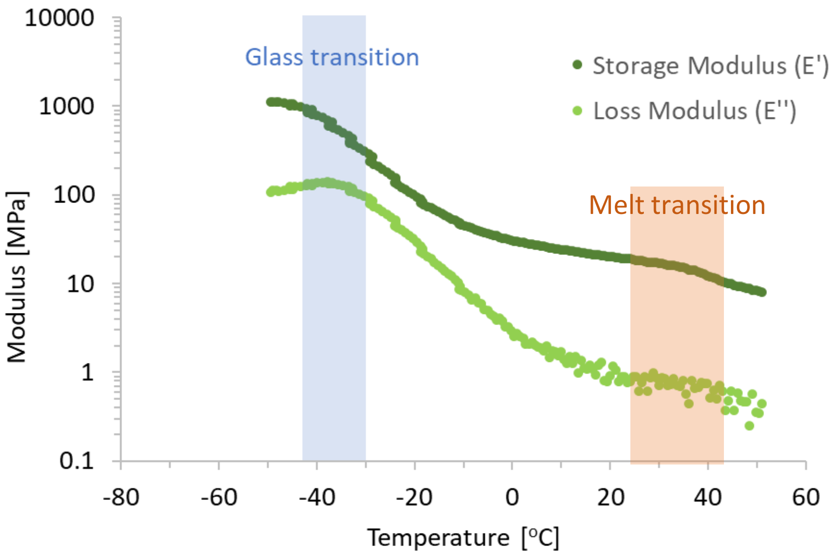




Modulus v. T: POE



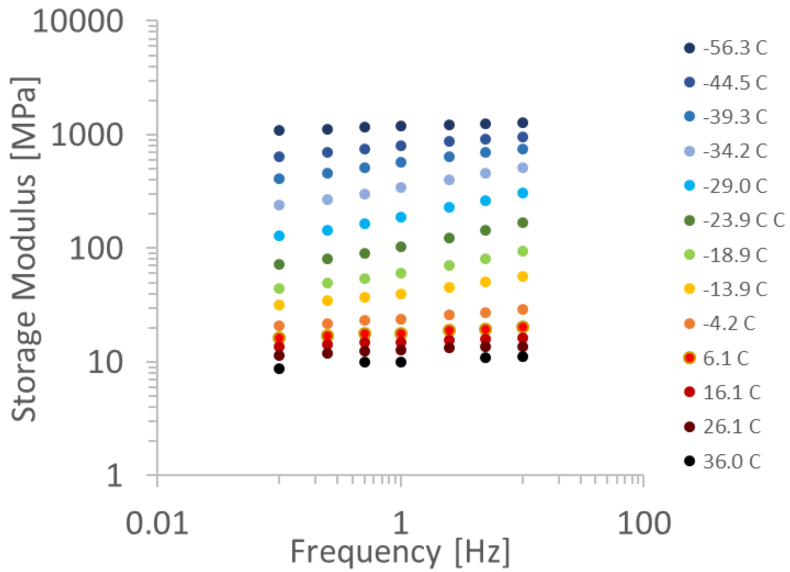
Modulus v. T: EVA



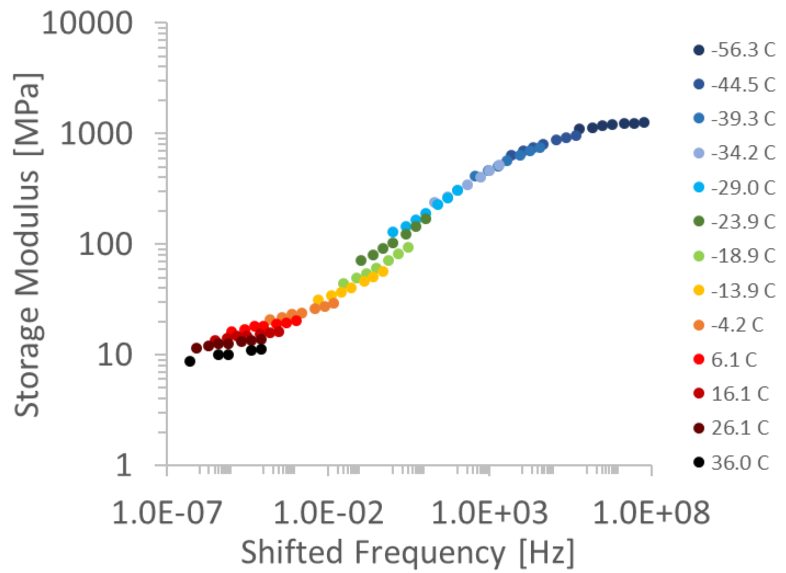
Time-Temperature Superposition: Application

- Measurements of modulus at very low frequencies are time consuming and at very high frequencies can be unfeasible

Frequency Sweeps: EVA



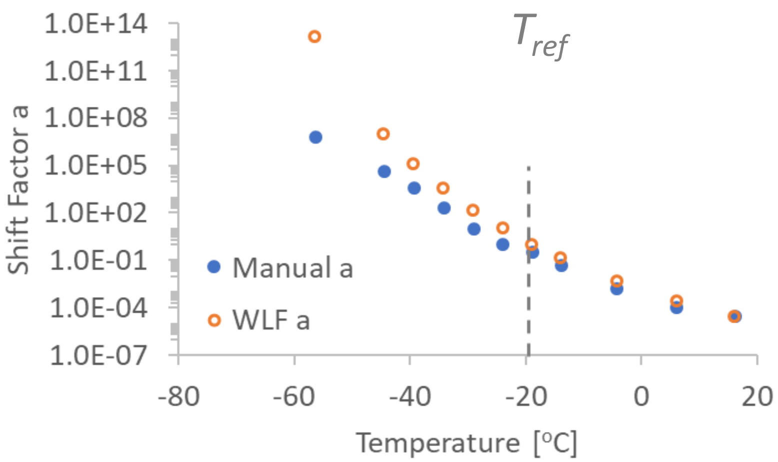
Storage Modulus Master Curve: EVA



Williams-Landel-Ferry (WLF) equation:

$$\log(a_T) = \frac{-C_1(T - T_{ref})}{C_2 + (T - T_{ref})}$$

TTS Shift Factors: EVA

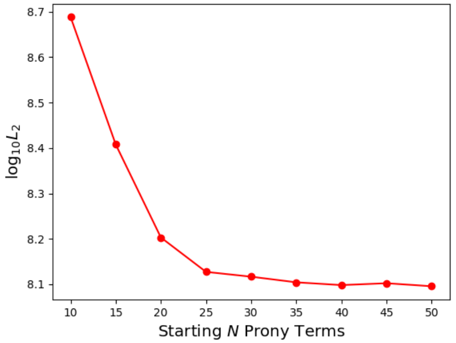


Times Scale: Module Temp. Changes   Wind Gusts

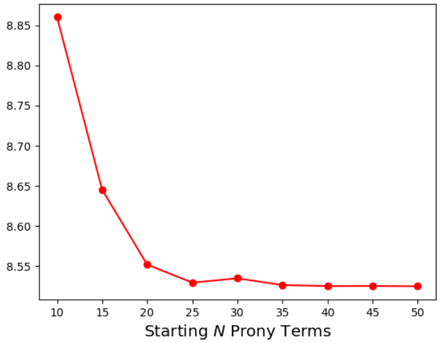
Time-Temperature Superposition: Fit

- Master curves of each material consist of shifted DMA data collected on multiple samples and smoothed
- The number of Prony terms was varied from 10 to 50, with 25 terms selected to minimize L_2 *(below)*

L_2 Error: POE

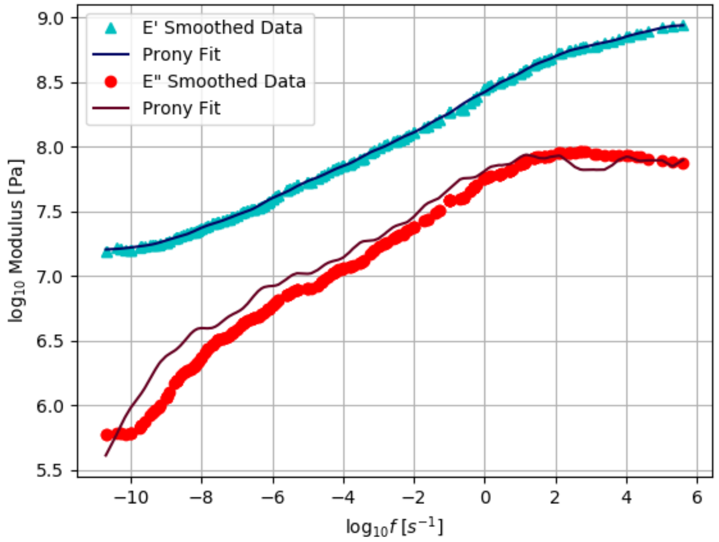


L_2 Error: EVA

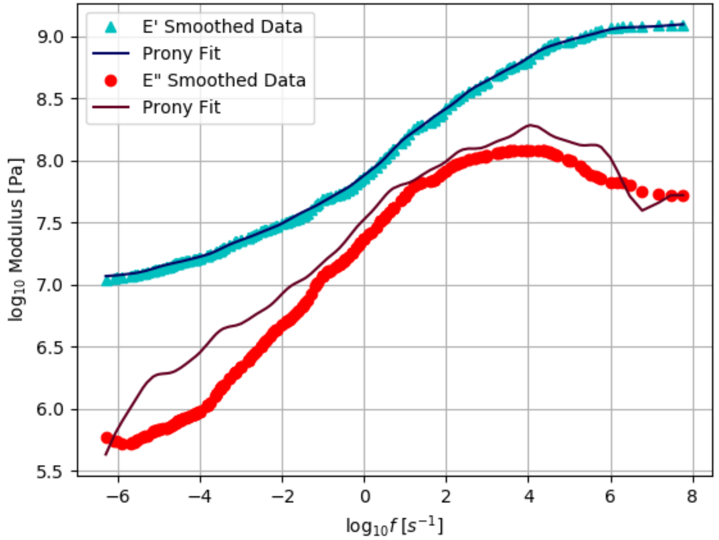


- Prony series fits *(lines in plots right)* capture both the elastic and viscous material responses of polymers

Modulus Fit: POE

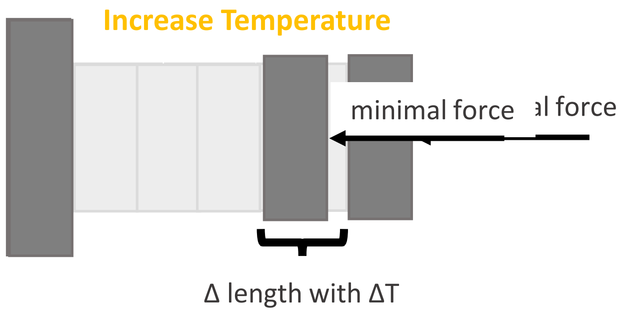


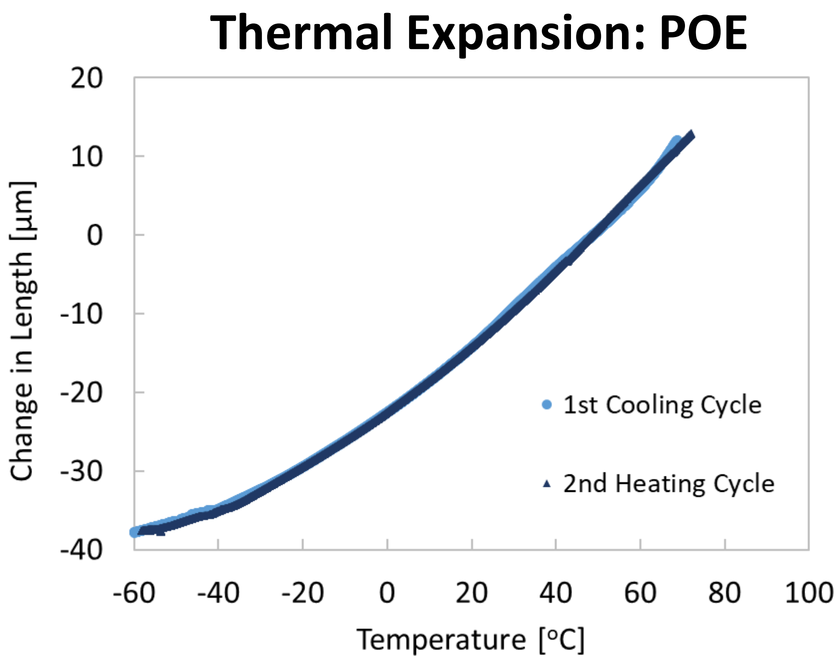
Modulus Fit: EVA

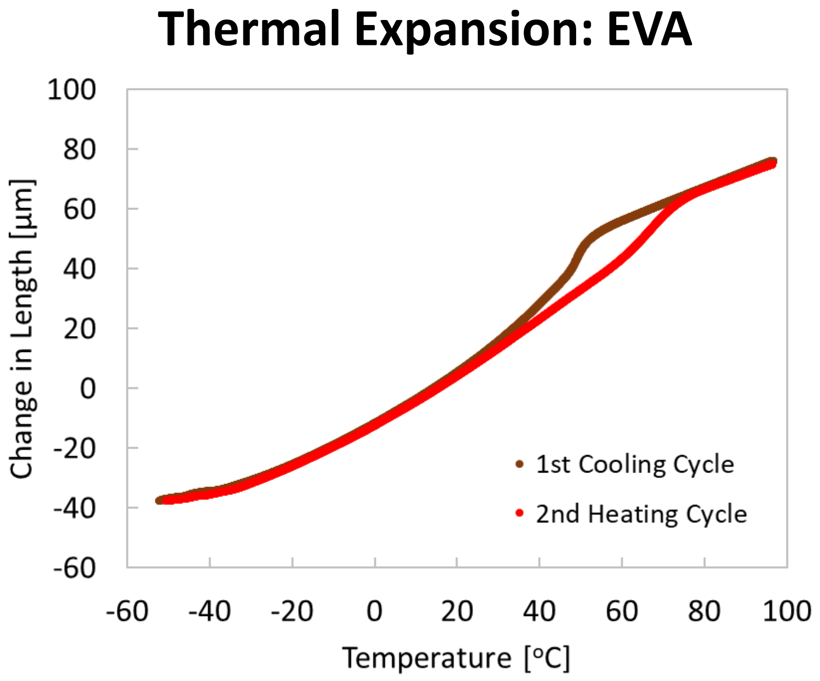


Thermal Expansion Coefficient

- Measure thermal expansion over operating temperatures with a thermal mechanical analyzer (TMA)







Calibrating Sandia's Universal Polymer Model

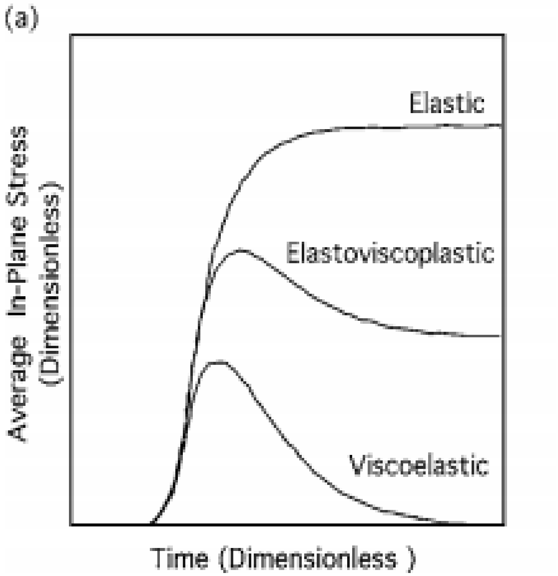
- Viscoleastic properties are captured with parameters from master curve creation and prony-series fit:
  - C_1 , C_2 , T_{ref} , E_o , E_∞ , τ_i , f_i

- Thermal expansion properties captured with the series fit of TMA data
  - τ_i, β_i

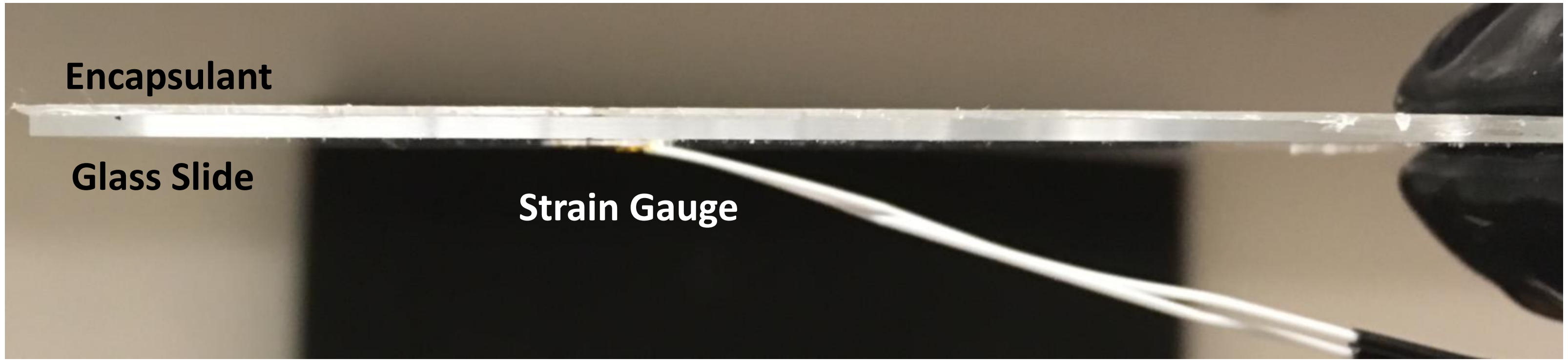
- Model is also capable of handling curing kinetics, future work could capture full lamination conditions

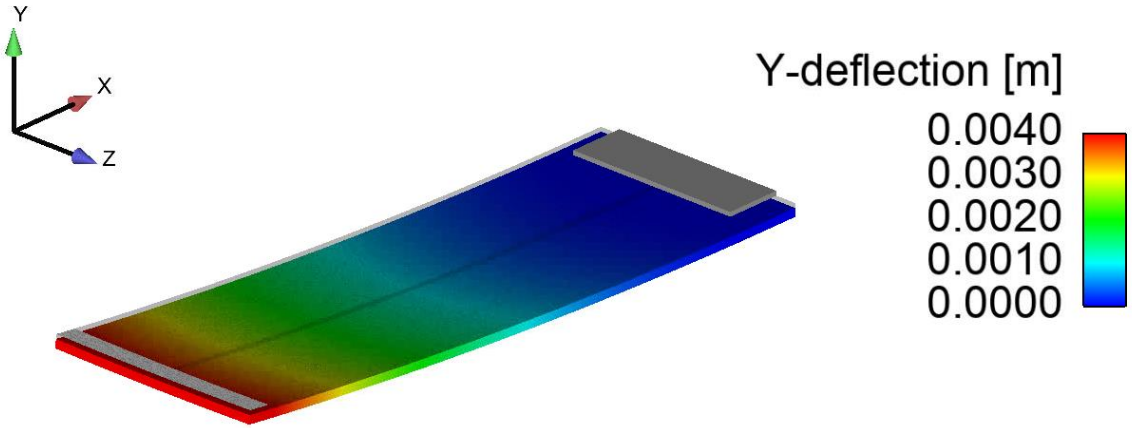
Validation Experiments: Cantilever Beam Method

- Simple geometry for experimental validation of encapsulant material model



L.F. Francis, et al., *JMatSci* 2002

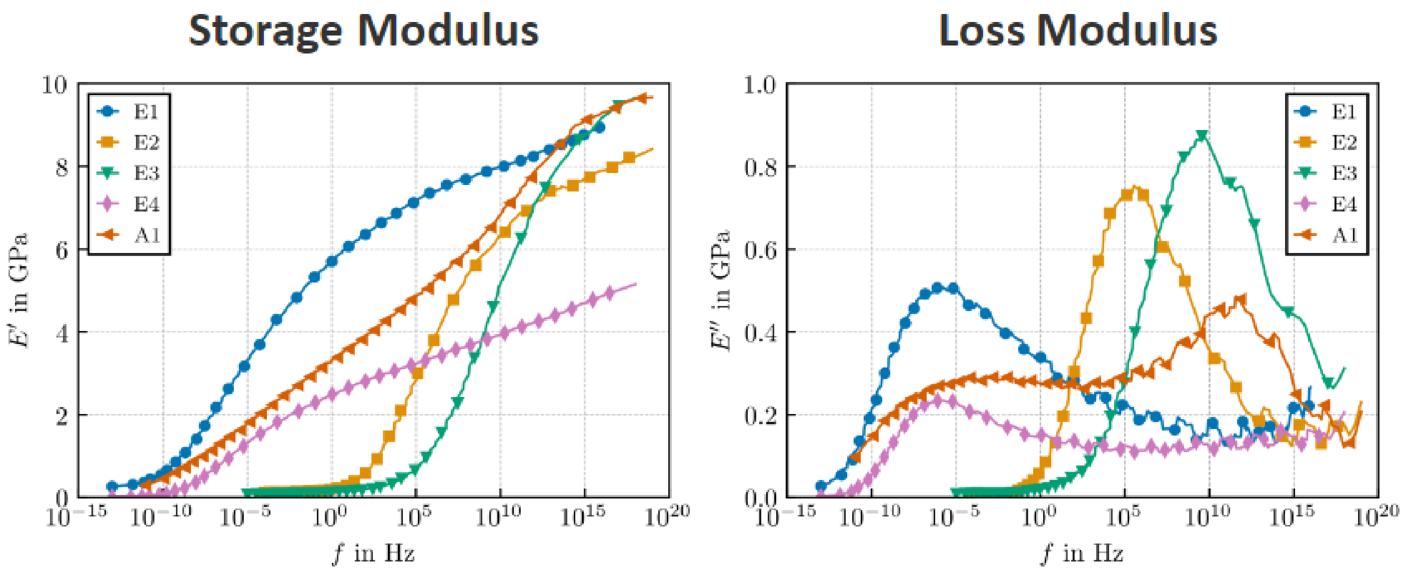




- System can also be modeled in an FEM for quick troubleshooting during incorporation of Universal Polymer Model into SIERRA

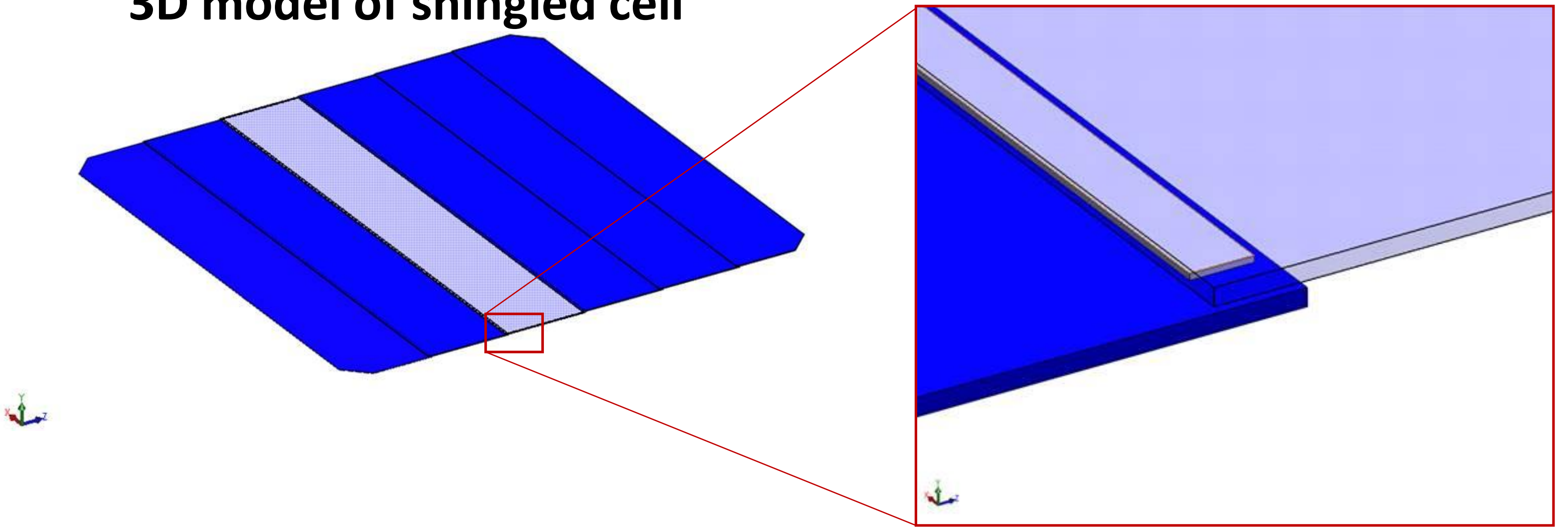
Ongoing Work: Incorporation of Viscoelastic Model for ECAs

- Several electrically conductive adhesives (ECAs) have been characterized at NREL using similar methods to capture viscoelastic parameters
- Ongoing effort to implement these material models into a 3D module-relevant geometry with deformations informed by full module models



M. Springer, N. Bosco; 2019 DuraMAT Fall Workshop

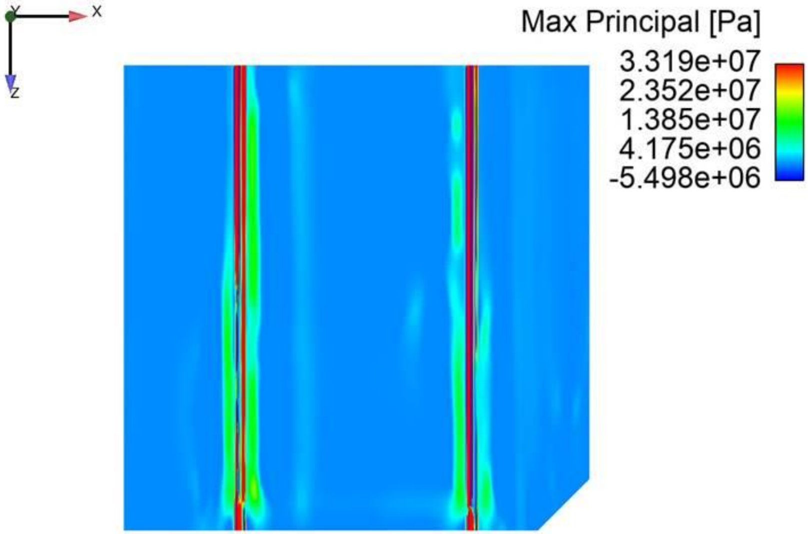
3D model of shingled cell



Future Direction: Cell Cracking

- Will use a probability-based approach to check predicted high stress regions against experimental data of stress-at-failure.

Max Principal Stress on Cell: coupon w/ glass, EVA, backsheet



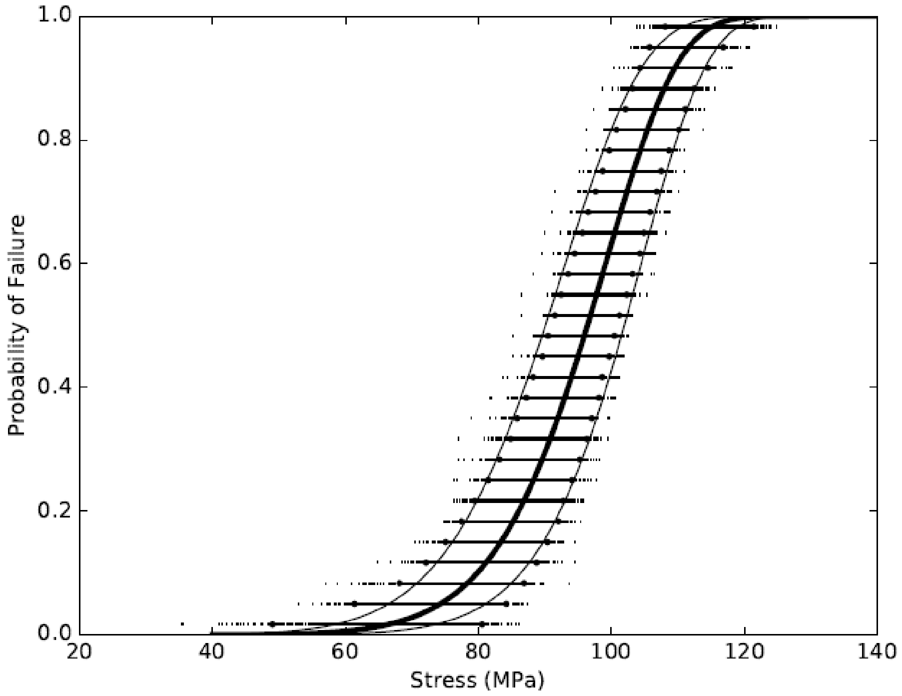


Figure 3: Uncertainty in P_f given nominal values $\sigma_0 = 100$ and $\rho = 10$ and a sample size $n = 30$

S. Gutziak et al., SAND 2019-3477 CTF

Summary

- Multi-scale, multi-physics modeling can be used to:
  - determine the sensitivity of module behavior to material or design changes
  - identify areas of stress that can lead to failures
- Encapsulant thermal and viscoelastic behavior was characterized for two commercial materials: EVA and POE
- This work improves our ability to model modules under the wide range of stresses seen in operation and accelerated tests

Questions?