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Materials model development and instrumented PV module testing to improve finite element modeling capabilities

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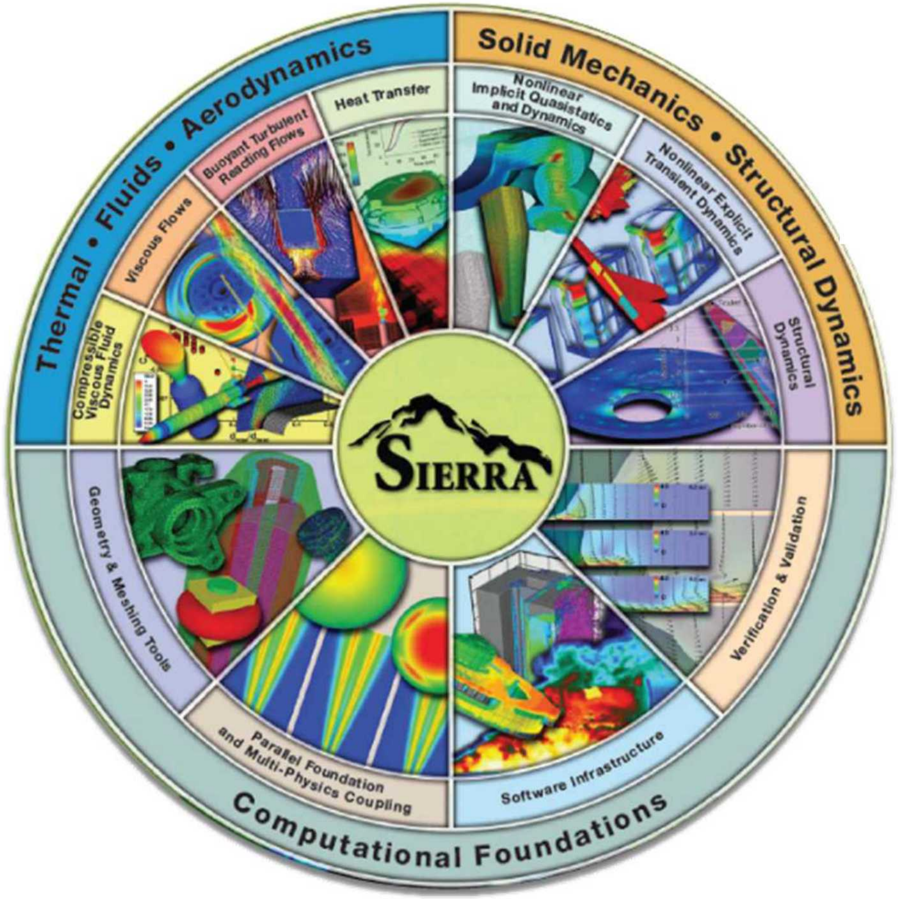
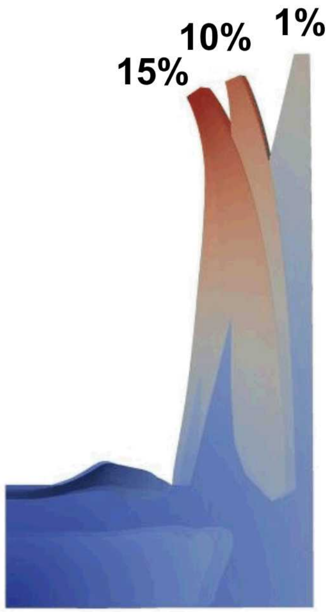
Outline

- Finite Element Modeling Capability Background
- Encapsulant Thermal and Viscoelastic Characterization
- Model Parameterization and Validation Techniques
- Custom Instrumented Modules

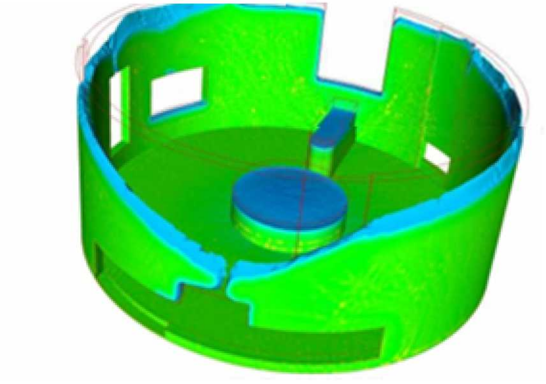
Sandia's Foundation for Advanced Computational Modeling

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

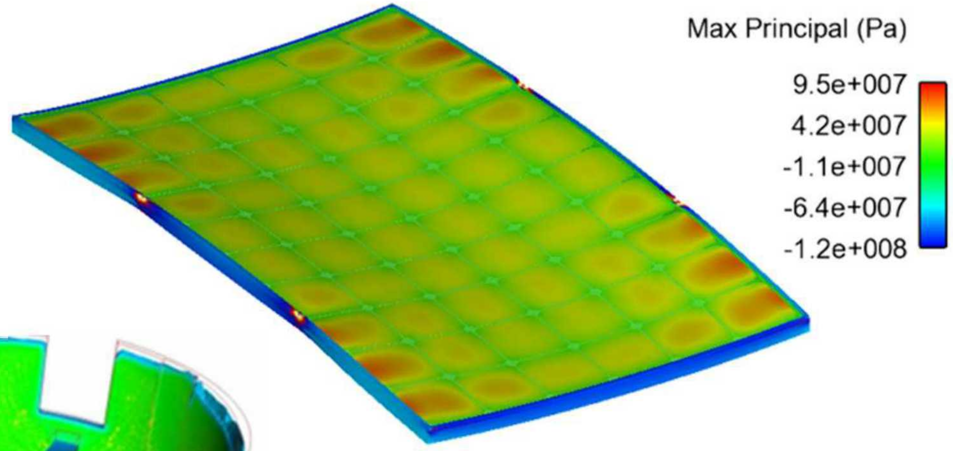




Cure shrinkage causes warpage of a solid part



Liquid foam reacts, expands, solidifies to fill a mold

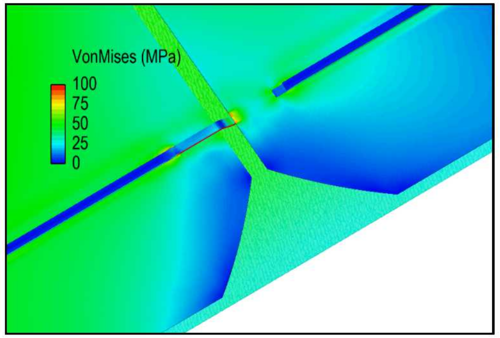


Some adaptations needed to use this platform for PV modules in their operating and testing environments

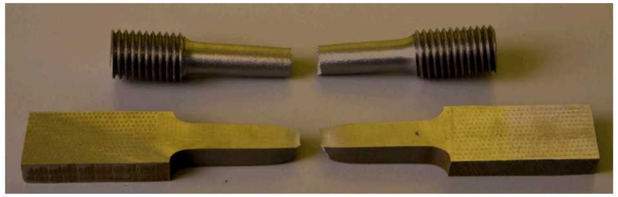
Capability Development of Multi-Physics Models for PV

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

Mechanical stress
[Hartley, SNL]

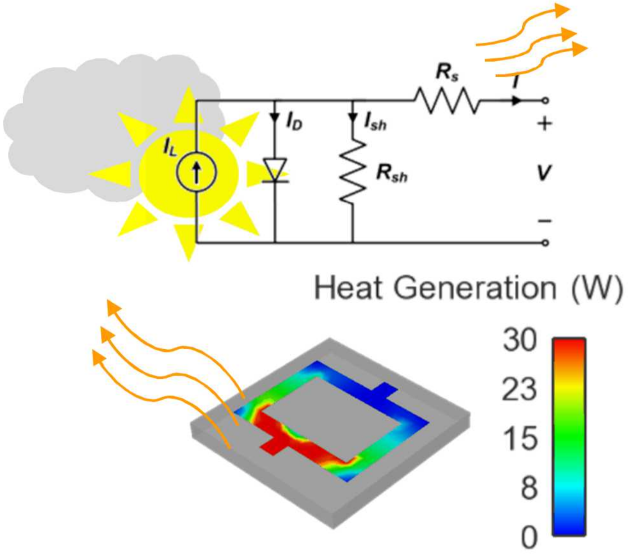


Thermal stress
[Hartley, SNL]



Material responses:

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



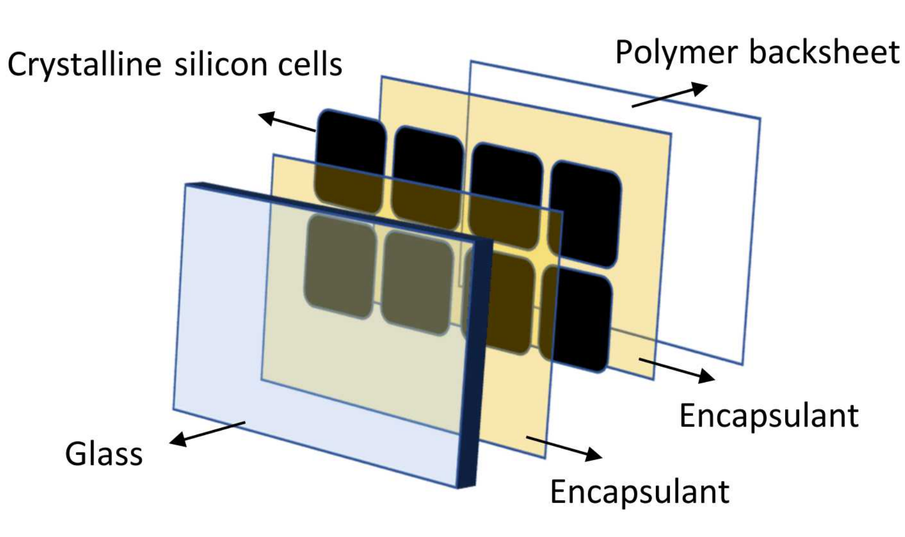
Electrical-thermal coupling [SNL]

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

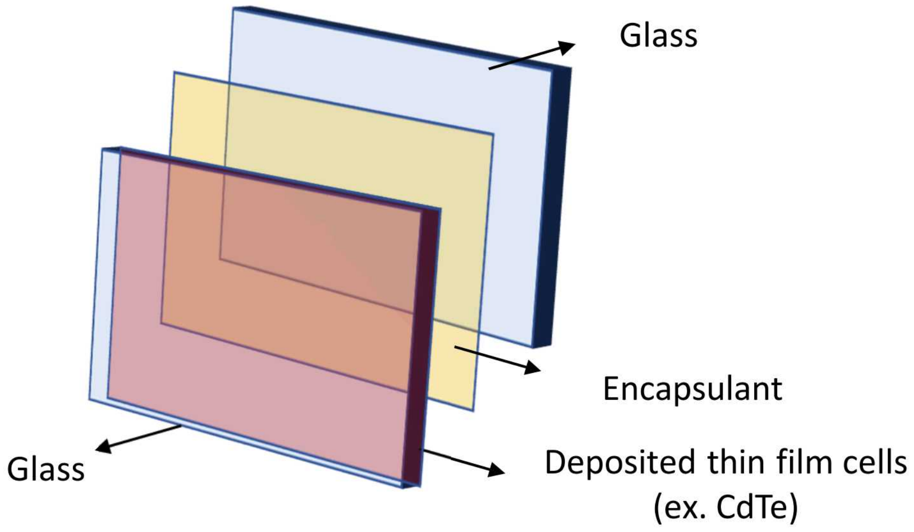
Polymer Materials in PV Modules

- Encapsulants and backsheets must perform several key roles including:

  protect cells and metallization from water and other environmental stresses, maintain electrical insulation, provide adhesion between layers of the laminate, and maintain high transparency through PV-relevant wavelengths



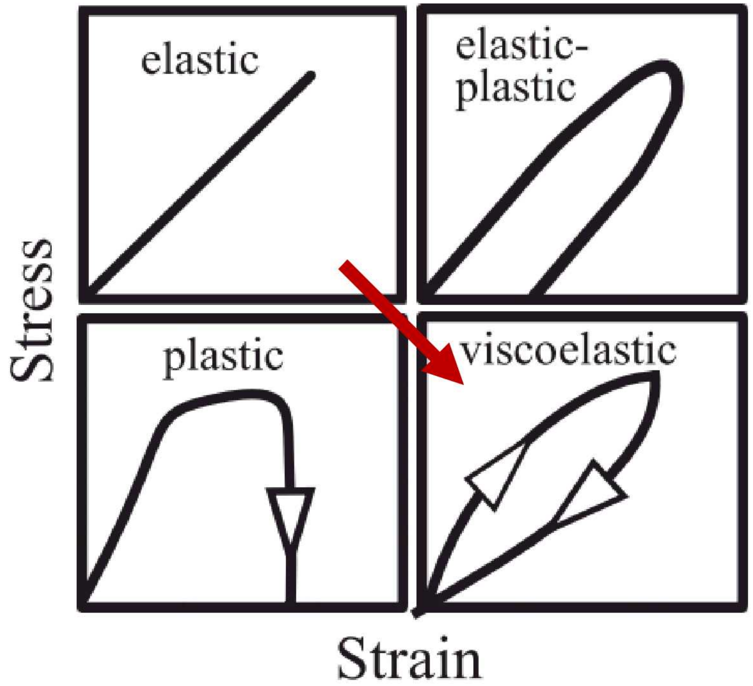
Layers in silicon PV modules

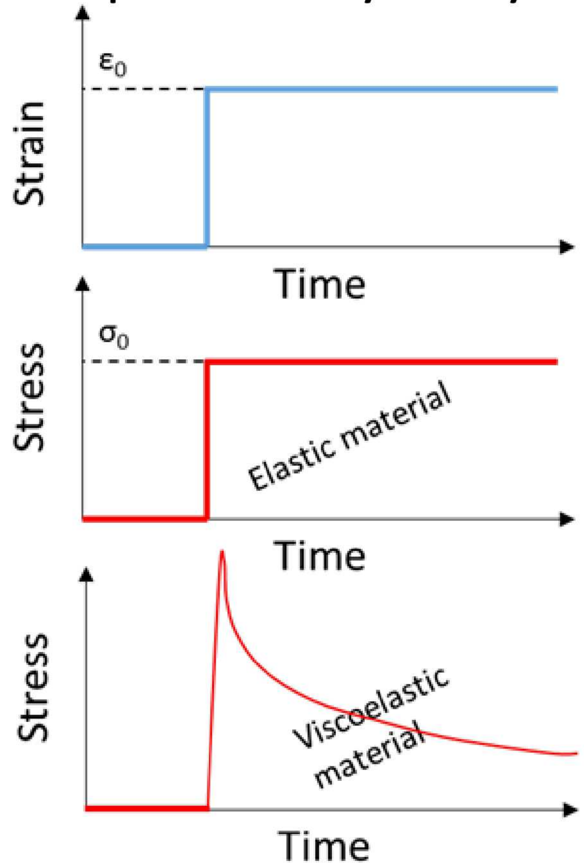


Layers in thin-film PV modules

Adding Time and Temperature Dependency of Polymer Materials

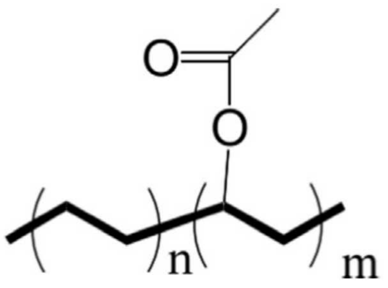
- The viscoelastic nature of polymer encapsulants is potentially a key factor affecting component stress states



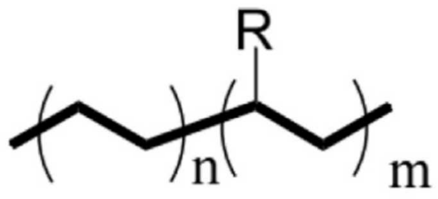


- The polymeric layers of modules are known to have higher thermal expansion coefficients than surrounding materials, leading to stress during thermal cycling

Adding Time and Temperature Dependency of Polymer Materials



- **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

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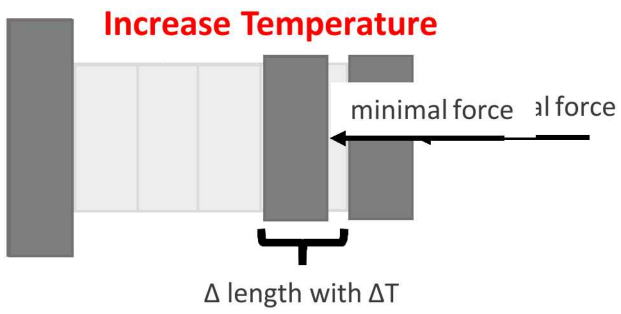
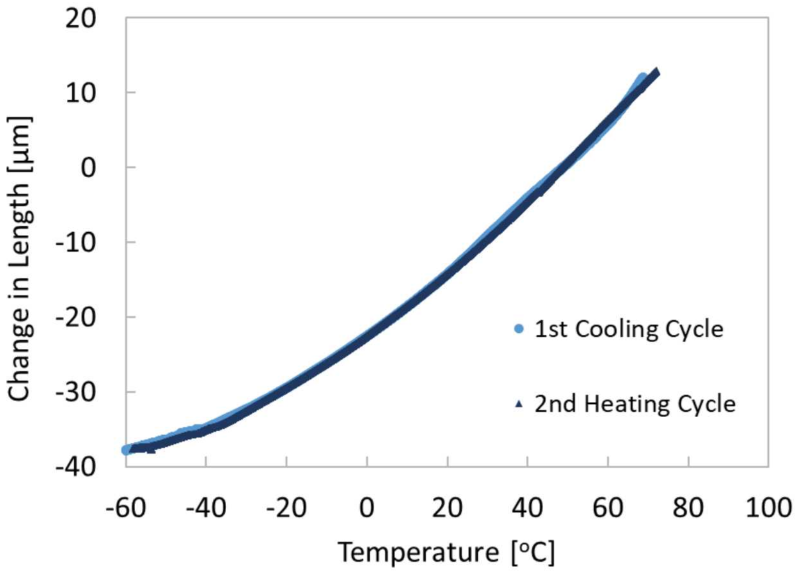
Thermal Expansion Coefficient

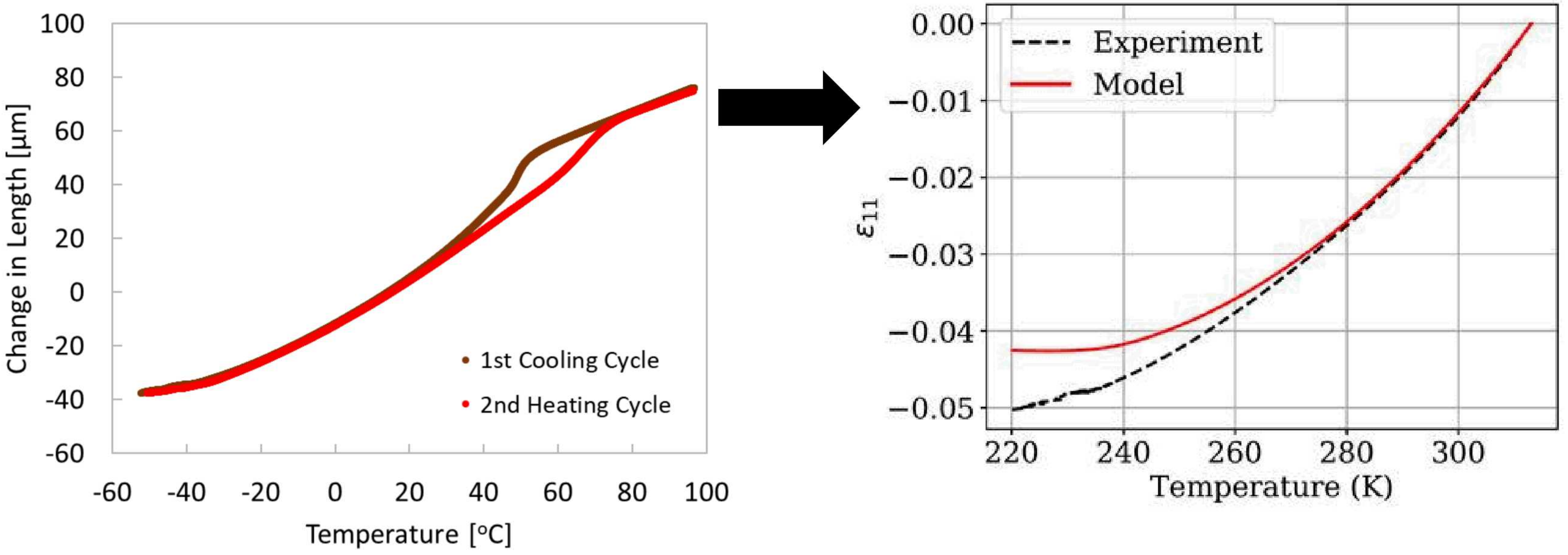
- Measure thermal expansion over operating temperatures with a thermal mechanical analyzer (TMA)



Thermal Expansion: POE

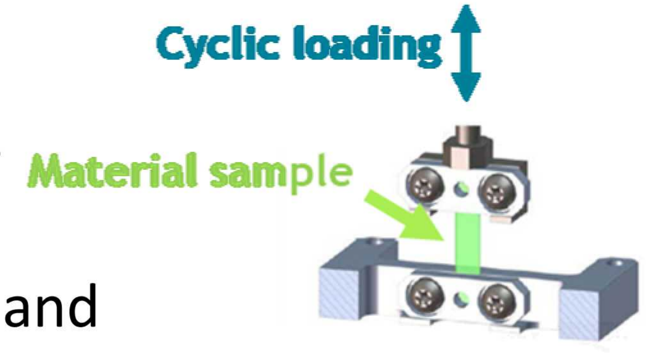


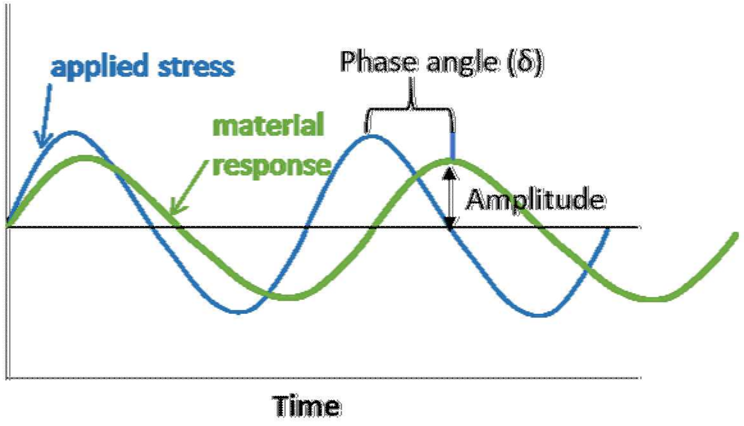
Thermal Expansion: EVA



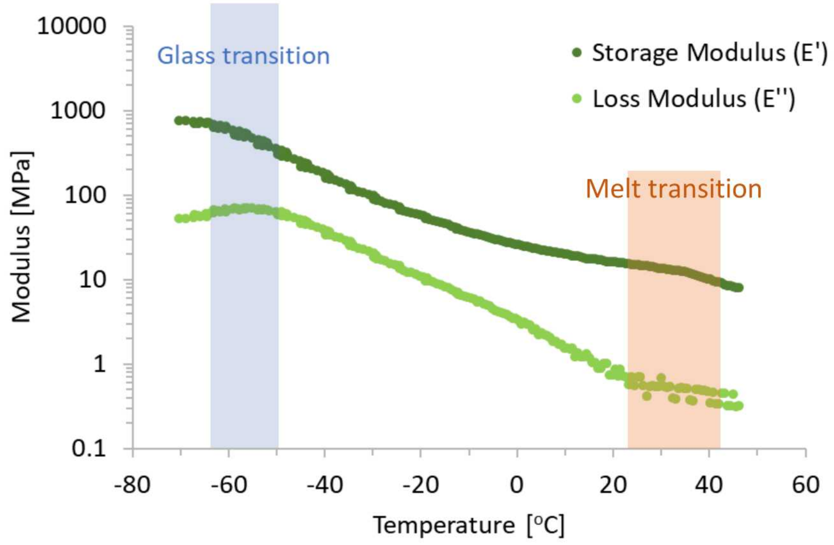
Dynamic Mechanical Analysis (DMA) to Measure Viscoelastic Behavior

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

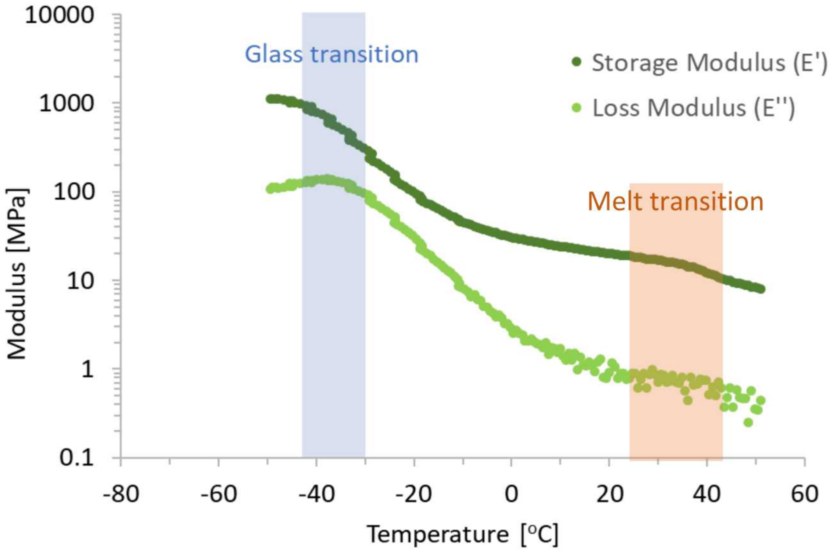




Modulus v. T: POE



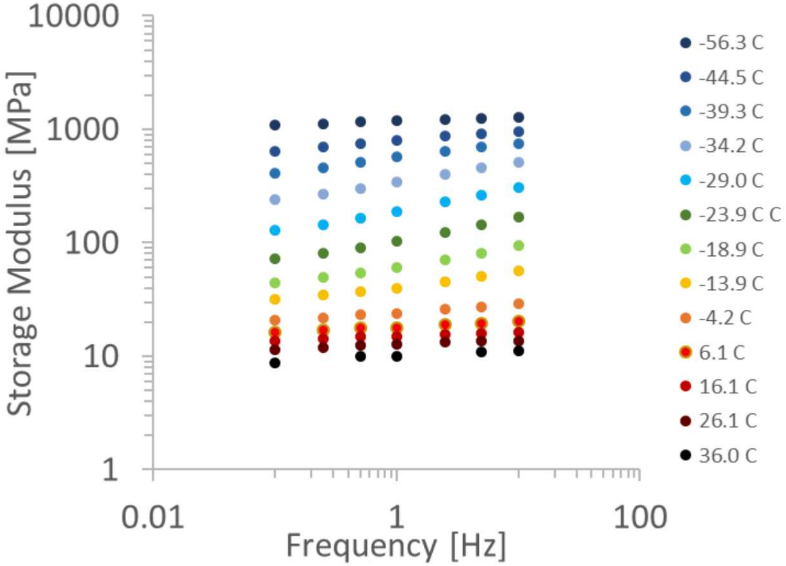
Modulus v. T: EVA



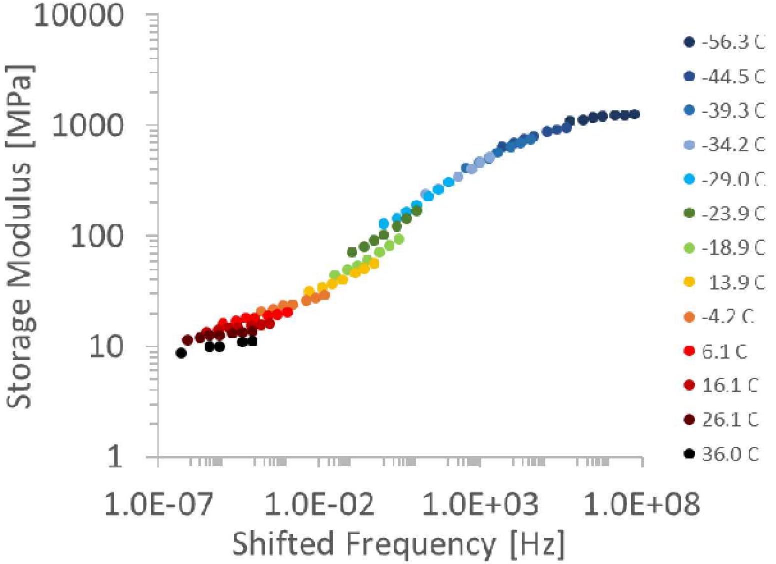
Time-Temperature Superposition: Application

- 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

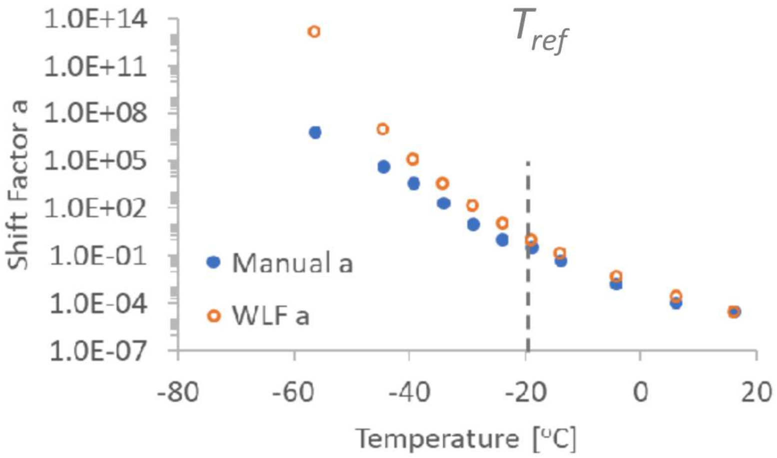


Times Scale: Module Temp. Changes Wind Gusts

Williams-Landel-Ferry (WLF) equation:

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

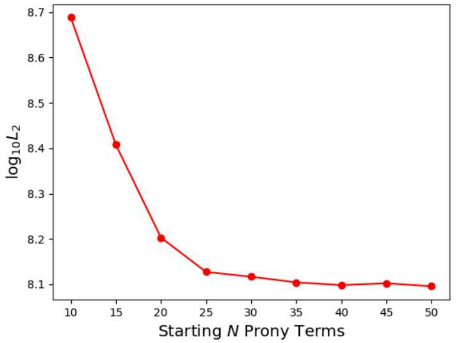
TTS Shift Factors: EVA



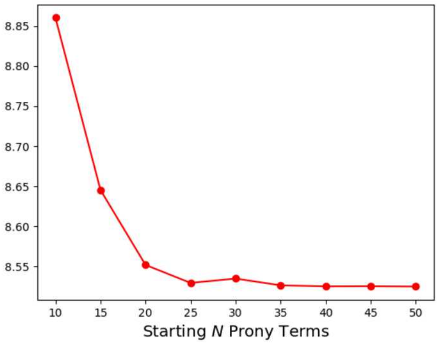
Time-Temperature Superposition: Fit

- 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

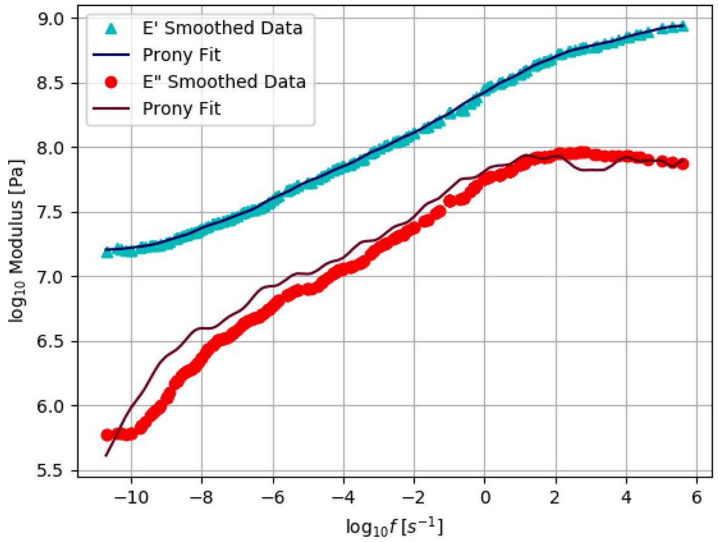


L_2 Error: EVA

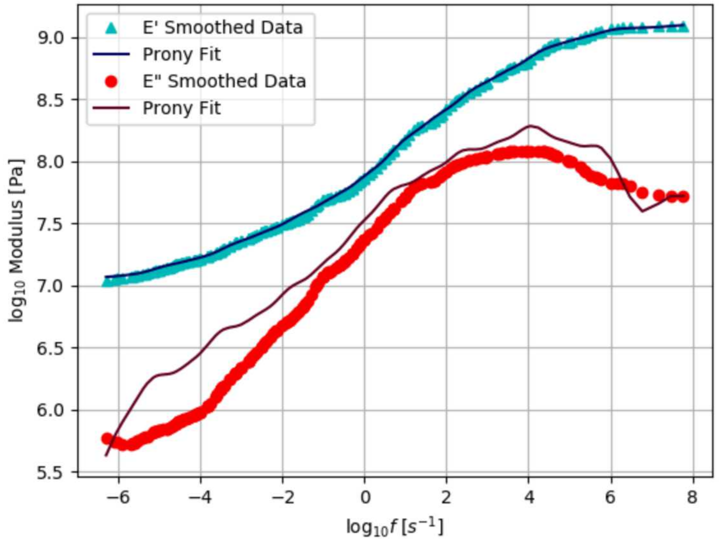


- Prony series fits capture both the elastic (blue) and viscous (red) material responses of polymers

Modulus Fit: POE



Modulus Fit: EVA



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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

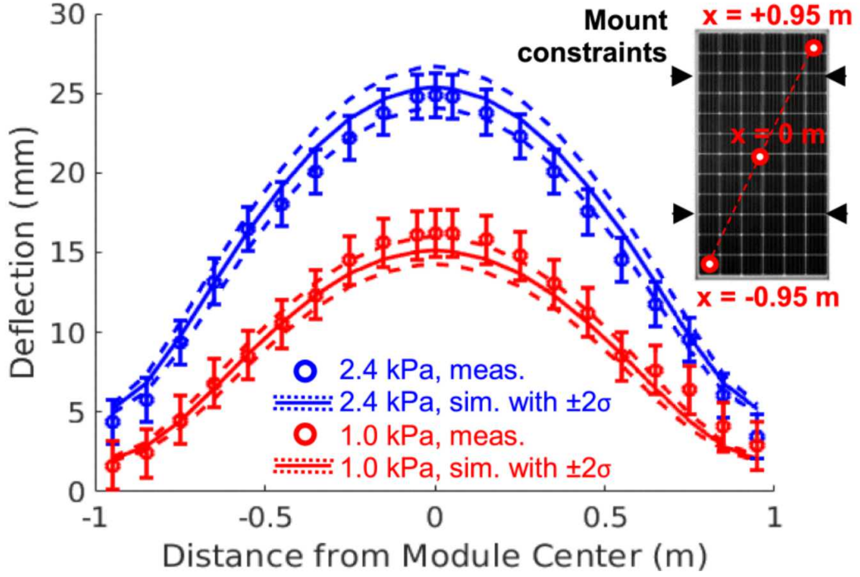
- Thermal expansion properties captured with the series fit of TMA data
  - $VolCTE_{rubbery}$, $VolCTE_{glassy}$, τ_i, $\beta_{i,}$

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

DB Adolf and RS Chambers, J. Rheology, 2007

Validation Efforts

- Validate material model
  - Stress relaxation measurements offer an alternative measurement of viscoelastic behavior of films
  - Directly comparable to DMA results and simple FEA geometry
- Validate FEM Output
  - Module deflection measured under static load on two module types [JY Hartley et al., IEEE-JPV, 2020]



  - Novel instrumented modules were designed and fabricated to allow *in situ* measurements of cell strain [AM Maes et al., IEEE-PVSC Proceedings, 2020]

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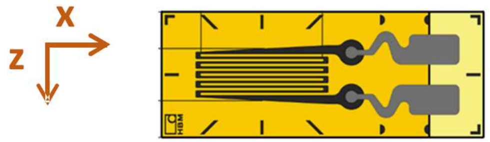
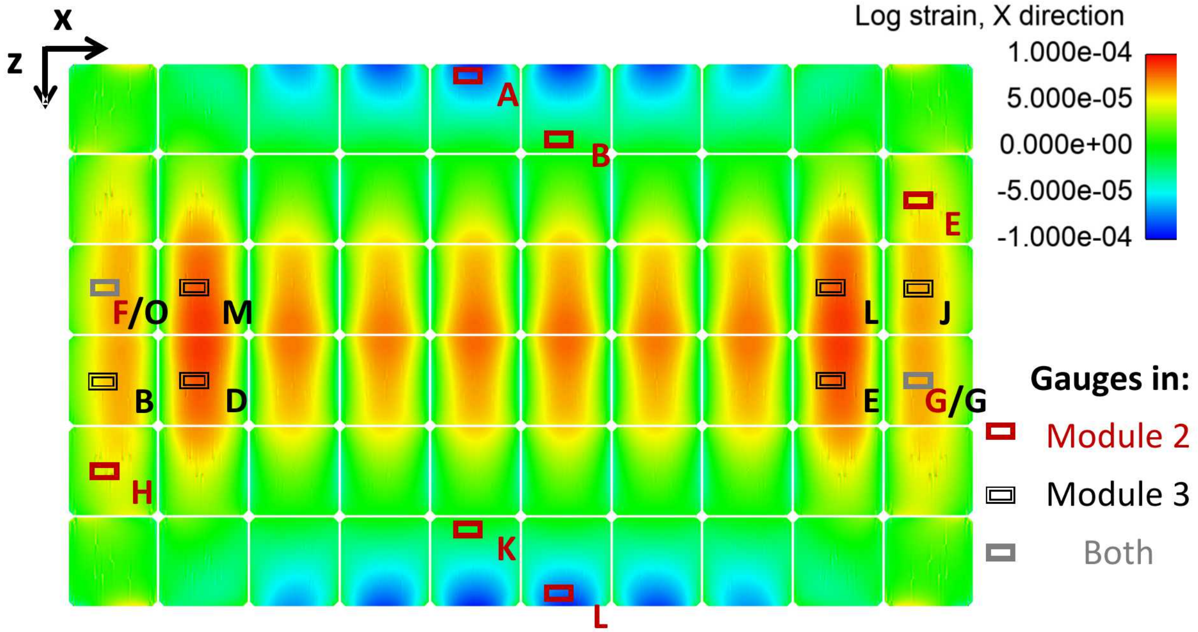
Design of Instrumented Modules

- Strain gauges allow continuous high precision measurement at high sampling rates, and their thin profile allows them to be encapsulated in PV module laminates without disrupting stress states.

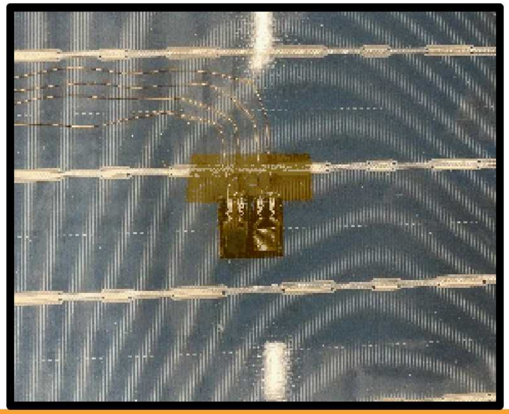


Linear gauge sensitive to strain in x-direction



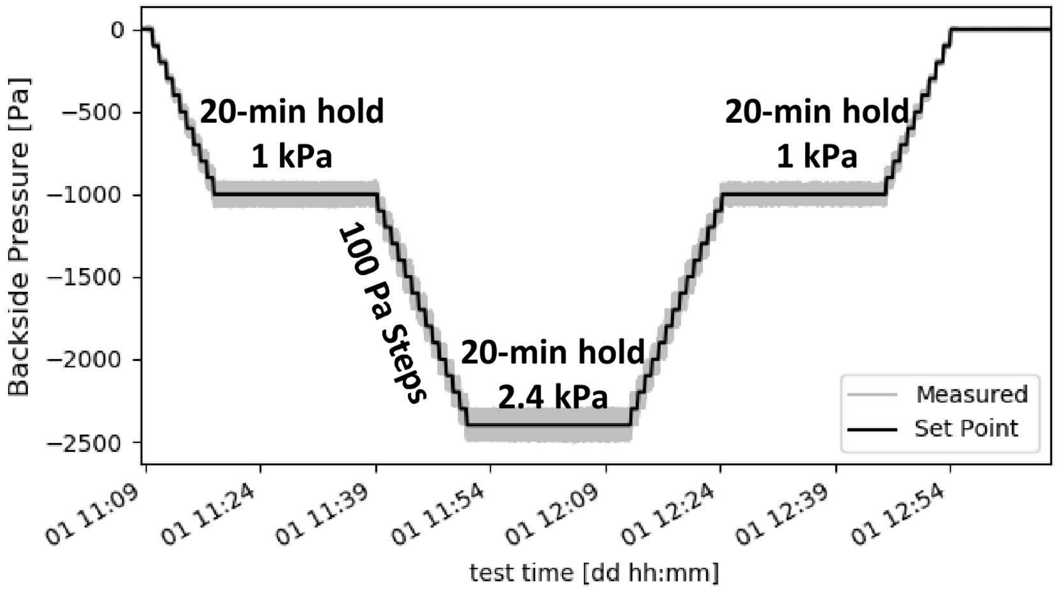
Model-predicted strain maps under 2.4 kPa frontside load with strain gauge locations

- Cell strain maps of a glass-BS PV module (right) were used to select strain gauge locations
- 4 modules were constructed, 1 control and 3 with unique data objectives
- Wiring continuity checks and EL imaging confirm the instrumentation survived lamination and did not cause cell cracks

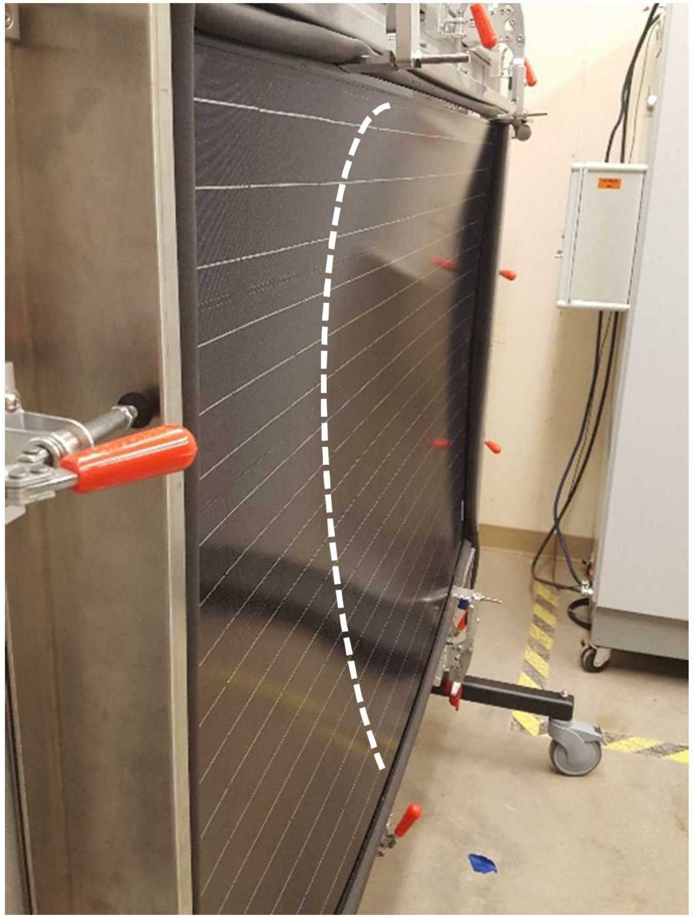


Mechanical Testing with a LoadSpot Tester

- The LoadSpot is an air pressure based mechanical tester which enables repeatable, controlled loads with simultaneous internal and external data collection
- Identical load sequences were applied by pulling vacuum on the back of each module:



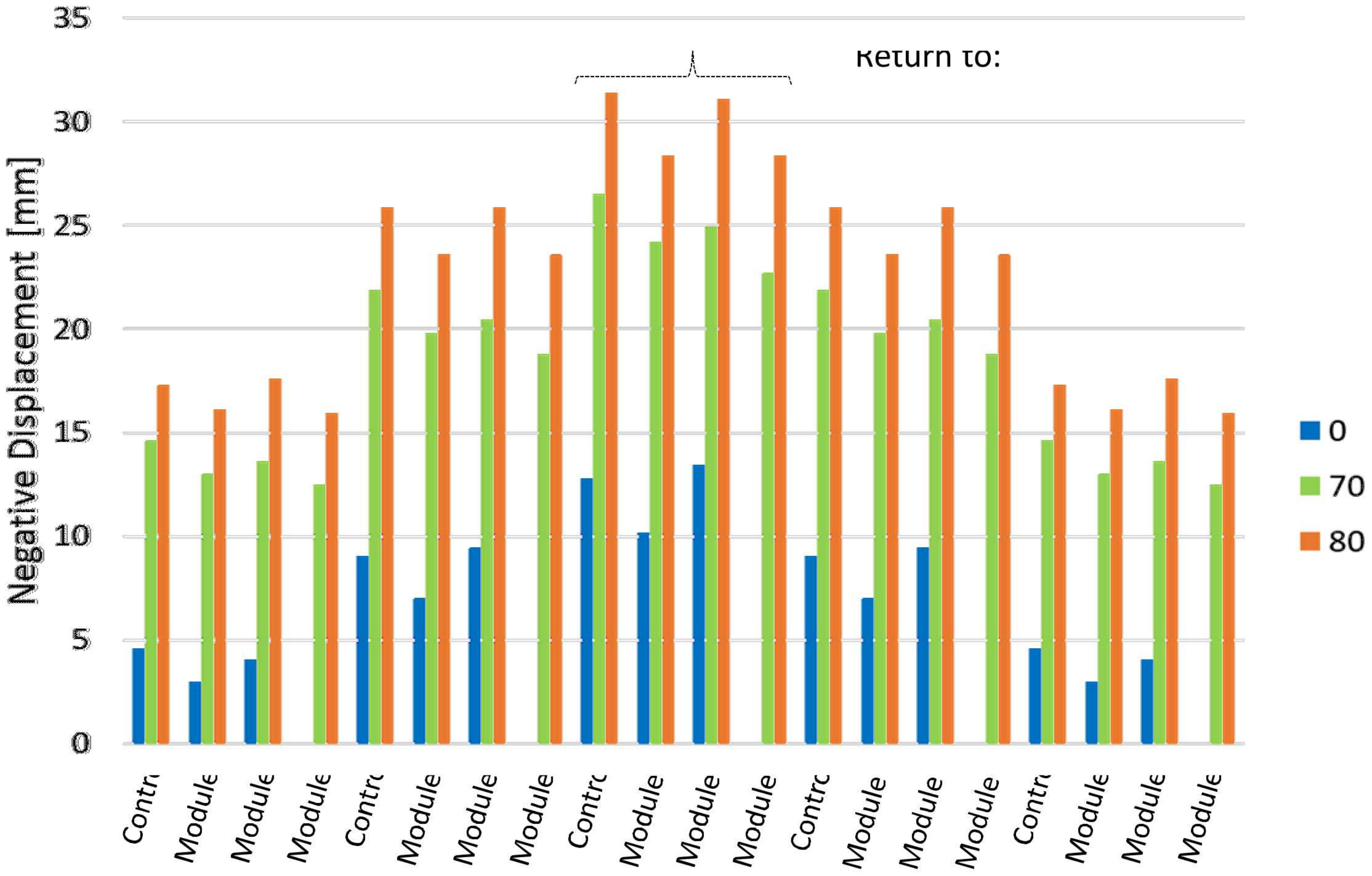
BrightSpot Automation



Module deflecting under 5.4kPa load conditions (imposed via vacuum behind the module)

Module Deflection Results

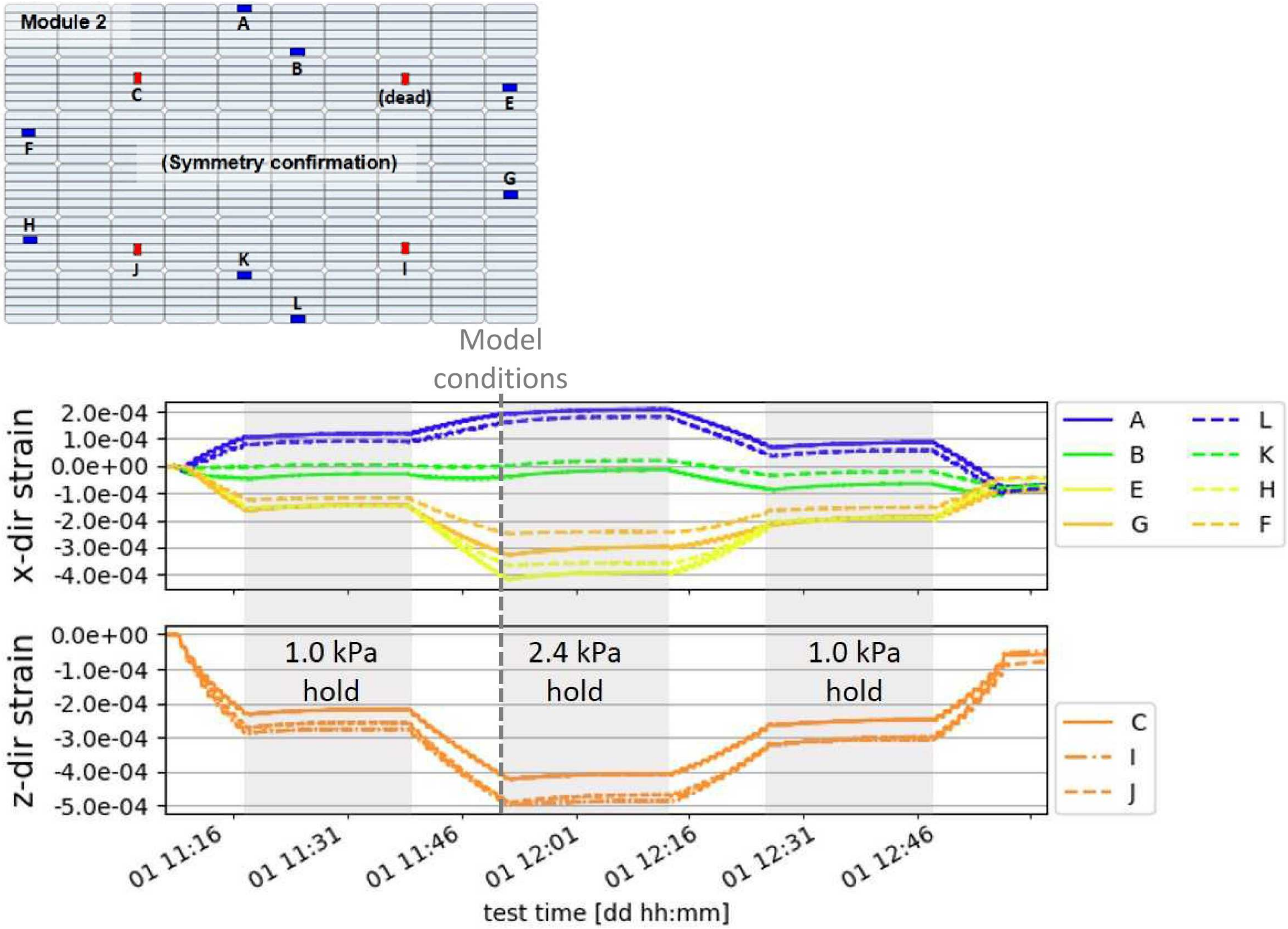
- Optical sensors measured displacement of the backsheet surface in the y-direction during each test
- The addition of strain gauges and wiring did not greatly effect the bulk mechanical behavior of modules compared to the control



Negative displacement at 3 sensor locations under various load setpoints

Cell Strain Measurement Results: Symmetry

- Largest strains are measured in the module center, as predicted by computational model. Edge-module gauges "A" and "L" measure strains opposite in direction to center module gauges, as expected.
- Trends match in symmetric gauge locations but magnitudes vary up to 20%, perhaps due to module inconsistences or misaligned strain gauges.

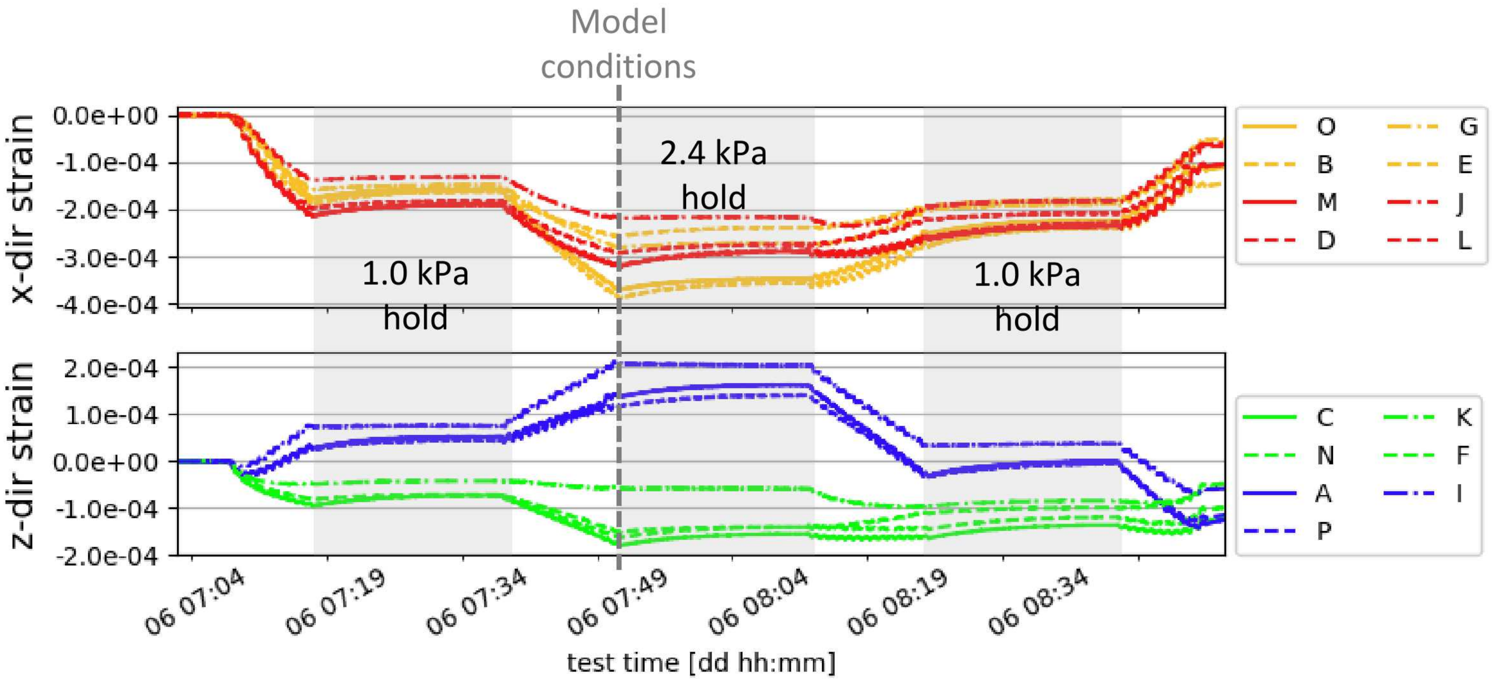


Module 2 strain gauge readings from 0 ->2.4 kPa -> 0 ramp experiment

Cell Strain Measurement Results: Effect of Junction Box

- Module 3 instrumented to assess influence of junction box on surrounding cells

- Largest difference between module left/right sides observed in x-direction readings surrounding J-box, where J-box seemed to relieve strain (J and G w/ J-box, B and O w/o)



Module 3 strain gauge readings from 0 ->2.4 kPa -> 0 ramp experiment

Instrumented Modules: Ongoing Work and Future Applications

- An area of further investigation is the irreversibility observed in the strain measurements. Strain after the return to zero load tends to remain below zero, likely due to a combination of temperature effects on instrumentation and irreversible changes in the mounting or module structure.
- These results are useful as model validation data to improve confidence in more complex FEM predictions of internal components
- Use of these instrumented modules in the future could include:
  - collection of mechanical histories of modules in the field under snow loading or high wind conditions
  - assessment of cell strain during accelerated test protocols

Summary

- Multi-scale, multi-physics modeling can be used to:
  - determine the sensitivity of module behavior to material or design changes
  - identify locations of stress that can lead to failures
  - assess smaller test geometries used in accelerated stress testing
- Encapsulant thermal and viscoelastic behavior was characterized for two commercial materials: EVA and POE
- Validation techniques were developed to increase confidence in the material model and overall FEM results
- This work improves our ability to model modules under the wide range of stresses seen in operation and accelerated tests

Questions?