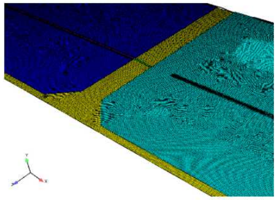
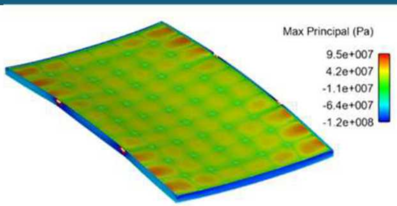
SAND2019-10090C

DuraMAT
Durable Module Materials Consortium

DuraMAT capability area:

# Multi-scale, Multi-physics Modeling for PV Reliability




PRESENTED BY

**James Hartley,** Sandia National Laboratories

DuraMAT Fall Workshop, August 27, 2019

SLAC NATIONAL ACCELERATOR LABORATORY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

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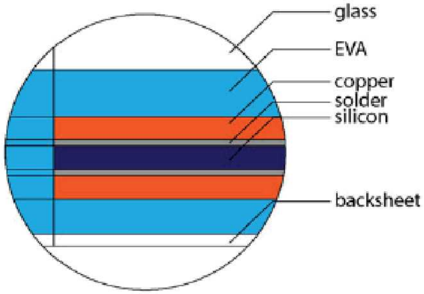
# Contents

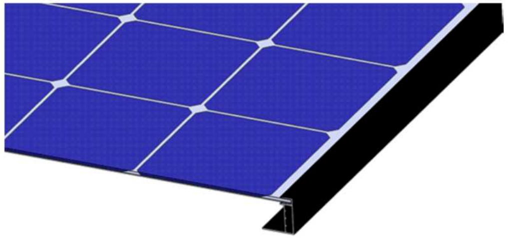
- **Capability area introduction and goals**
- Recent accomplishments and efforts
  - A full-scale module mechanical model with sensitivity analyses
  - SPARK project: Highly instrumented modules for simulation validation and environmental characterization
  - Incorporation of encapsulant viscoelasticity
- Future work

# Multi-scale, Multi-physics Modeling for PV Reliability

- **Goal:** A modeling capability to accurately predict module lifetime
  - Applicable to multiple PV **scales**: From interconnects to full modules
  - Incorporating multiple degradation **physics**: Mechanical stress, thermal stress, materials effects, and more

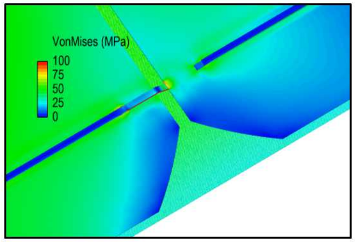



**Interconnect damage**
[Bosco, NREL]

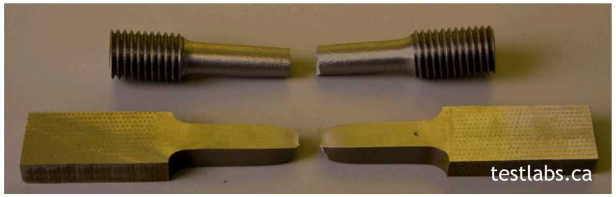


**Full Modules**

**Mini-Modules**
[Hacke, Owen-Bellini; NREL]




**Thermal stress**




**Material responses:**
- Encapsulant viscoelasticity [Maes, SNL]
- Electrically Conductive Adhesive damage mechanisms [Bosco, NREL]
- Backsheet aging [Owen-Bellini, NREL; Moffit, SLAC]


**Mechanical stress**

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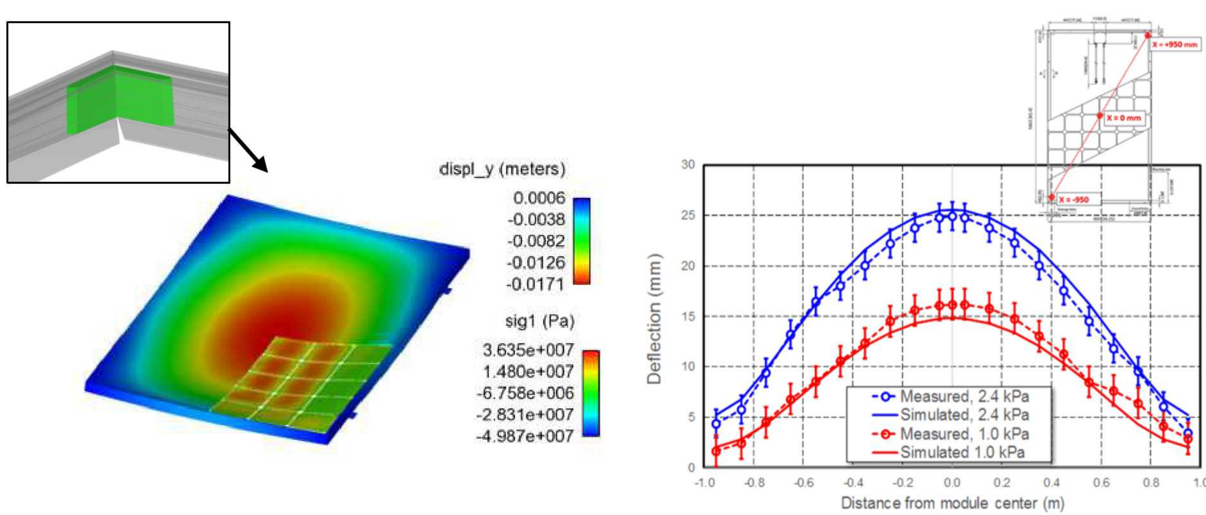
# A Full Module Mechanical Model with Sensitivity Analyses

- **Capability:** Beginning from a module design and Bill of Materials (BOM)- *of any architecture, real or prototype*- generate an accurate model of module response to mechanical load

- **Purpose and applications:**
  - Assessment of designs in arbitrary environments
  - Parametric design and material choice optimization
  - Derivation of internal-scale boundary conditions for accelerated testing

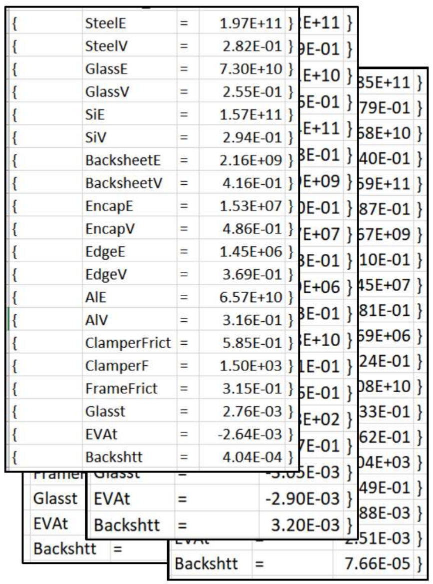

**Module design and Bill of Materials (BOM)**




**FEM representation validated against deflection vs. load comparisons**

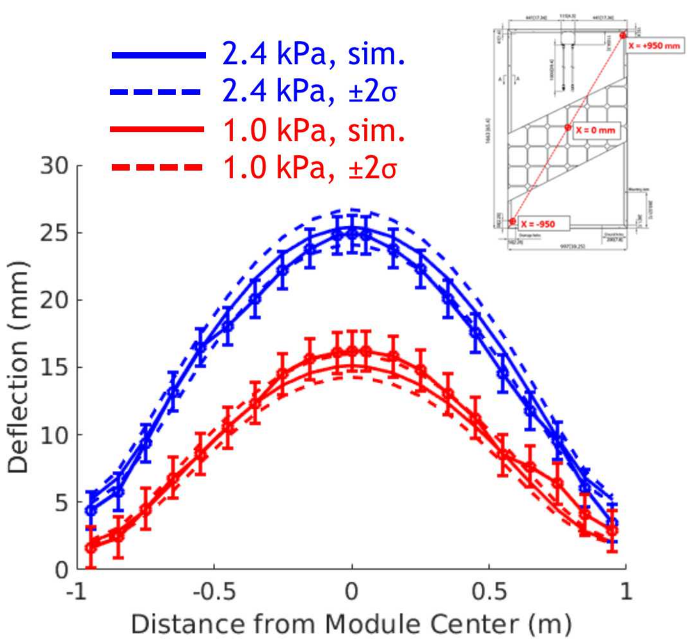
# A Full Module Mechanical Model with Sensitivity Analyses

- 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
- Input parameters (materials, dimensions) were varied parametrically to generate uncertainty estimates and analyze sensitivities
- Workflow is *in theory* applicable to any module and load scenario

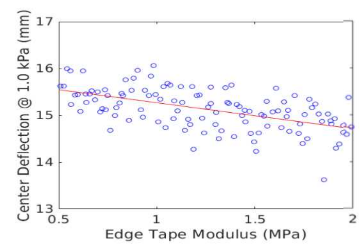


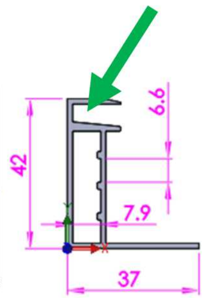
| | | | | |
|---|---|---|---|---|
| { | SteelE | = | 1.97E+11 | } |
| { | SteelV | = | 2.82E-01 | } |
| { | GlassE | = | 7.30E+10 | } |
| { | GlassV | = | 2.55E-01 | } |
| { | SiE | = | 1.57E+11 | } |
| { | SiV | = | 2.94E-01 | } |
| { | BacksheetE | = | 2.16E+09 | } |
| { | BacksheetV | = | 4.16E-01 | } |
| { | EncapE | = | 1.53E+07 | } |
| { | EncapV | = | 4.86E-01 | } |
| { | EdgeE | = | 1.45E+06 | } |
| { | EdgeV | = | 3.69E-01 | } |
| { | AlE | = | 6.57E+10 | } |
| { | AlV | = | 3.16E-01 | } |
| { | ClamperFrict | = | 5.85E-01 | } |
| { | ClamperF | = | 1.50E+03 | } |
| { | FrameFrict | = | 3.15E-01 | } |
| { | Glasst | = | 2.76E-03 | } |
| { | EVAt | = | -2.64E-03 | } |
| { | Backshtt | = | 4.04E-04 | } |

**Parametric inputs: Materials, dimensions 120 total samples**




**Predicted deflection vs. load with parametric uncertainty**




| 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 |

**Parameters highly correlated to module deflection**

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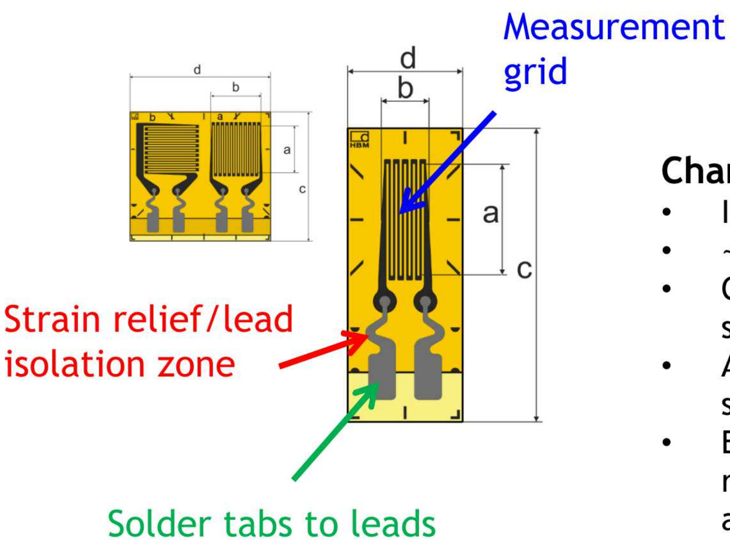
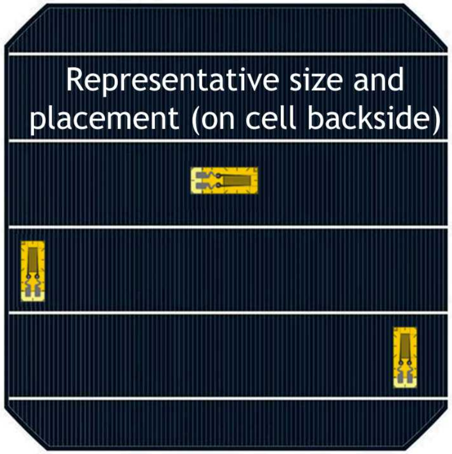
  - Incorporation of encapsulant viscoelasticity
- Future work

# SPARK: Highly instrumented modules for simulation model validation and environmental characterization

- Full module simulation models showed excellent agreement against uniform pressure loading test data, but:
  - Is external deflection vs. load enough to validate a model?
  - Is there a way to measure real fielded module mechanical loads (other than uniform pressure)?
- **Proposed solution:** Embed mechanical instrumentation– strain gauges- into modules to collect internal data to validate internal quantities and assess ability to record mechanical exposures in the field



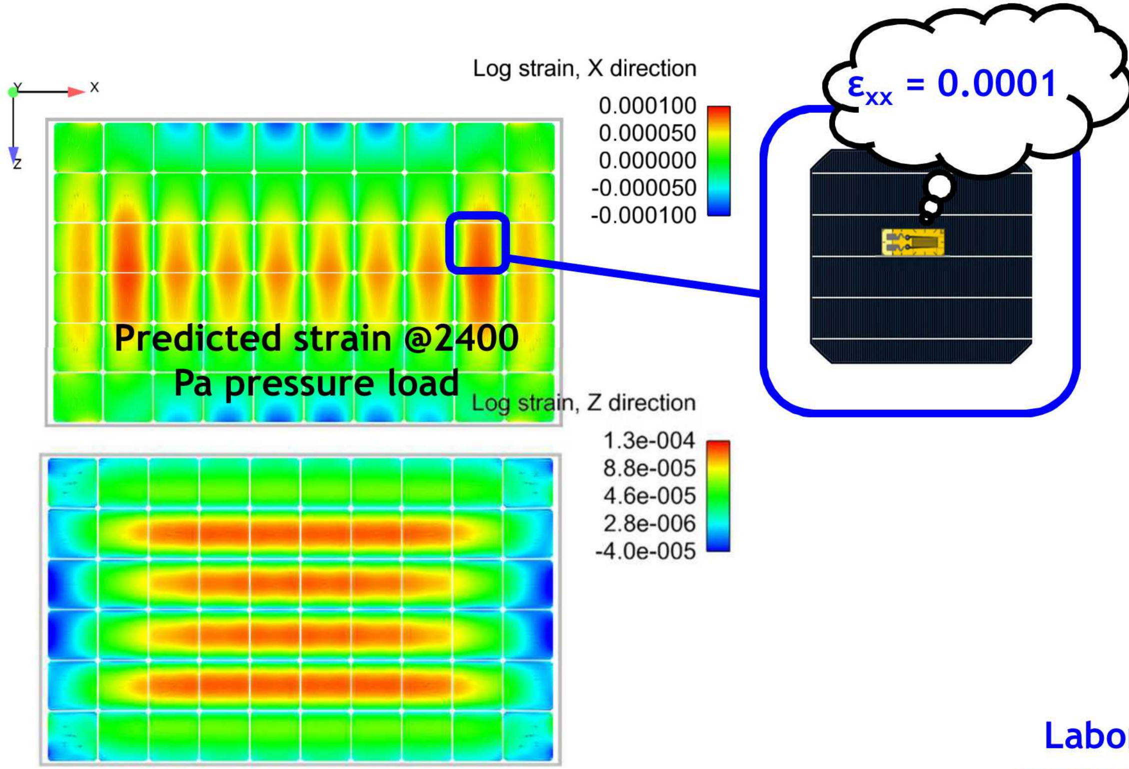

**Characteristics:**
- Insulated polyimide carrier
- ~50 μm package thickness
- Commercially available in various sizes and configurations
- Adhered to substrate to gather strain data
- Electrical signal output (Δ resistance)- high sampling rate and resolution possible




**Strain gauges are flat sensors which report strain (i.e. length change) as a change in electrical resistance**

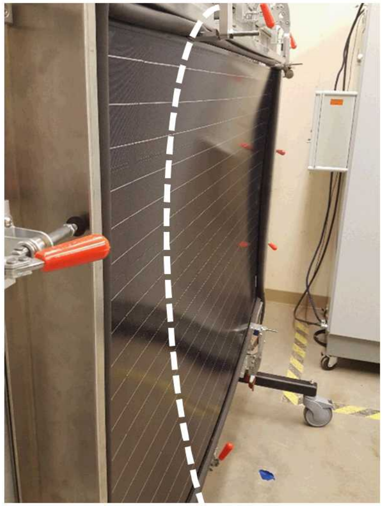
# SPARK: Highly instrumented modules for simulation model validation and environmental characterization

- **Project workflow:**
  1. Design and build instrumented modules
  2. Conduct laboratory testing on instrumented modules
  3. Correlate internal data output to simulation model predictions and conventional external measurements (lasers, image correlation, etc.)




Gauge placements should seek to verify predicted high/low strain locations

BrightSpot Automation

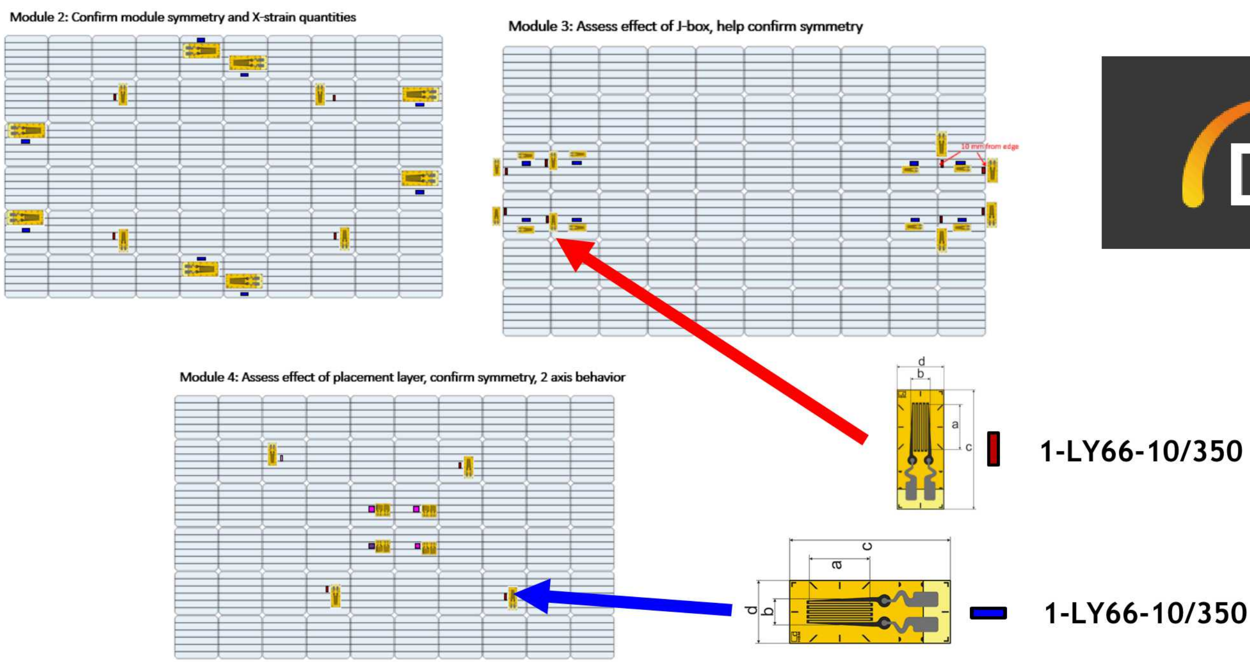


Module under test, -5400 Pa

Laboratory testing enables external measurements to be compared against strain gauge output

# SPARK: Highly instrumented modules for simulation model validation and environmental characterization

- Current status: Designs delivered to D2 Solar for fabrication
  - Discussing implementation considerations (i.e. wire routing, process steps to accommodate gauge placement)
  - 4 modules commissioned (3 instrumented, 1 control)
- Corresponding module FEM under development to match frame designs etc.




Proposed instrumented module designs with stain gauge placements

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# Incorporation of encapsulant viscoelasticity

- **Current effort:** Calibrate Sandia's Universal Polymer Model to the viscoelastic and thermal expansion properties of encapsulant polymers

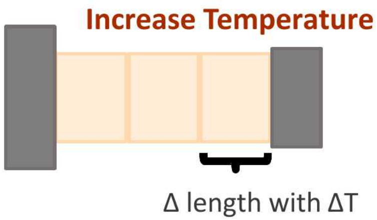
- **Purpose and applications:**
  - Include viscoelastic polymer behavior to capture the *time dependence* of the encapsulants' mechanical response
  - Include thermal expansion measurements through transitions temperature to capture behavior in glassy and rubbery state
  - **Influential to modeled thermal-mechanical response of cells, interconnects, and interfaces**

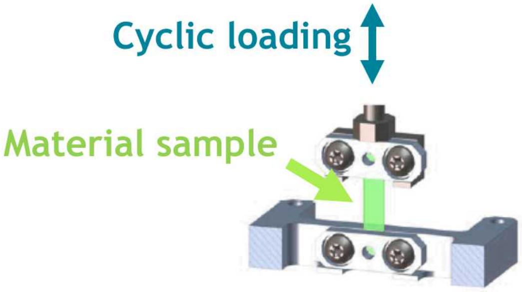
**Measure Properties** ➡ **Fit mathematical model** ➡ **Validate fit** ➡ **Implement and validate material model**

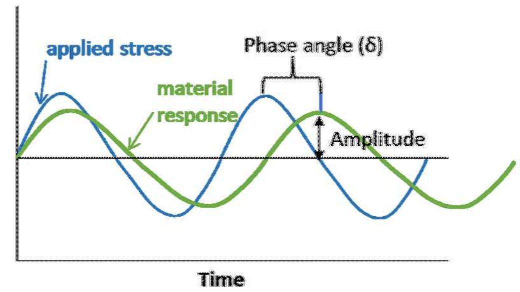
**Material model fitting process**

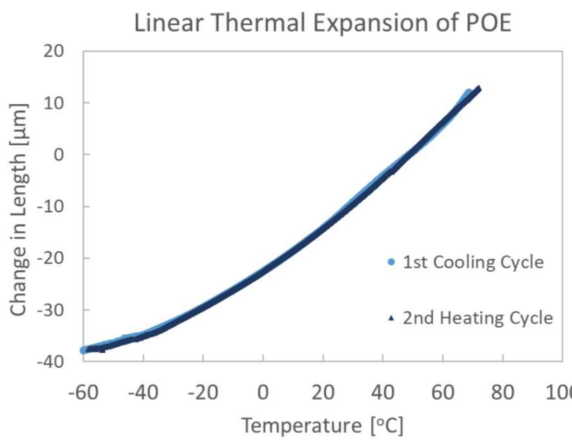
# Incorporation of encapsulant viscoelasticity

- **Measure** representative samples
  - Thermal expansion
  - Viscoelastic behavior

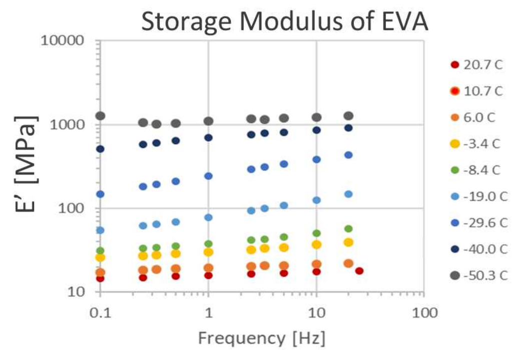


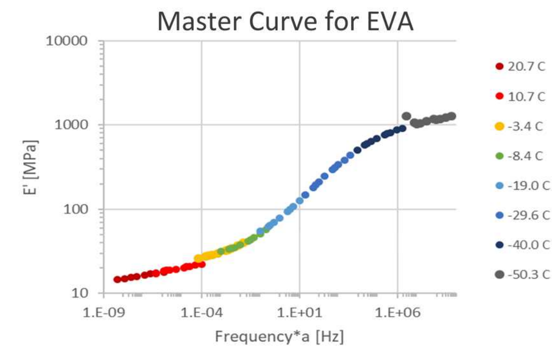




Thermal expansion measured with thermal mechanical analyzer (TMA)

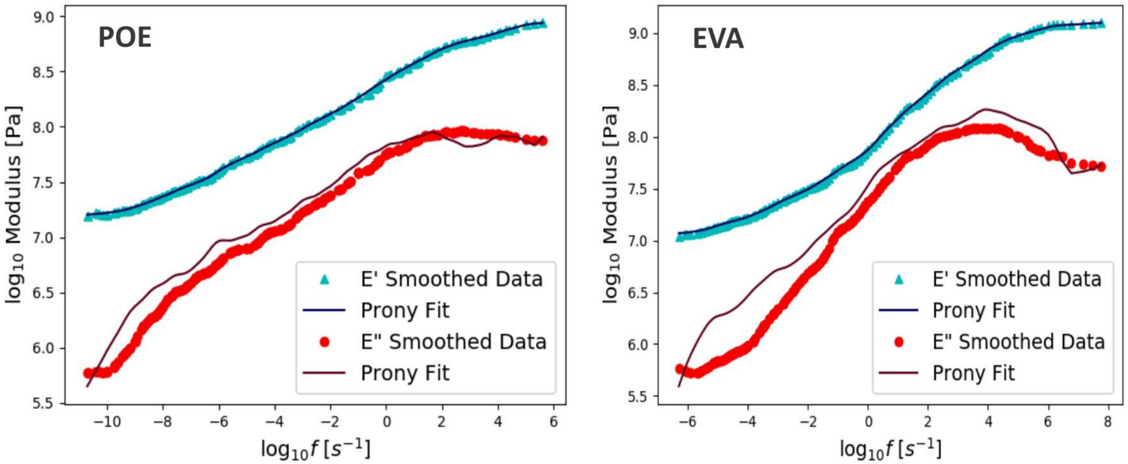


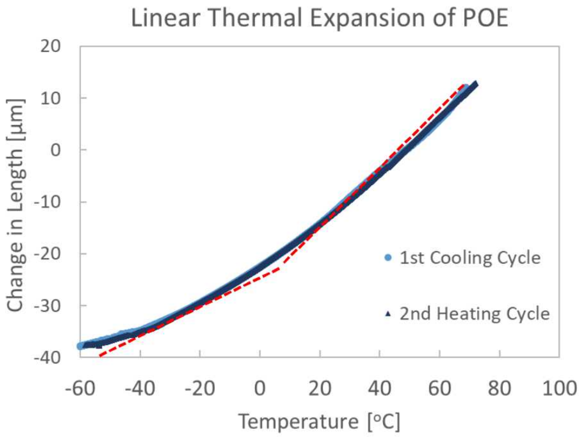

Complex modulus measured over temperature and frequency sweeps to generate a master curve

# Incorporation of encapsulant viscoelasticity

- **Measure** representative samples
- **Fit mathematical model** to measured data
  - Prony series fit to complex master curve
  - Thermal expansion coefficient ($\alpha_{vol}$) above and below $T_g$



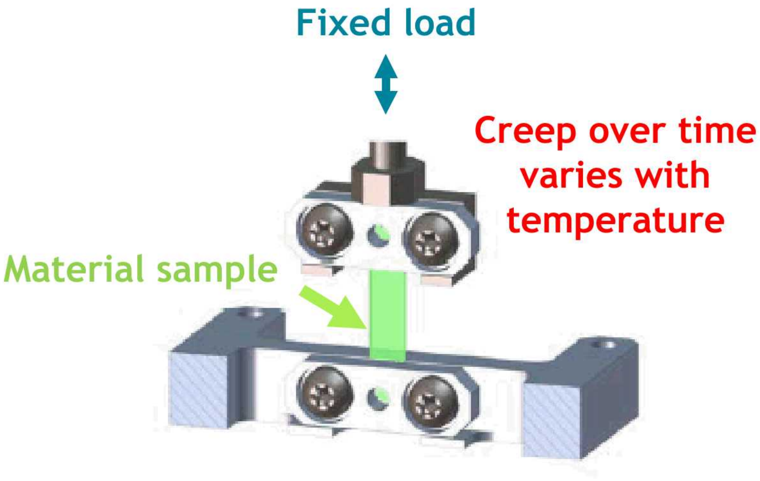

Prony series fits to POE and EVA encapsulant master curves



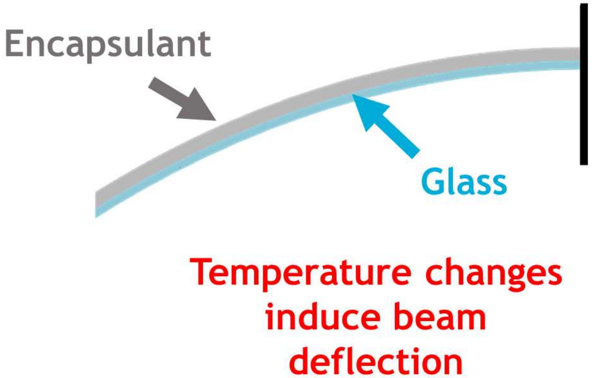

Linear coefficients of thermal expansion fitted against length change data

# Incorporation of encapsulant viscoelasticity

- **Measure** representative samples
- **Fit mathematical model** to measured data
- **Validate fit** against simple, independent experiments exercising properties
  - Creep tests on encapsulant samples at varied temperatures
  - Cantilever beam sandwich geometry to test thermal expansion
- Allows reconstruction of master curves and thermal expansion behavior



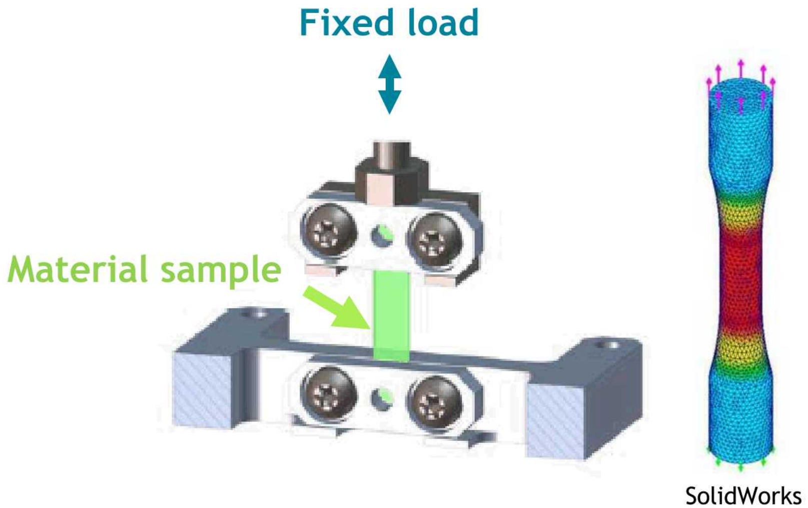

Creep tests applying fixed loads at varied temperature



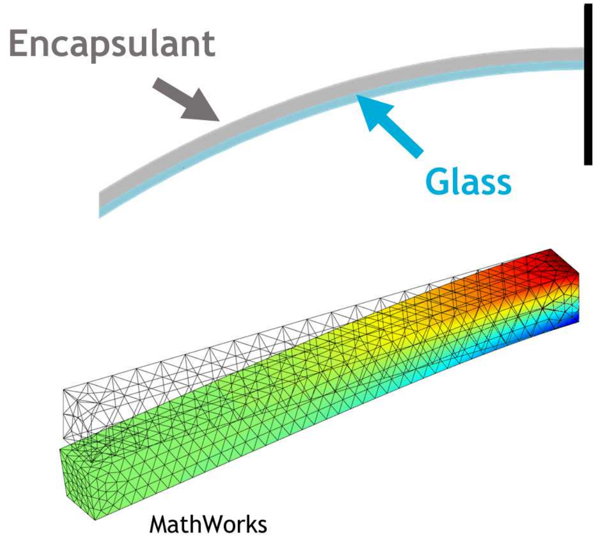

Cantilever laminate beams deflect with temperature changes

# Incorporation of encapsulant viscoelasticity

- **Measure** representative samples
- **Fit mathematical model** to measured data
- **Validate fit** against simple, independent experiments exercising properties
- **Implement and validation** in finite element models
  - Add fit parameters to Universal Polymer Model framework
  - Construct simplified FEM of test geometries
  - Upon validation, model is ready for application to module geometries




Finite element model of creep test experiments validate viscoelastic material model




Finite element model of laminate cantilever beam experiment validates thermal expansion model

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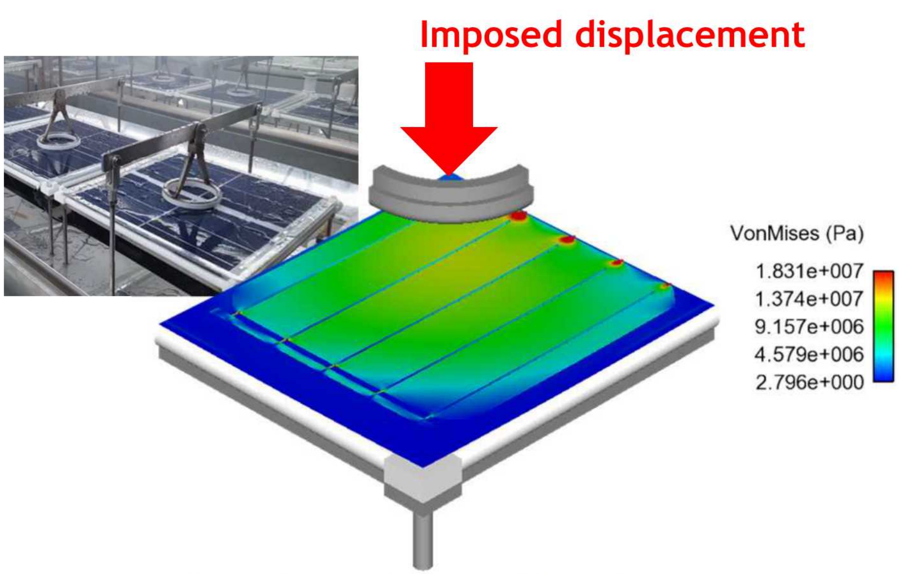
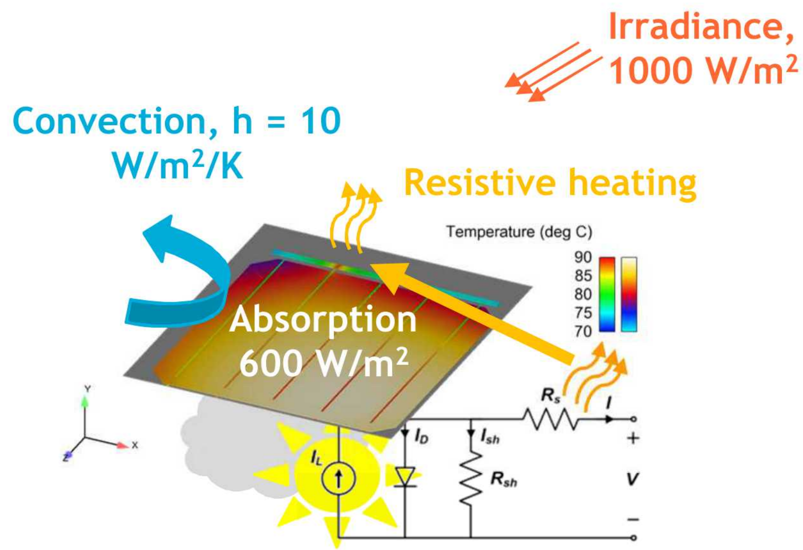
# A multi-physics mini-module modeling platform

- A high-fidelity mini-module model is under development to integrate modeling efforts to date
  - Mechanical loading
  - Thermal effects (expansion mismatches and property changes)
  - Coupled electrical thermal heating
  - High fidelity material and interface adhesion models
- Models Combined Accelerated Stress Testing (C-AST) mini-modules for validation comparisons




Simulated mechanical loading on mini-module model




Simulated thermal profiles on mini-module exposed to environment with electrical effects

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