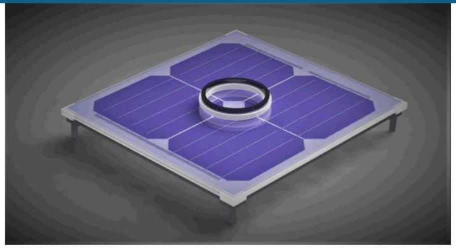
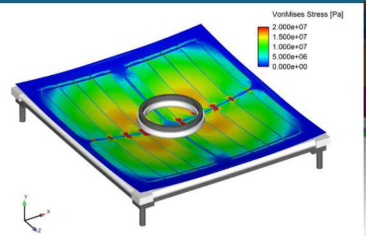
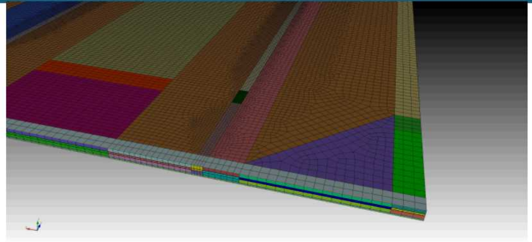
This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2020-5891C

Computational Modeling of Photovoltaic Mini-Modules Undergoing Accelerated Stress Testing







Joseph J. Meert, Michael Owen-Bellini, Peter Hacke, James Y. Hartley

47th IEEE Photovoltaic Specialists Conference, June 15th – August 21st 2020

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Introduction – Mini-Modules and C-AST

C-AST: Combined-Accelerated Stress Testing

- Subject modules to a combination of environmental stress factors
- Mimic deployed module conditions
- Identify weaknesses
- **How do multiple stress factors and their combined effects impact modules?**

Mini-Modules:

- Four-cell photovoltaic modules
- Account for size considerations of climate chamber

Mini-modules undergoing C-AST procedure [1].

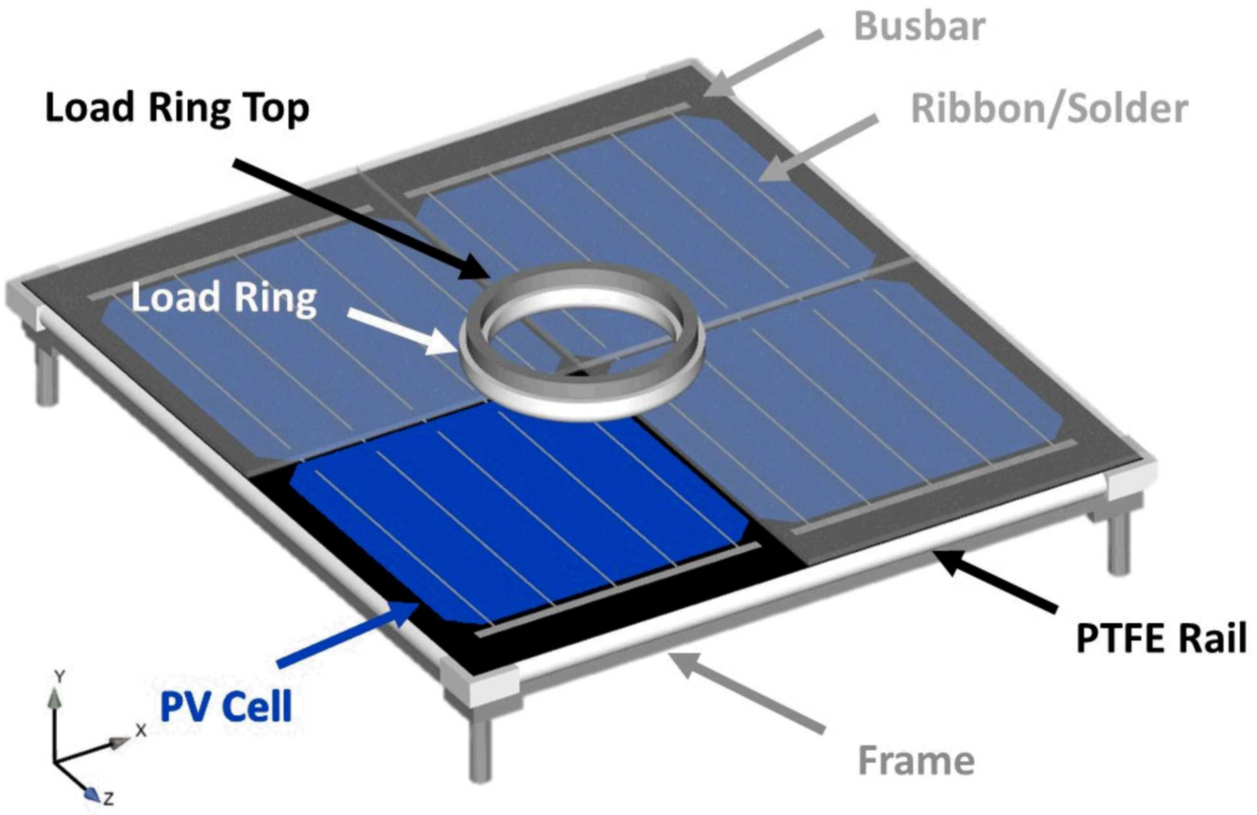
Goals

- Use finite element modeling to simulate this procedure
  - Is a mini-module FEM representative of experimental modules?
    - Validate simulation results against experimental measurements
  - Are mini-modules representative of full-sized modules?
    - Compare mini-module deflection curvature to full module curvature under qualification loading
  - How do temperature changes impact stress states of silicon cells and backsheet?
    - Thermal simulation analysis
  - Are these results valid?
    - Model validation and uncertainty quantification
    - Convergence study

Finite Element Modeling Procedure – Geometry

Geometry Development

- The geometry used to develop the finite element model was based on an experimental setup
- The model includes the frame and load ring as used in C-AST
- The model includes internal details surrounded by encapsulant
- Interconnects are connected to PV cells with solder



Mini-module components and internal details

Slide 4

HJY5 Add a descriptive caption for each picture

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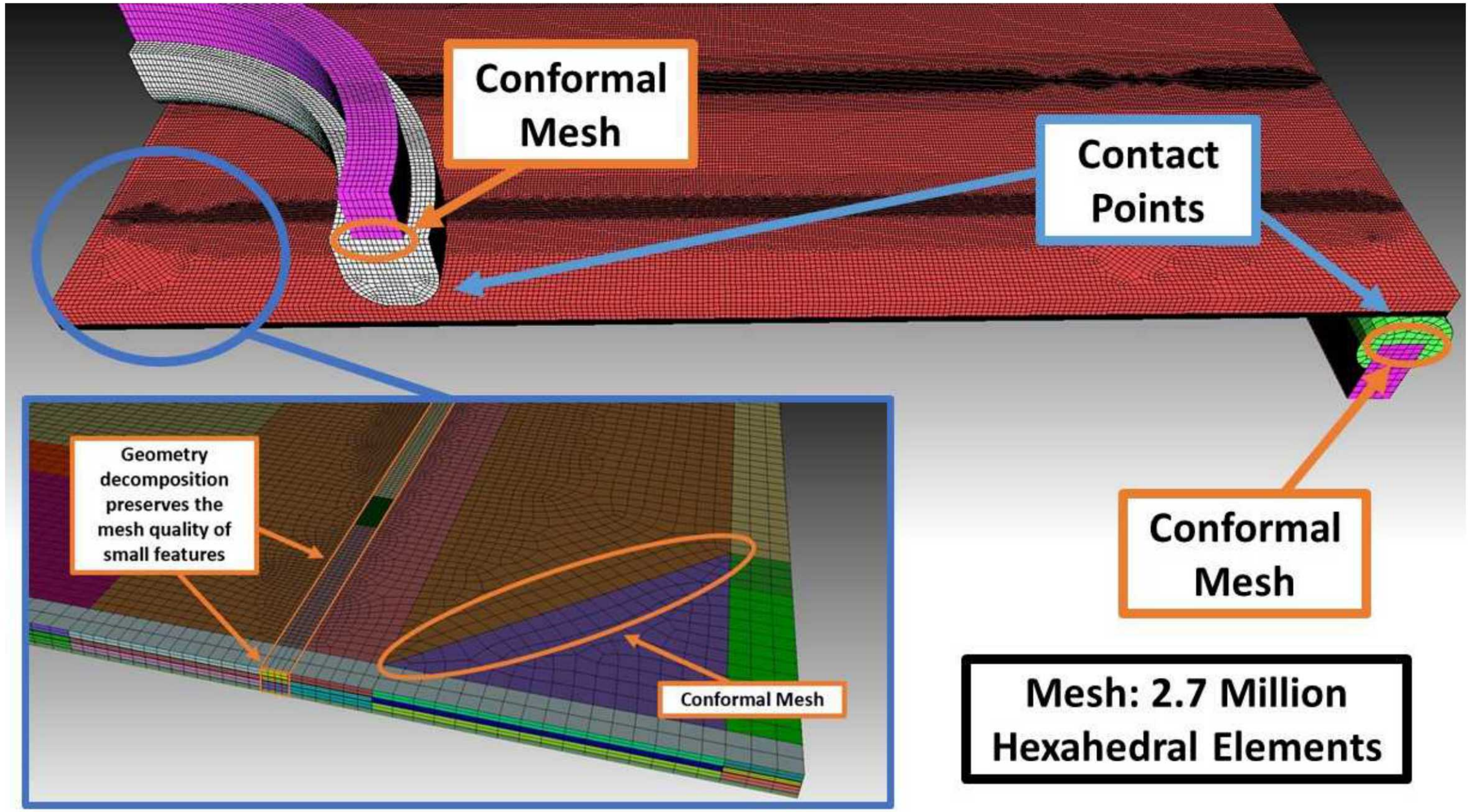
Finite Element Modeling Procedure – Geometry

Geometry Decomposition and Meshing

- CUBIT software used to decompose and mesh mini-module geometry for simulation
- Conformal mesh assigned to laminated or welded surfaces
- Decomposition preserves quality of complex and small features
- 10 million element mesh demonstrated model convergence

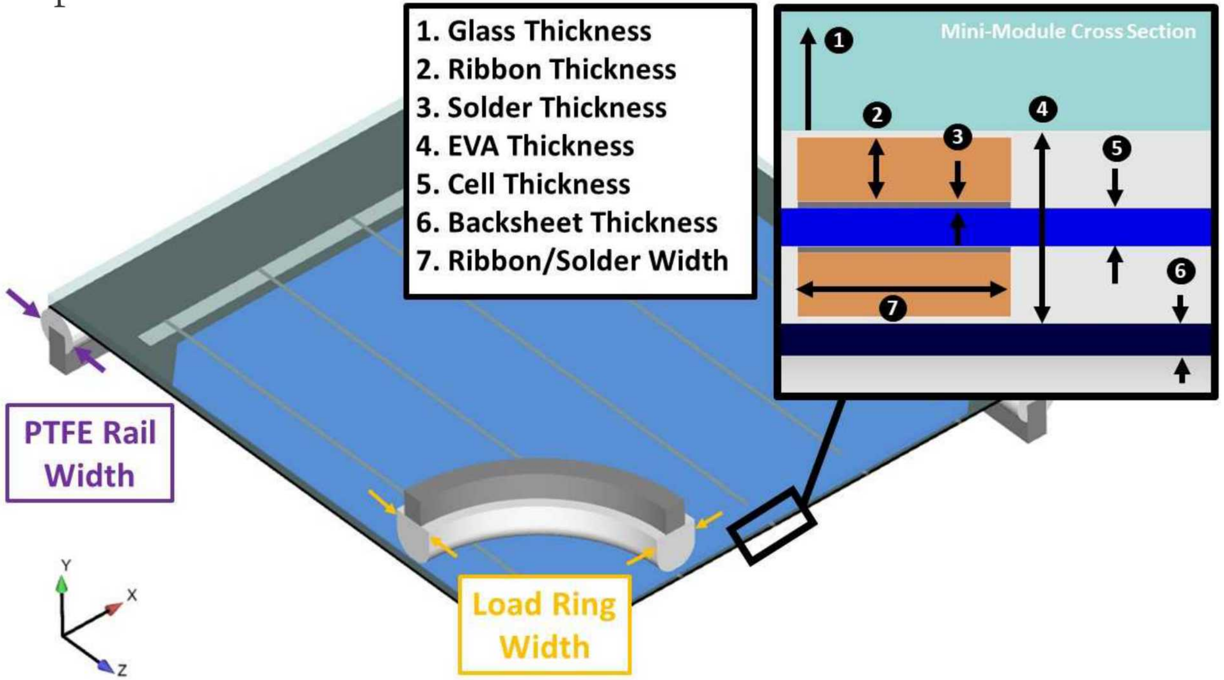


Mini-module mesh and geometry decomposition

Uncertainty Quantification Set-Up

How do small changes in model parameters impact simulation results?

- 26 parameters were varied to determine their impact on simulation results
- Parameters included geometric dimensions, material properties, and the coefficient of friction
- Incremental Latin Hypercube Sampling approach used to take 120 samples



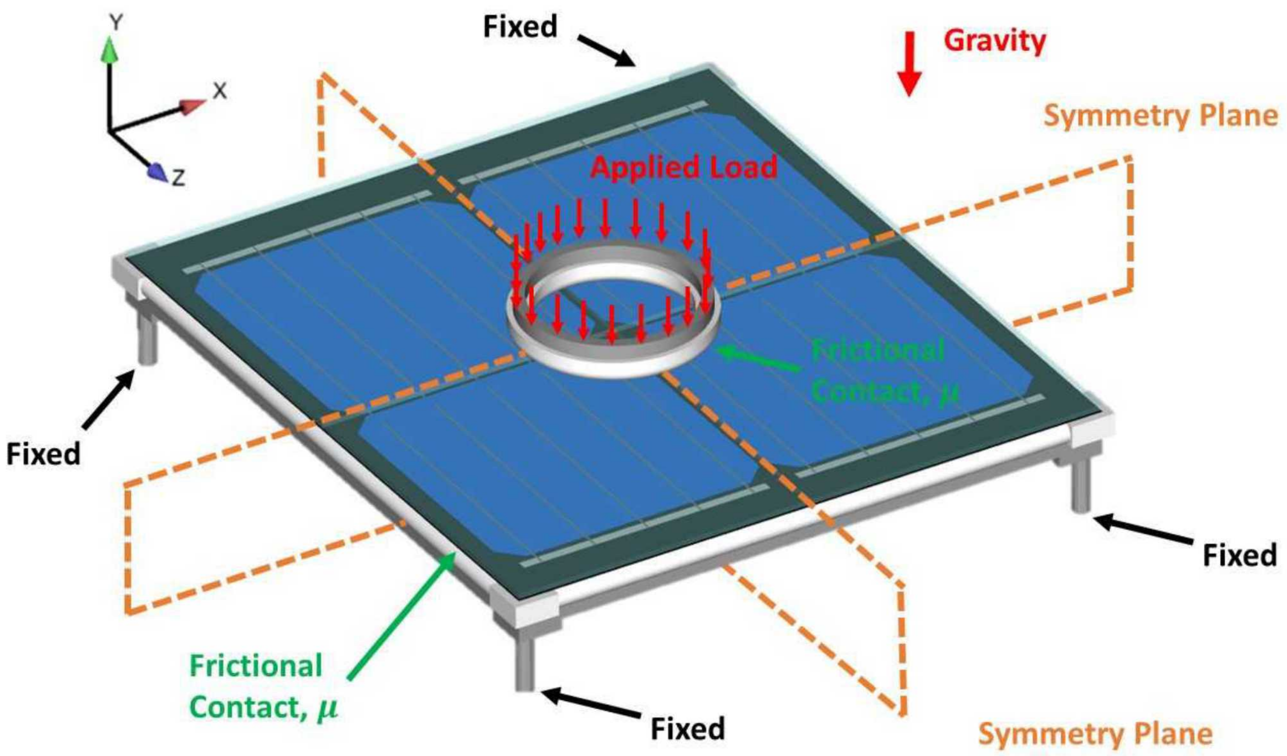
Mini-module geometry definitions for uncertainty analysis

Varied Parameters for Uncertainty Quantification

#	Parameter	Lower Bound	Upper Bound
1	Glass Thickness	3.00	3.40
2	Interconnect Thickness, [mm]	0.27	0.33
3	Solder Thickness, [mm]	0.025	0.035
4	Encapsulant Thickness, [mm]	0.80	1.00
5	Cell Thickness, [mm]	0.16	0.20
6	Backsheet Thickness, [mm]	0.15	0.40
7	Interconnect and Solder Width, [mm]	0.90	1.10
8	Load Ring Width, [mm]	11.4	14.0
9	PTFE Rail Width, [mm]	11.4	14.0
10	Steel - Elastic Modulus [GPa]	174	212
11	Steel - Poisson's Ratio	0.276	0.305
12	Glass - Elastic Modulus [GPa]	40	60
13	Glass - Poisson's Ratio	0.162	0.179
14	PTFE - Elastic Modulus [GPa]	0.458	0.506
15	PTFE - Poisson's Ratio	0.437	0.483
16	Solder - Elastic Modulus [GPa]	20	60
17	Solder - Poisson's Ratio	0.30	0.40
18	Silicon - Elastic Modulus [GPa]	162	179
19	Silicon - Poisson's Ratio	0.266	0.294
20	Backsheet - Elastic Modulus [GPa]	0.968	1.450
21	Backsheet - Poisson's Ratio	0.4	0.499
22	Encapsulant - Elastic Modulus [GPa]	0.0021	0.0031
23	Encapsulant - Poisson's Ratio	0.45	0.499
24	Copper - Elastic Modulus [GPa]	117	130
25	Copper - Poisson's Ratio	0.296	0.327
26	Coefficient of Static Friction	0.05	0.30

Finite Element Modeling Procedure – Boundary Conditions

- **Quarter symmetry** conditions applied along XY and YZ planes
- **Frictional contact** acts between ring and glass as well as between backsheet and rails
- **Mechanical load** applied to load ring and **gravity** imposed on all components
- **Frame post** is fixed in all directions



Mini-module boundary conditions

Slide 7

HJY10 add a caption to the figure..

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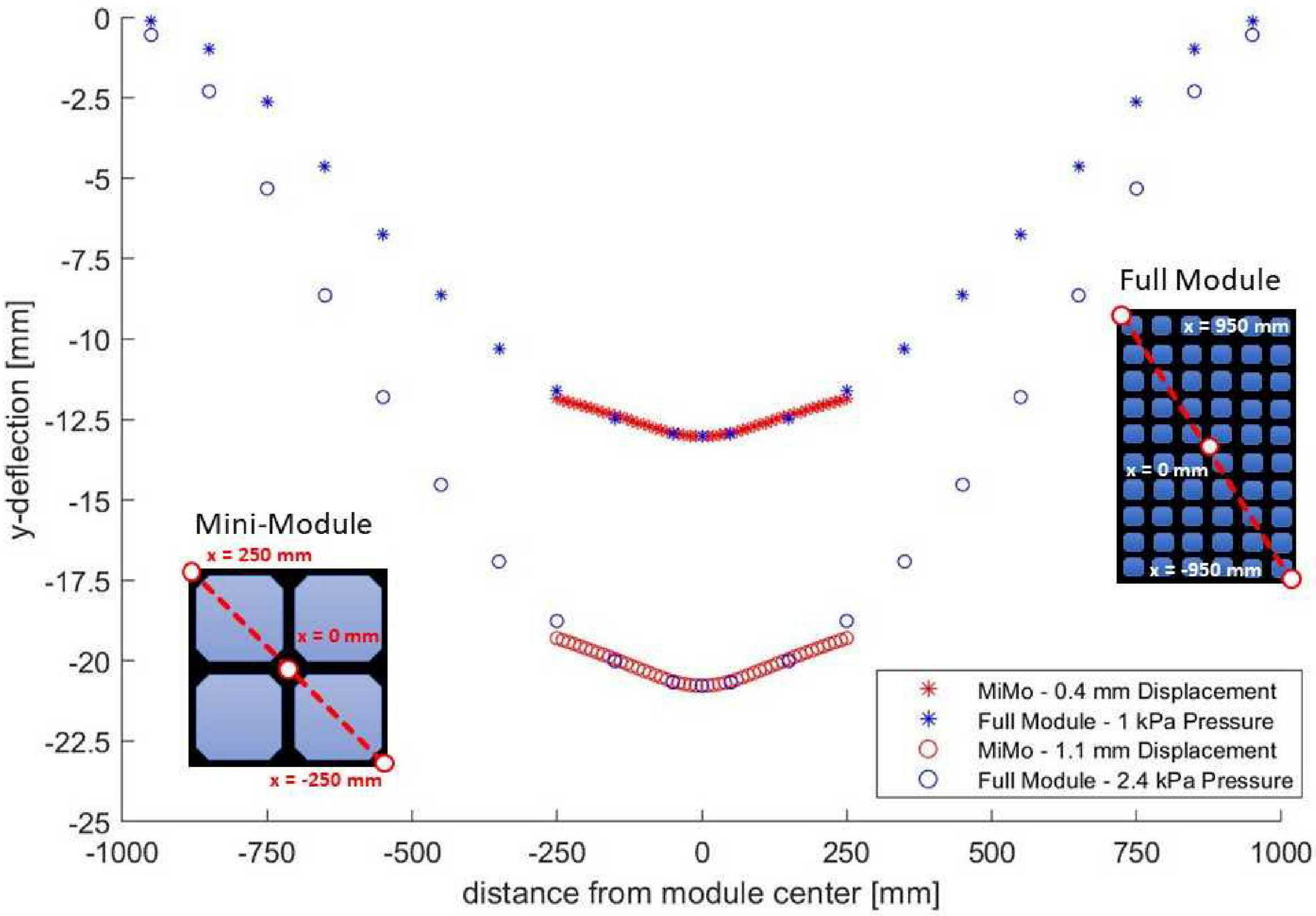
Model Results – Mini-Module Shape vs. Full Module Shape

How does the deflected mini-module compare to a deflected full module?

- Points taken across the diagonal of both photovoltaic modules
- Mini-module deflection curvature plotted against deflection curvature of a full module
- Curvature roughly matches that of full module

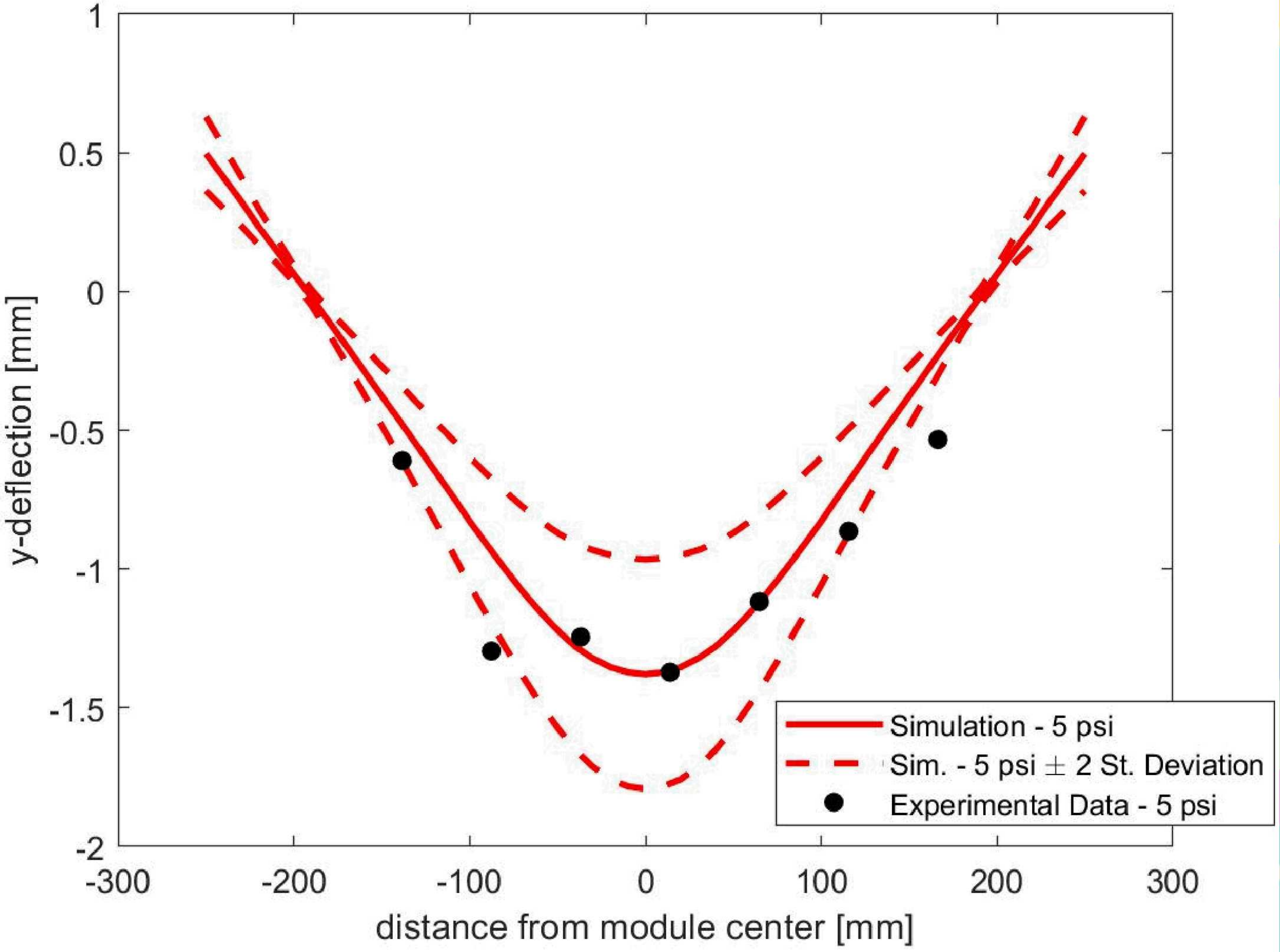


Comparison of full module and mini-module deflection curvature under module qualification loading conditions

Model Results – Mechanical Deflection vs. Load

How do model predicted deflections compare to measured deflections under a known load?

- Preliminary results of uncertainty quantification
- Geometric and material variables sampled over known and estimated uncertainties
- Mean and mean ± two standard deviations of backsheet deflection plotted under 5 psi actuation pressure
- Simulation results plotted against experimental data under two known loading conditions

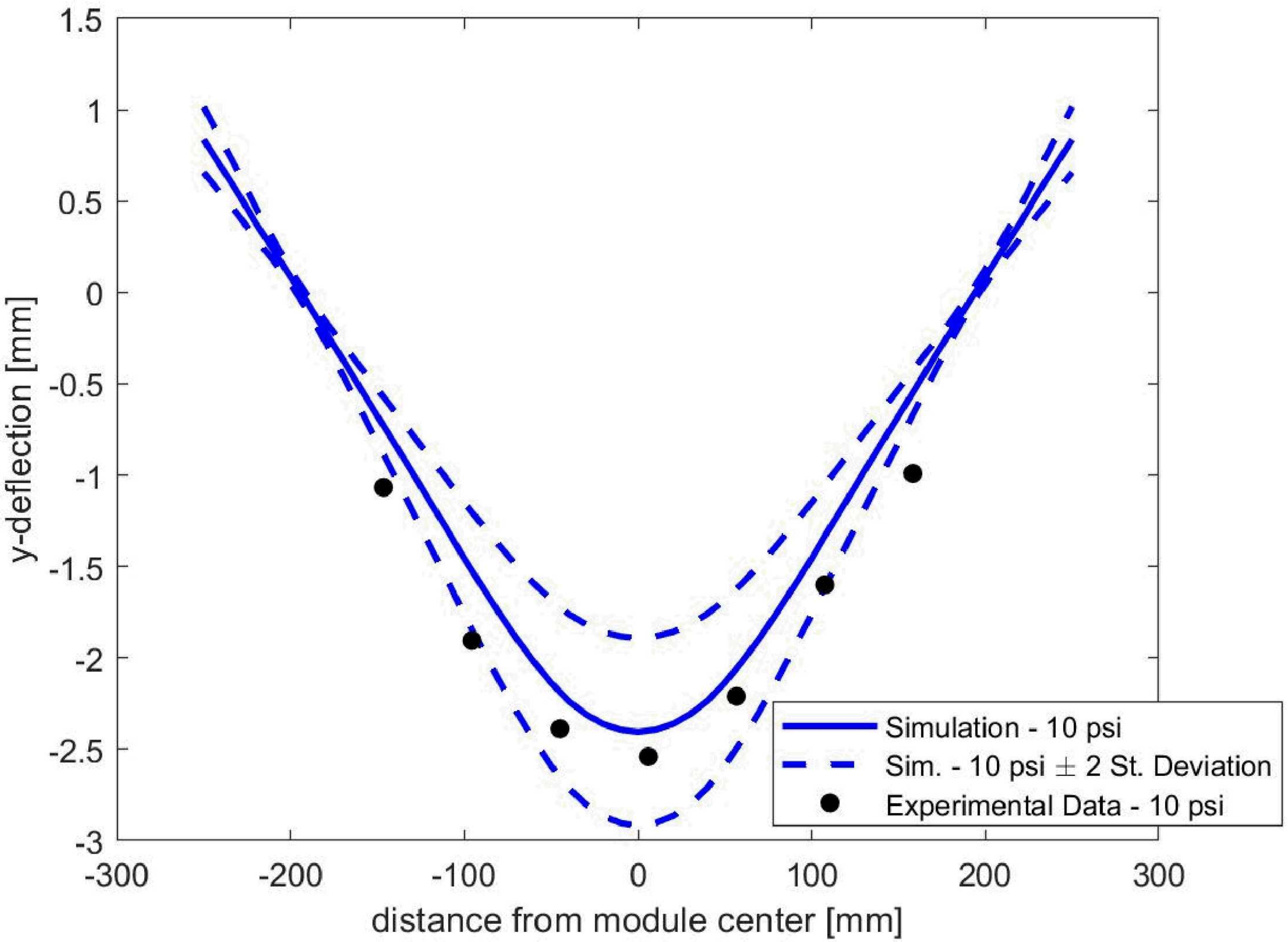


Comparison of simulated and experimental mini-module deflection under 5 psi actuation pressure

Model Results – Mechanical Deflection vs. Load

How do model predicted deflections compare to measured deflections under a known load?

- Mean and mean ± two standard deviations of backsheet deflection plotted under 10 psi actuation pressure
- Measured values mostly fall within two standard deviations of the mean
- Mean deflection appears to overshoot experimental measurements
- Additional experimental data and simulations over the full sample set needed to validate model

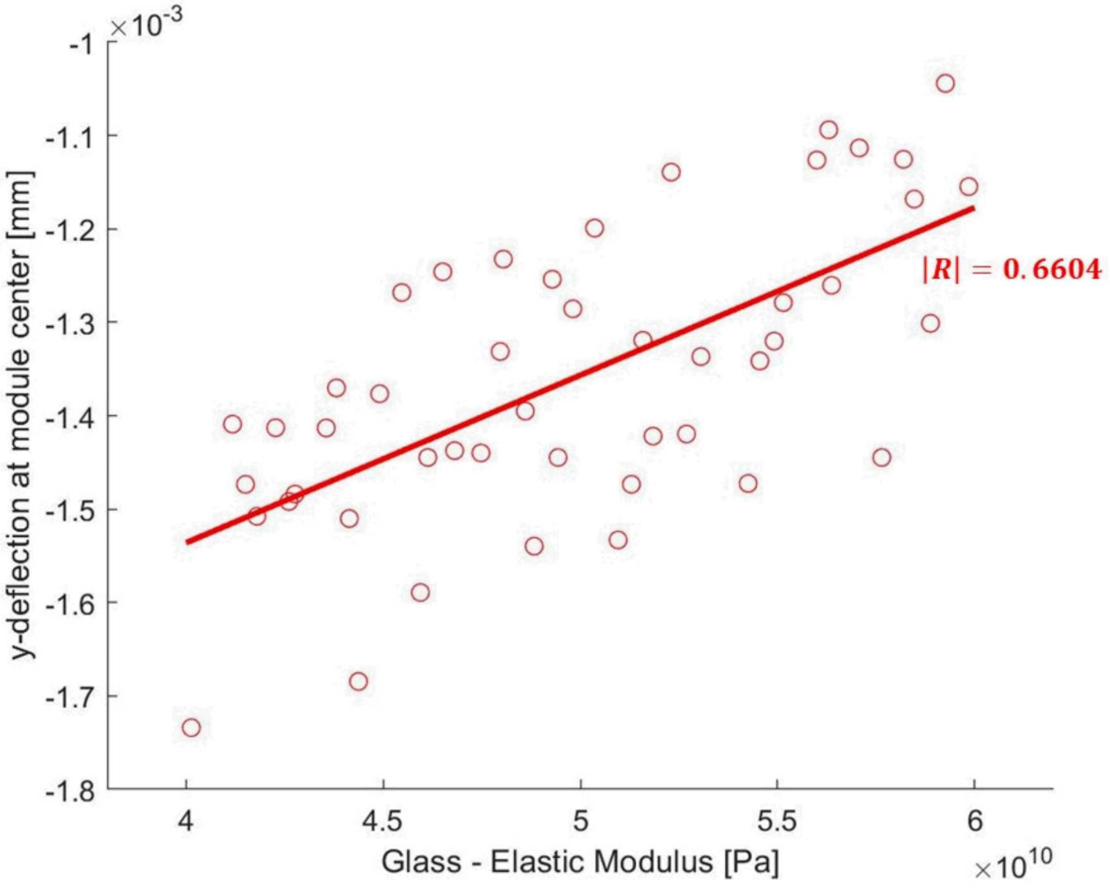


Comparison of simulated and experimental mini-module deflection under 10 psi actuation pressure

Model Results – Sensitivity

Which varied parameter is mini-module deflection most sensitive to?

- Linear correlation coefficients calculated for 26 sampled variables under a standard loading condition
- Glass elastic modulus demonstrated to be the variable most-correlated with backsheet deflection
- Glass elastic modulus is sensitive to the composition of the glass
- Glass used in mini-modules is not as well characterized as that used in full modules



Mini-module deflection sensitivity to variations in the elastic modulus of glass

Slide 11

HJY24 Be prepared to explain why we thought glass modulus would vary (i.e. modulus is sensitive to glass composition, and we suspect composition for mini-module sheets isn't as well characterized as full size since it's not a standard qualified product)

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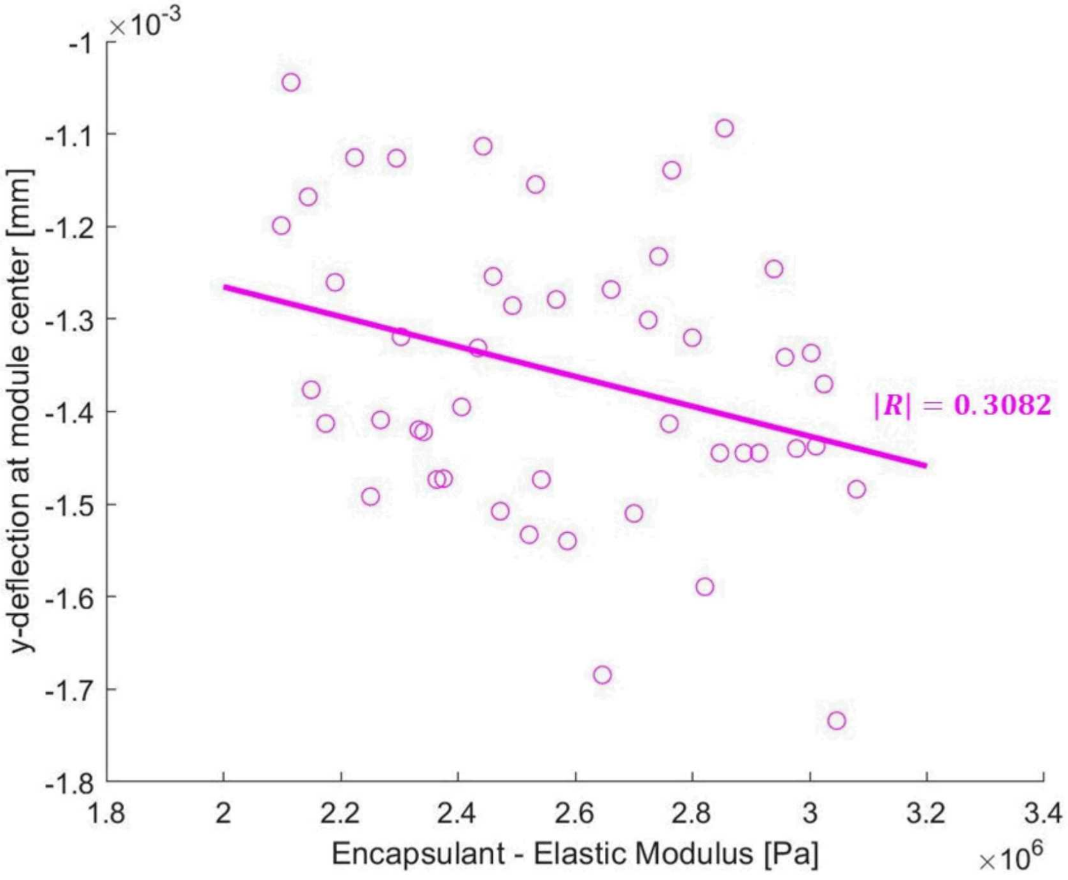
Model Results – Sensitivity

Which varied parameter is mini-module deflection most sensitive to?

- Second most-correlated parameter is the elastic modulus of the encapsulant
- Top two most-correlated variables are significantly greater than the others

Module Sensitivity to Varied Parameters

Parameter	Correlation Coefficient
Glass – Elastic Modulus	0.6604
Encapsulant – Elastic Modulus	0.3082
PTFE – Elastic Modulus	0.2004
Copper – Elastic Modulus	0.1914
Coefficient of Friction	0.1595
Interconnect Thickness	0.1275

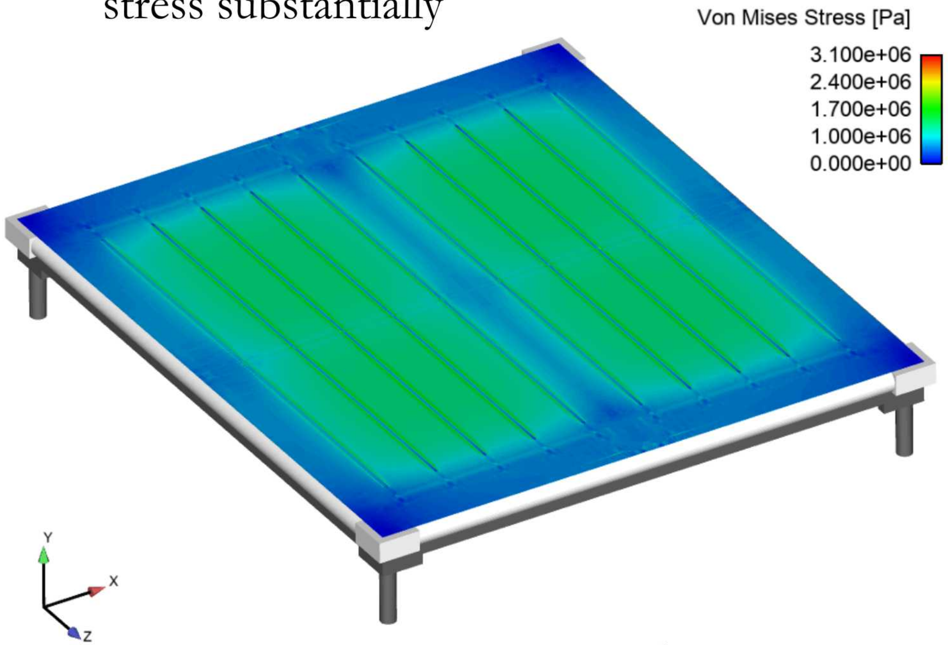


Mini-module deflection sensitivity to variations in the elastic modulus of encapsulant

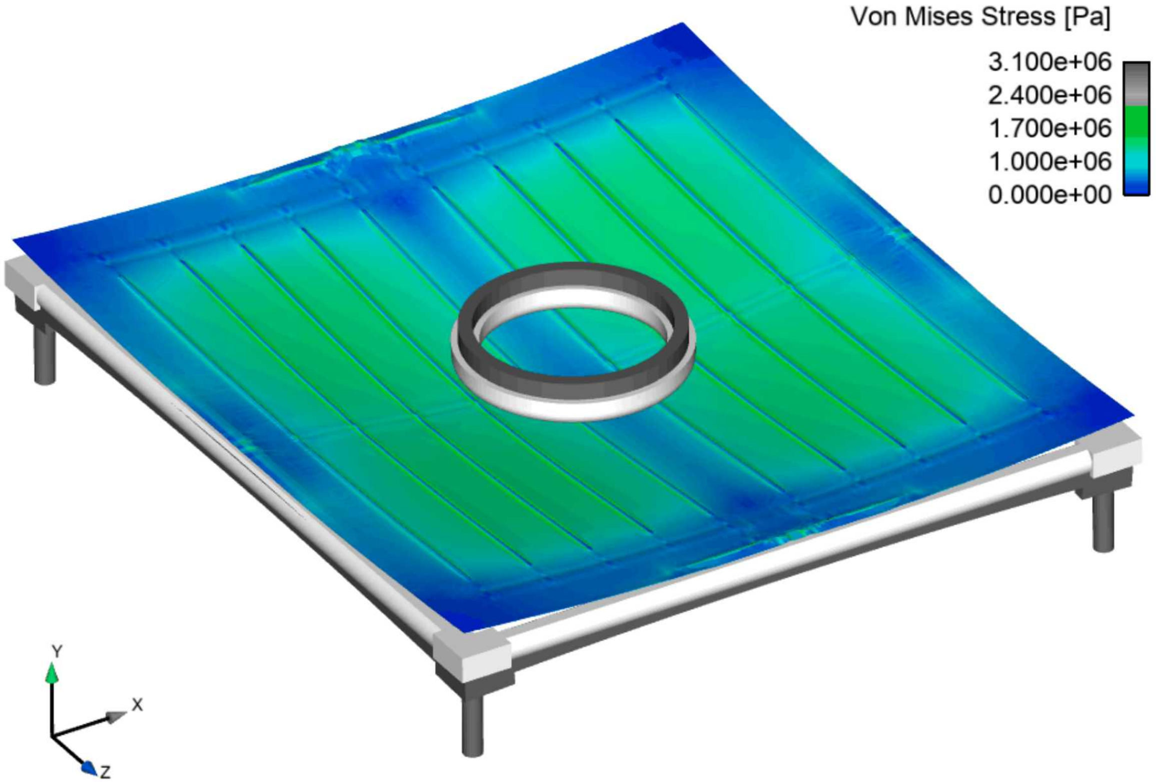
Model Results – Backsheet Behavior at 85 °C

Mini-module behavior at 85 ˚C with and without 1.1 mm displacement

- Mechanical load causes backsheet deflection
- Backsheet lifts off of the rails under mechanical load
- Does not increase the magnitude of maximum stress substantially



Von Mises stress on backsheet at 85 ˚C, no mechanical load.

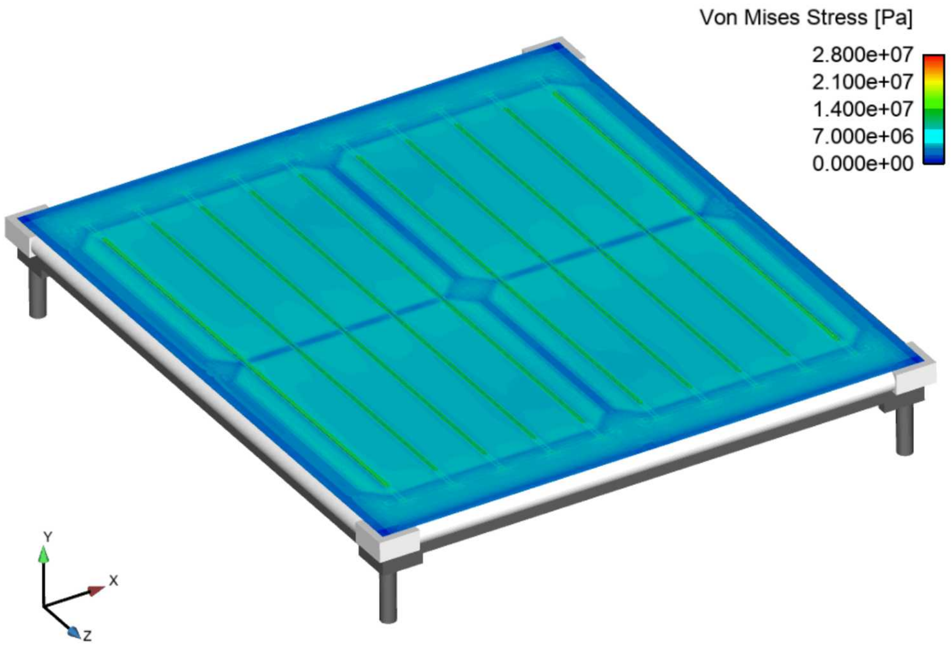


Von Mises stress on backsheet at 85 ˚C, 1.1 mm displacement. Displacement in the y-direction exaggerated 10 times.

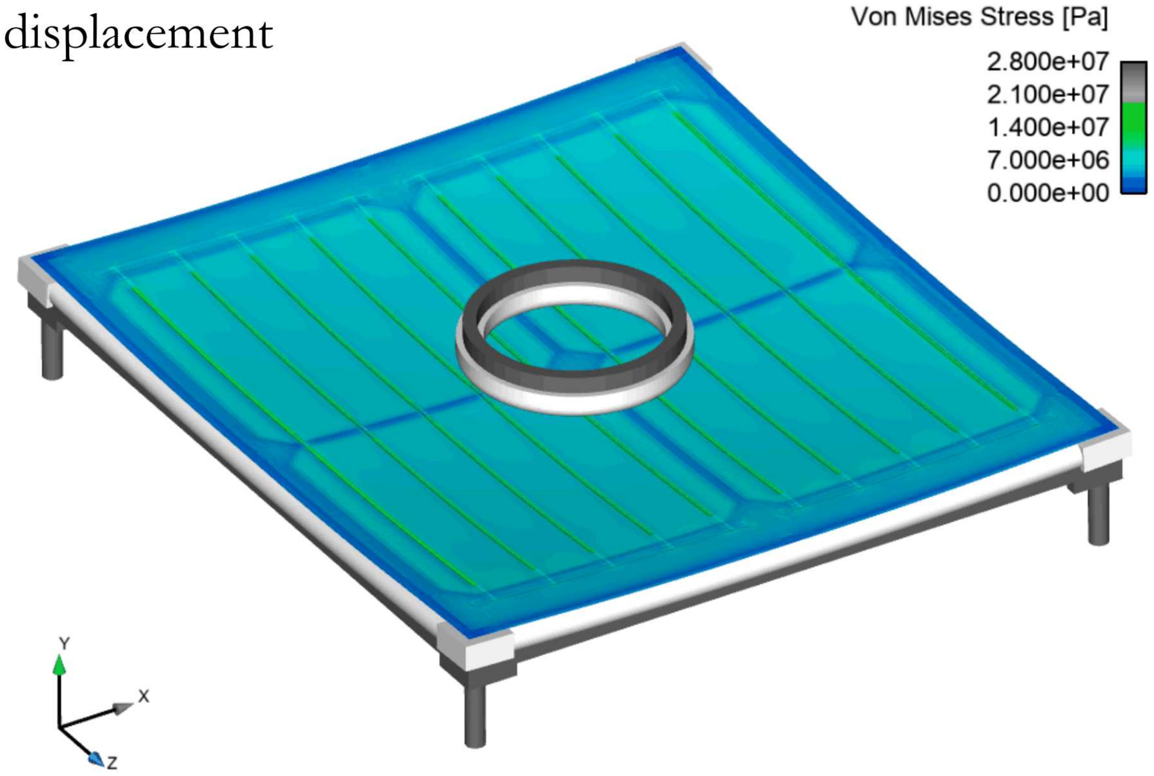
Model Results – Backsheet Behavior at -40 °C

Mini-module behavior at -40 ˚C with and without 1.1 mm displacement

- Mechanical load causes backsheet deflection, but does not increase the magnitude of stress substantially
- Backsheet material contracts at lower temperatures (-40 ˚C) and remains in frictional contact with the rails



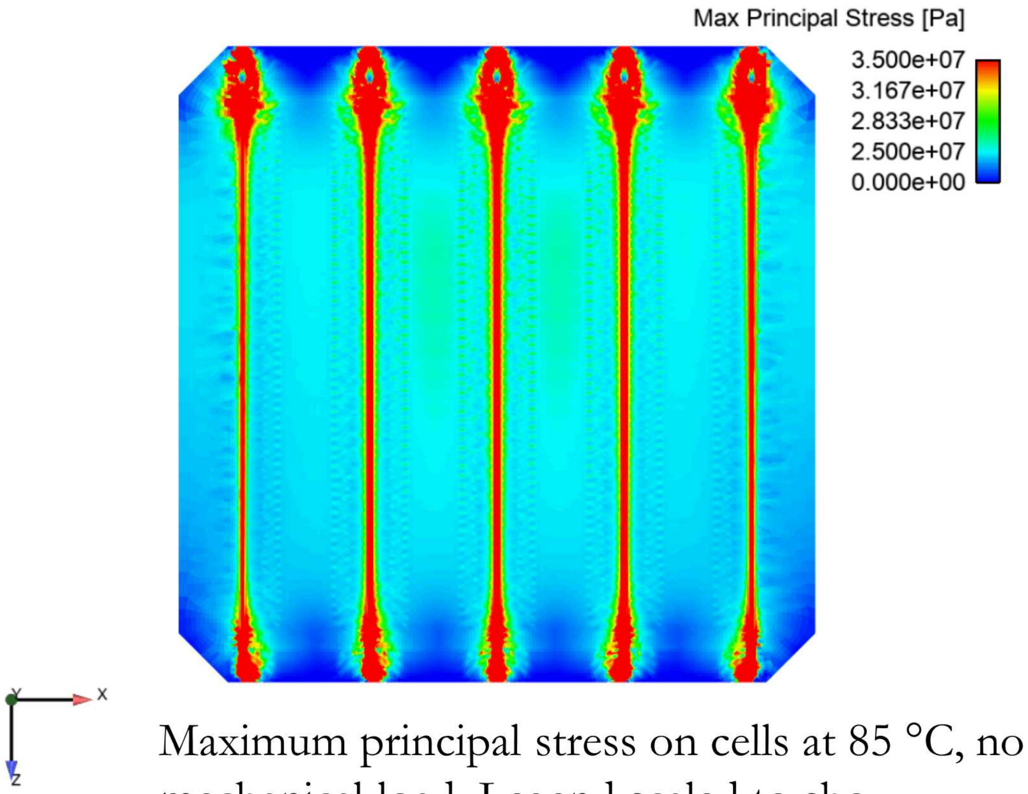
Von Mises stress on backsheet at -40 ˚C, no mechanical load.



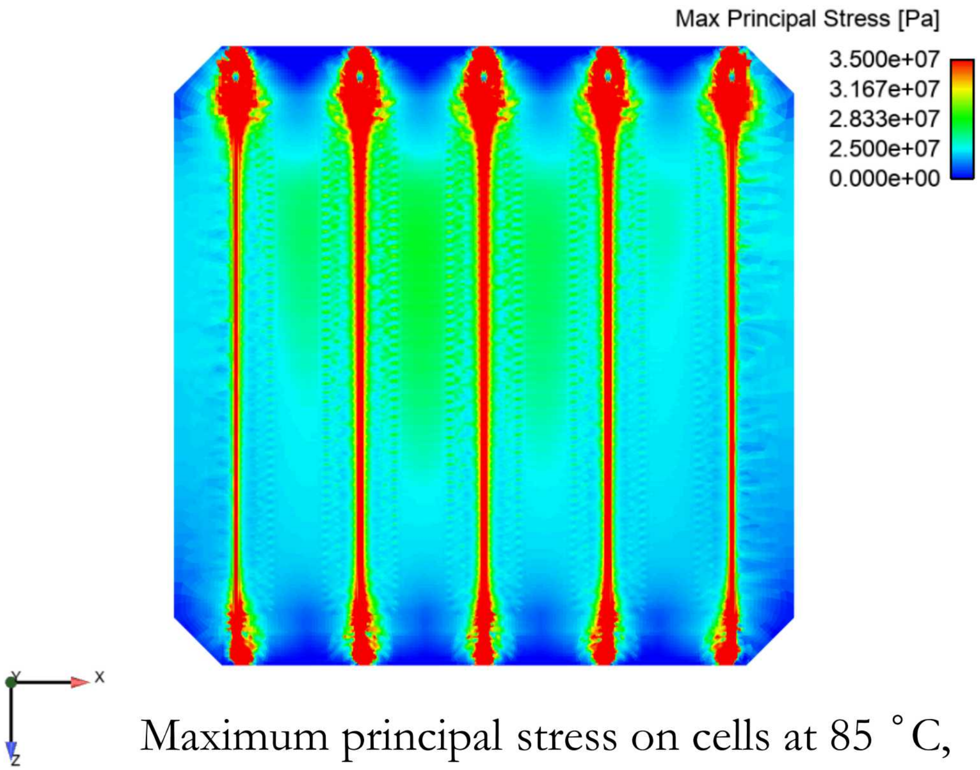
Von Mises stress on backsheet at -40 °C, 1.1 mm displacement. Displacement in the y-direction exaggerated 10 times.

Model Results – Cell Behavior under Thermal & Mechanical Loads

- Obvious influence of load ring on the stress distribution on the cell
- Maximum stress magnitude on the cells does not appear to be substantially impacted by mechanical loading



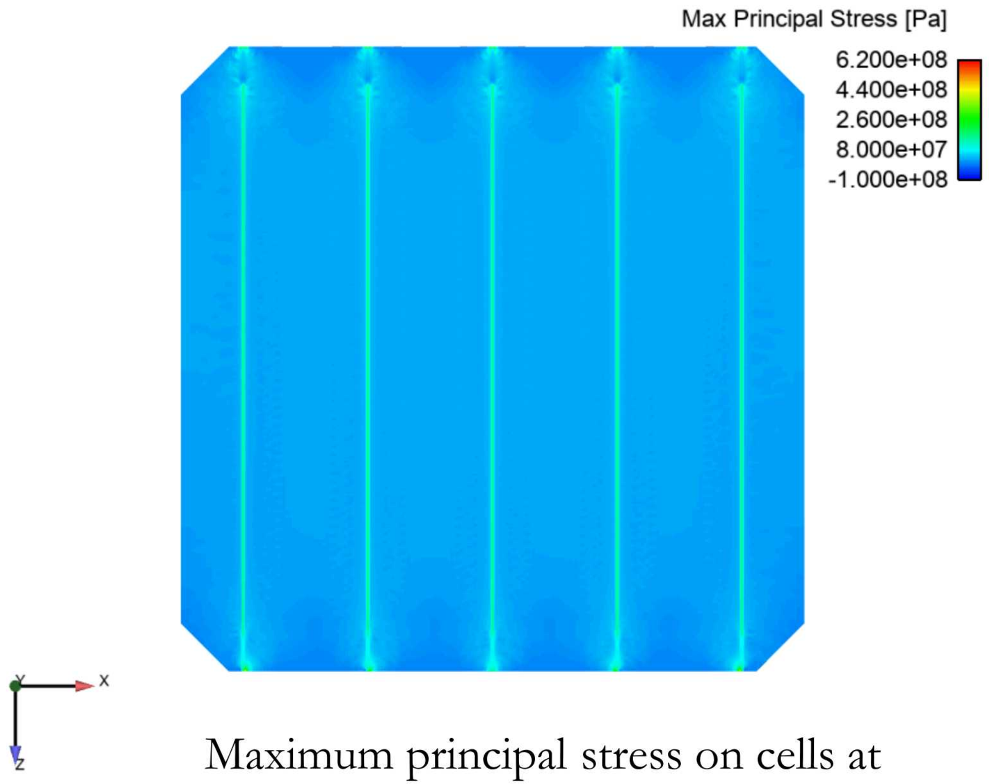
Maximum principal stress on cells at 85 °C, no mechanical load. Legend scaled to show influence of interconnects.



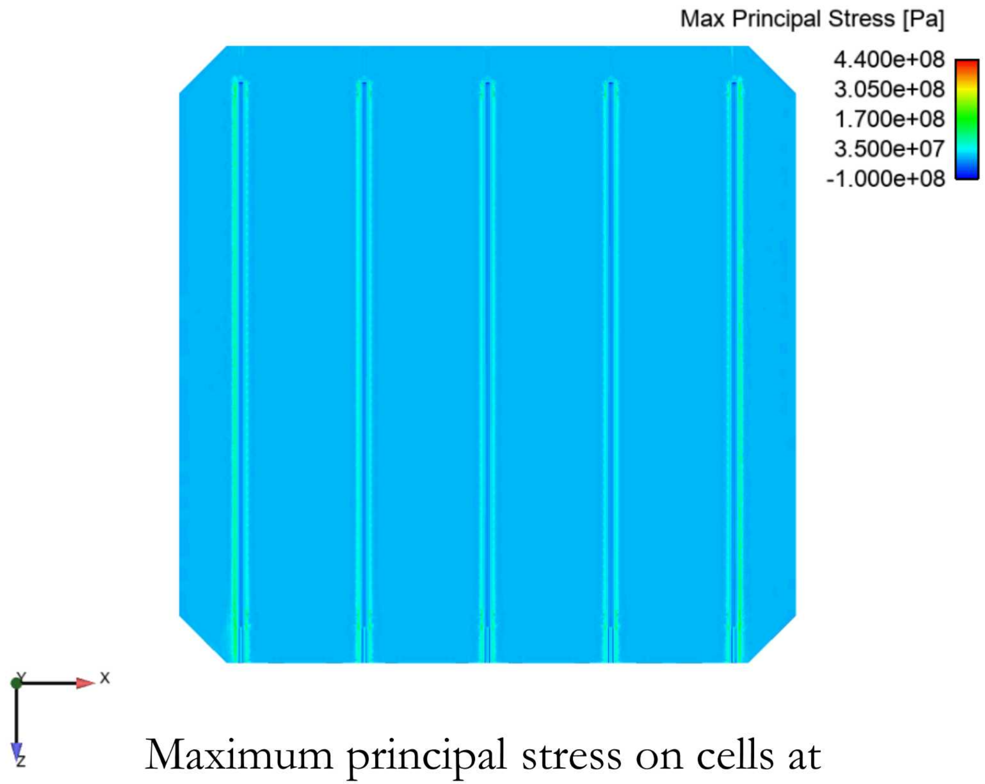
Maximum principal stress on cells at 85 ˚C, 1.1 mm displacement. Legend scaled to show influence of load ring.

Model Results – Cell Behavior under Thermal & Mechanical Loads

- Maximum stress magnitude is greater in the 85 °C case than the -40 °C case
- Impacted of the interconnects on the stress distribution is visible



Maximum principal stress on cells at 85 °C, 1.1 mm displacement.



Maximum principal stress on cells at -40 ˚C, 1.1 mm displacement.

Summary

- Mini-module under mechanical loading exhibits a similar deflection curvature as a full photovoltaic module
- Mini-module curvature exhibits a more shallow curvature than the full module
- FEM validated against mechanical experimental data
  - Deflection behavior of a mini-module under load in the C-AST procedure.
- FEM under thermal and mechanical loading:
  - Higher stress magnitudes are due to material expansion/contraction rather than mechanical loading
  - Backsheet stresses are influenced by the interconnects in both thermal & thermal-mechanical loading cases
- Uncertainty quantification and sensitivity analyses were completed with available results

Future Work

- Additional validation of the FEM against experimental results
- Complete uncertainty quantification and sensitivity analyses
- Explore module behavior under thermal cycling and compare to experimental data
- Inclusion of additional physical effects
  - Moisture diffusion
  - Material viscoelasticity
- Inclusion of junction box into finite element model

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