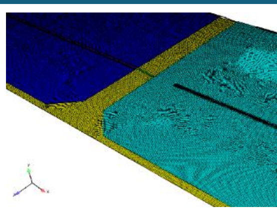
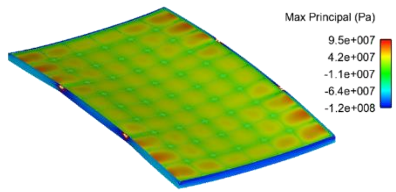
Finite Element Models to Predict Module-Level Degradation Mechanisms and Reliability





PRESENTED BY

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Sandia National Laboratories

The 11th PV Performance Modeling and Monitoring Workshop December 4-5, 2018, Weihai, China

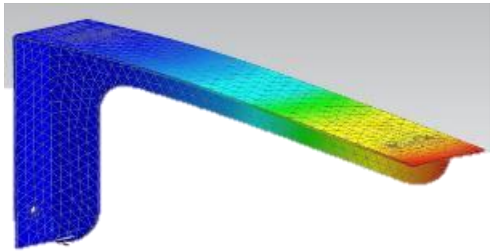
SAND2018-13336 C

Presentation Outline

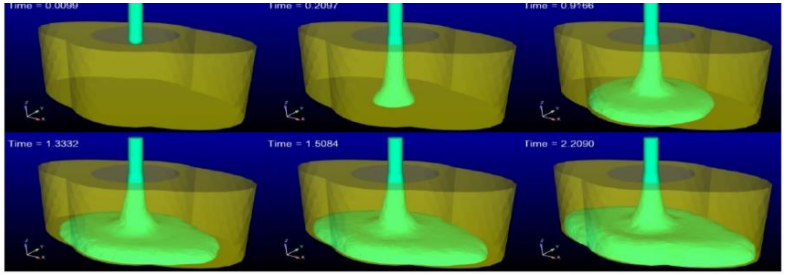
- Finite element modeling: Overview and applications
- Photovoltaic module level models and applications
- Component level models and applications
- Future directions and capabilities

Finite element modeling: Overview and applications

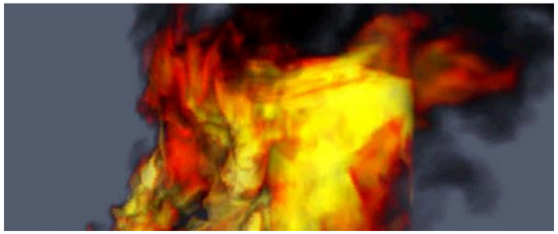
- Finite element method is a numerical method for solving complex engineering problems by discretizing a domain into many small elements
- Familiar tool in many engineering fields:
  - Computational fluid dynamics (CFD), heat transfer, structural mechanics & dynamics- among others



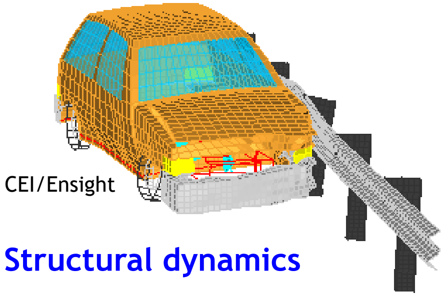
Structural mechanics



Non-Newtonian fluid constitutive modeling



Coupled CFD and chemical kinetics

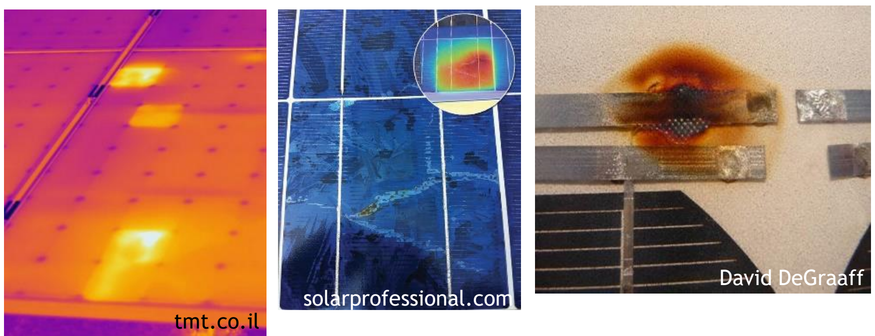


Structural dynamics

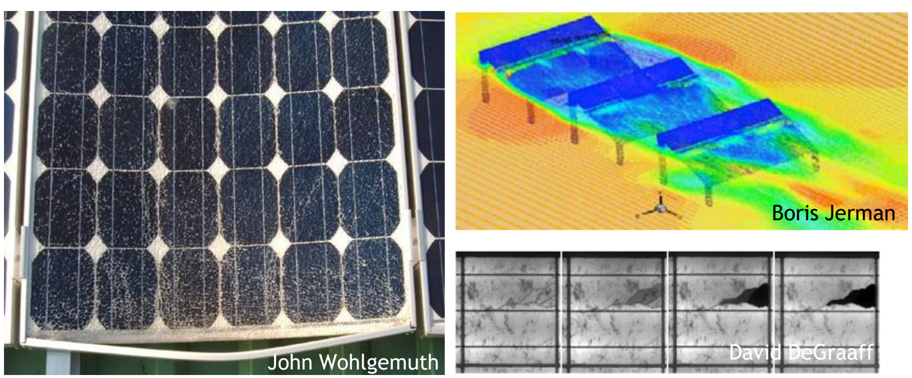
Sandia maintains world-class computational capabilities and codes through the Advanced Simulation and Computing (ASC) program

Finite element modeling and photovoltaics

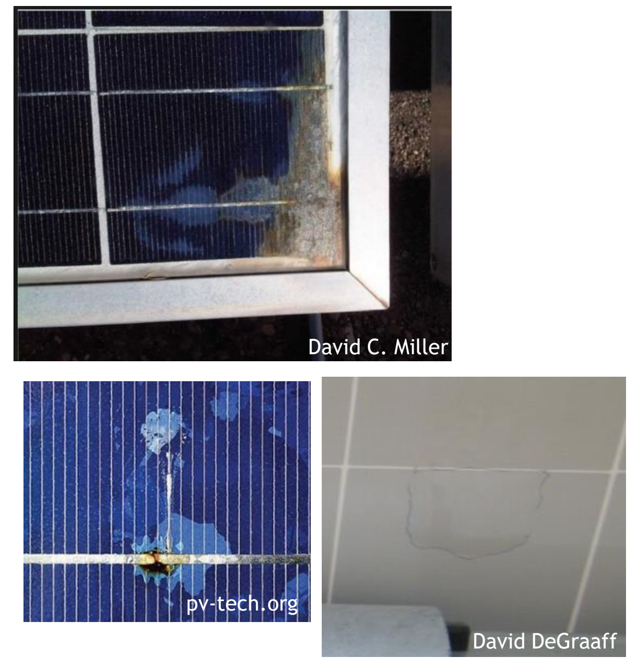
- Many applications for finite element models in the photovoltaics space
- This presentation will focus on how modeling can be used to address phenomena which may result in degradation:



Thermal effects



Mechanical damage



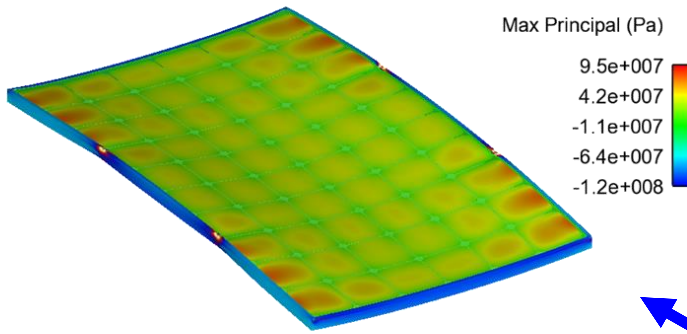
Coupled effects: Moisture ingress + temperature + mechanical stress …

This work is funded by the Durable Module Materials Consortium (DuraMAT), part of a US Department of Energy (DOE) Energy Materials Network (EMN)

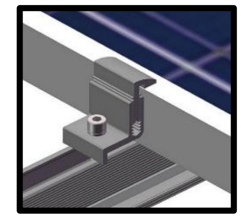
Module level model development

- Currently, we have developed full module mechanical + thermal models
- This takes into account many input parameters:

Module dimensions, materials, and design



Module level model



Constraint definitions

Material properties

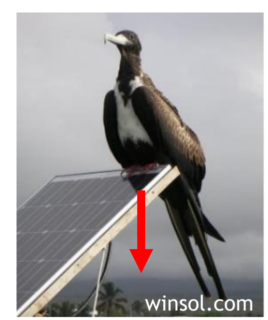
$$\vec{F} = m\vec{a}$$

$$\sigma_{ij} = \lambda\delta_{ij}\varepsilon_{kk} + 2\mu\varepsilon_{ij}$$

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)} \quad ; \quad \mu = \frac{E}{2(1+\nu)}$$

Governing equations

Initial conditions

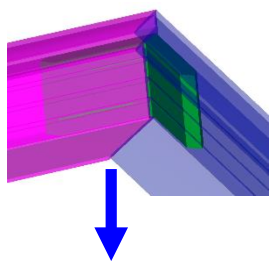


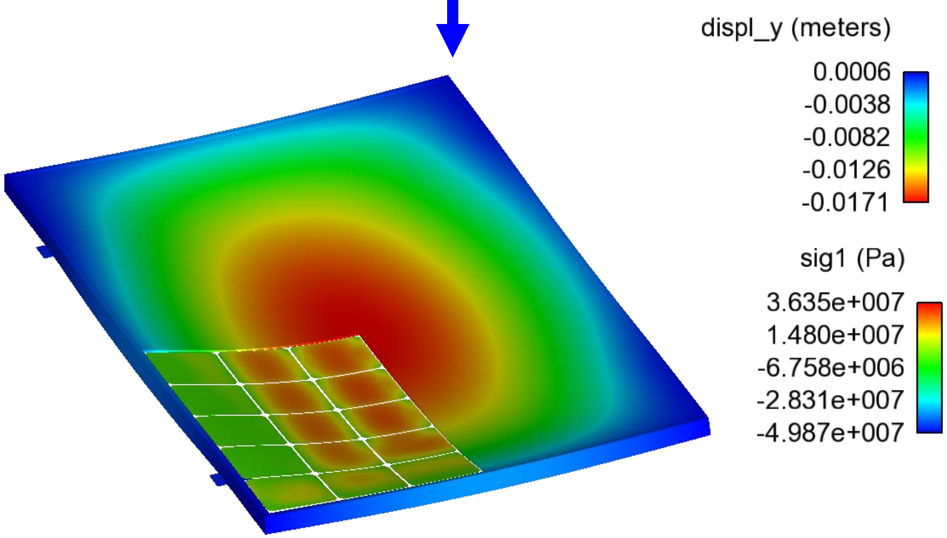
Loading conditions

Module level model applications

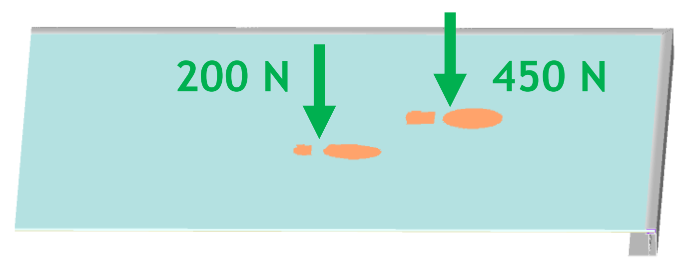
- Main application is analysis of environments- What stresses occur during:
  - Manufacture (Residual thermal stress, joint preloads)
  - Transportation/installation (Uneven or concentrated loading)
  - Deployment exposures (Wind pressure, thermal cycling)
- Modeling the effect of these exposures enables the causes of degradation to be understood

Detailed view: press-fitted joint





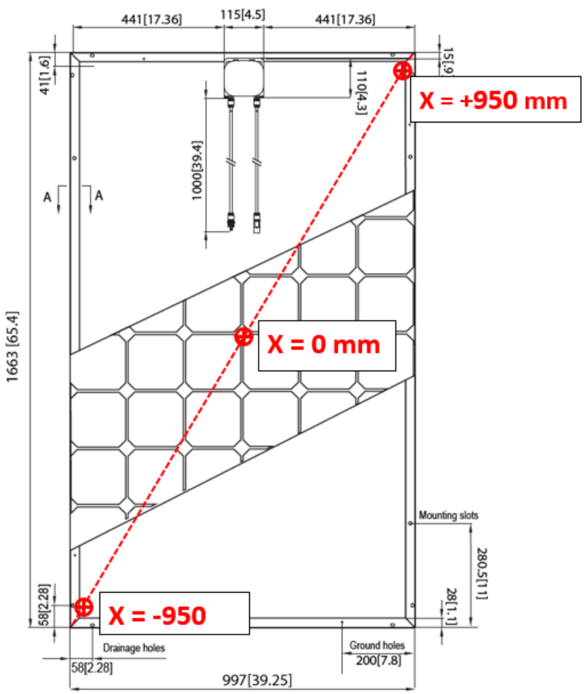
Deflection under a 2400 Pa wind load



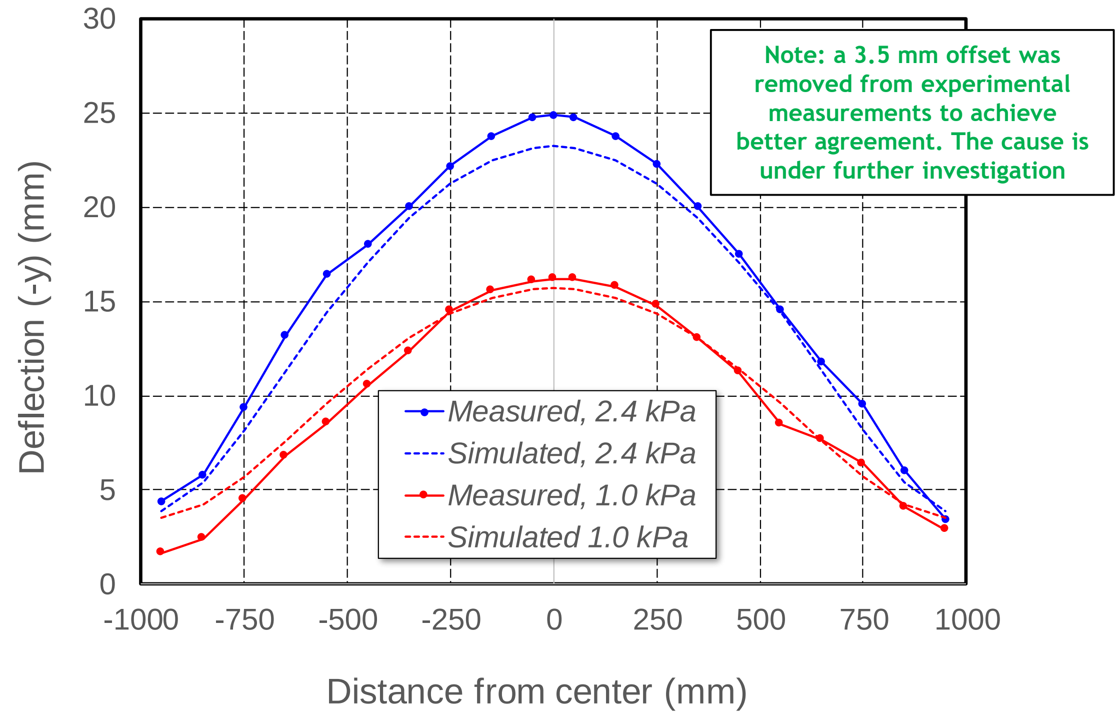
What are the stresses from walking on a module?

Module level model validation

- To be utilized with full confidence, model validation must be performed
  - Process of confirming model predictions against a known, measurable loading scenario- prior to extension into non-measured scenarios
  - For small deflections and linear, elastic material behavior, comparison of deflection vs. load is useful- uniform pressure load used as a test case



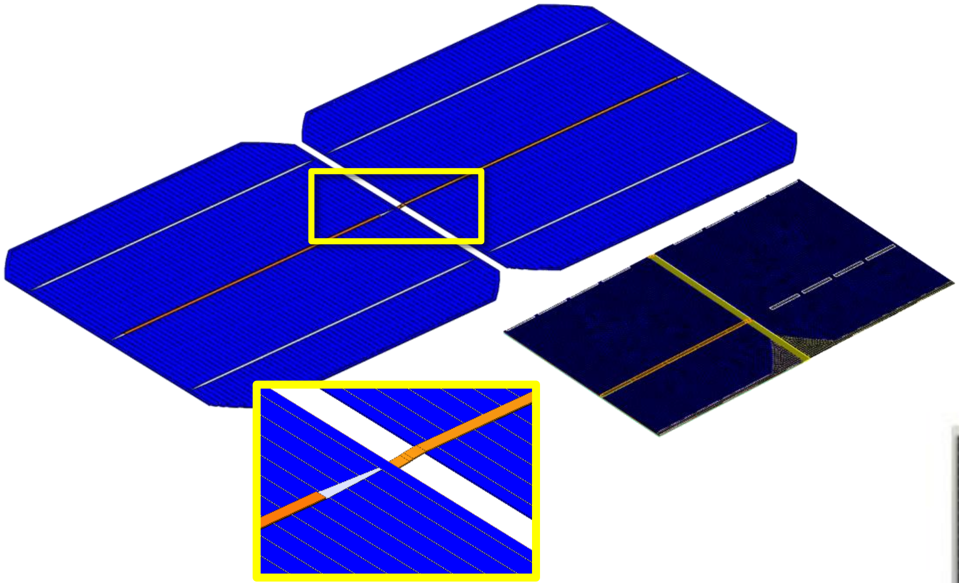
Solartechpower.com



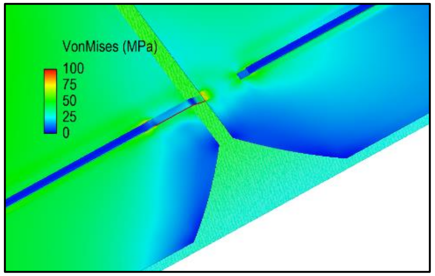
Simulated vs. Measured deflection vs. load @ 1.0 kPa and 2.4 kPa

Component level models and applications

- Component level models focusing on interconnects, solder joints, cells have been developed- degradation typically occurs at these discrete locations within a module
- Utilizes full scale model to inform boundary conditions
- Validation to be accomplished by deflection vs. load comparisons also

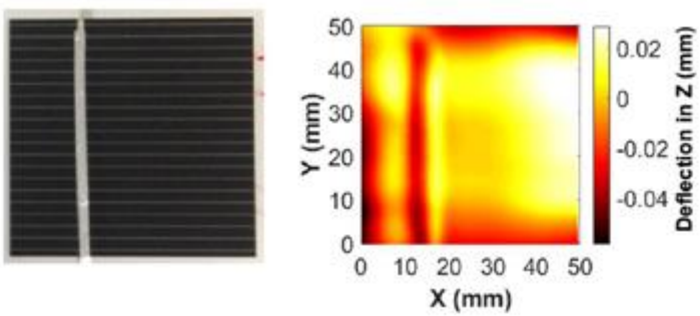


Component level model domain focusing on cell interconnection



Stress contour plot at +85°C

Meng et al. 2017



Deflection on cell after soldering Derived from X-ray imaging

Component level models and applications

- Parametric capability is a key application for simulations
  - Hundreds to thousands of simulations can be run: Possible to derive statistical correlations between parameters
  - Example design questions: Will switching to encapsulant A cause more stress than encapsulant B? If the modulus of glass is not well known, how much effect could it have on deflection?

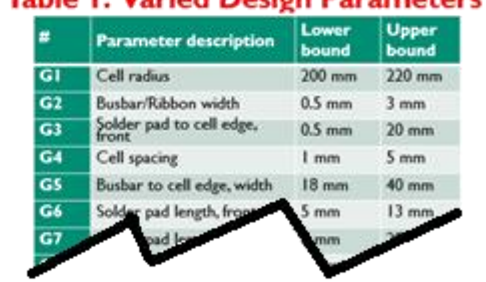
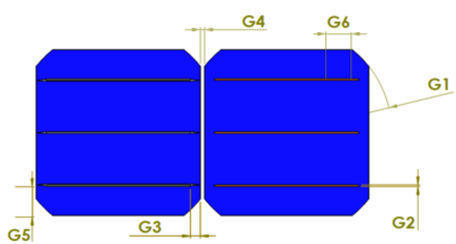


Table I: Varied Design Parameters

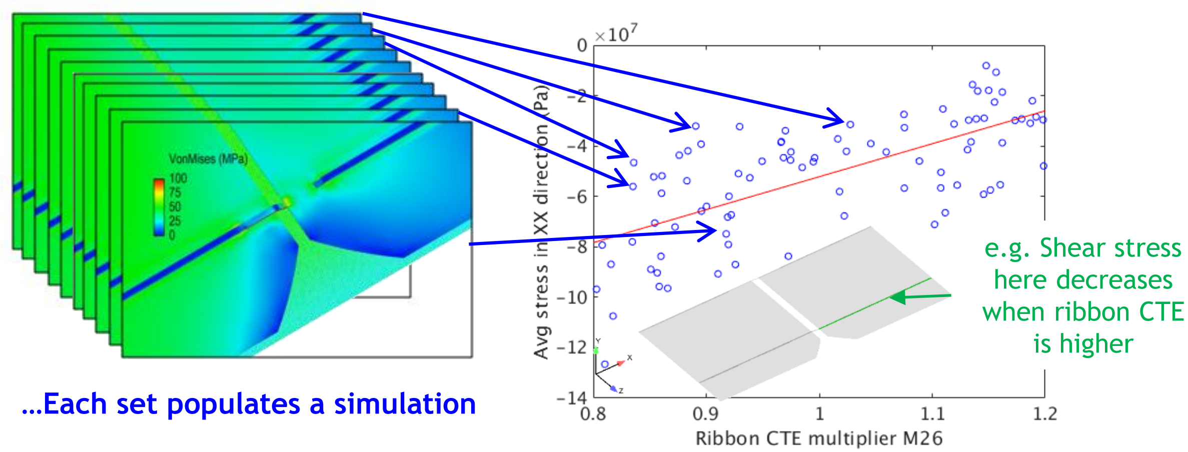
#	Parameter description	Lower bound	Upper bound
G1	Cell radius	200 mm	220 mm
G2	Busbar/Ribbon width	0.5 mm	3 mm
G3	Solder pad to cell edge, front	0.5 mm	20 mm
G4	Cell spacing	1 mm	5 mm
G5	Busbar to cell edge, width	18 mm	40 mm
G6	Solder pad length, fro[illegible]	5 mm	13 mm
G7	[illegible] pad le[illegible]	[illegible] mm	[illegible]



Design parameters and bounds are selected…

Many sets of parameter values are chosen by Latin Hypercube Sampling (LHS)...

…Quantities of interest are evaluated for each simulation and compared..



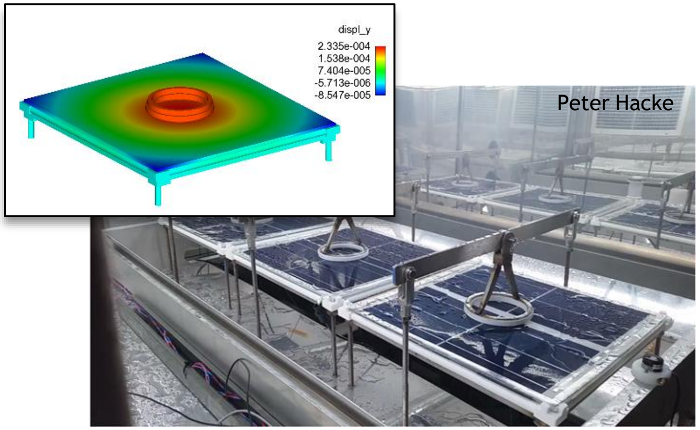
…Each set populates a simulation

Correlation of ribbon coefficient of thermal expansion to stress

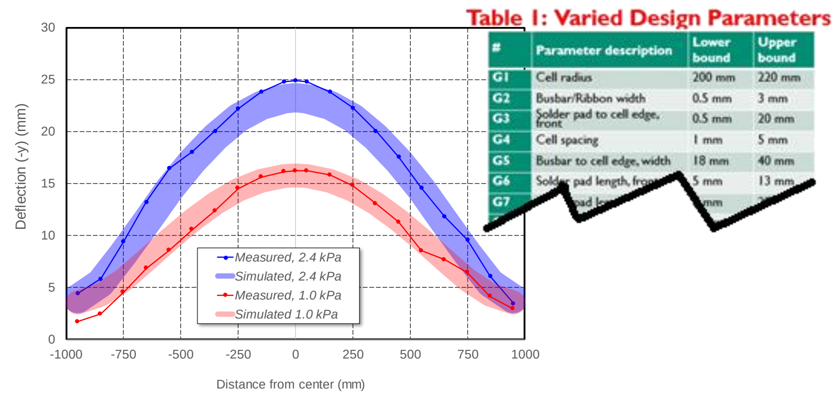
"Effects of Solar Cell Materials and Geometries on Thermally Induced Interfacial Stresses." James Y. Hartley; Scott Roberts. 45th IEEE PVSC Conference. Waikoloa, HI. June 10–15, 2018.

Current related modeling efforts

- Some current efforts extending from module- and component-level modeling:

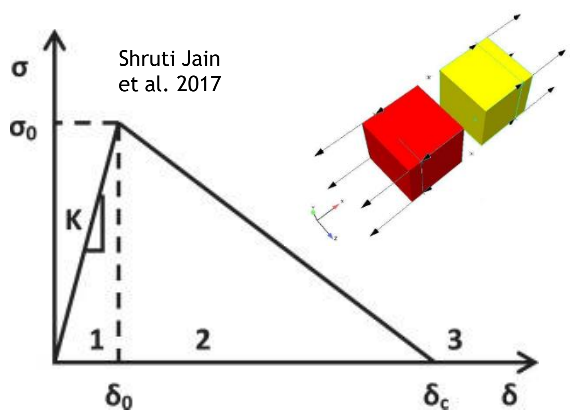


Mini module vs. full module stress confirmation

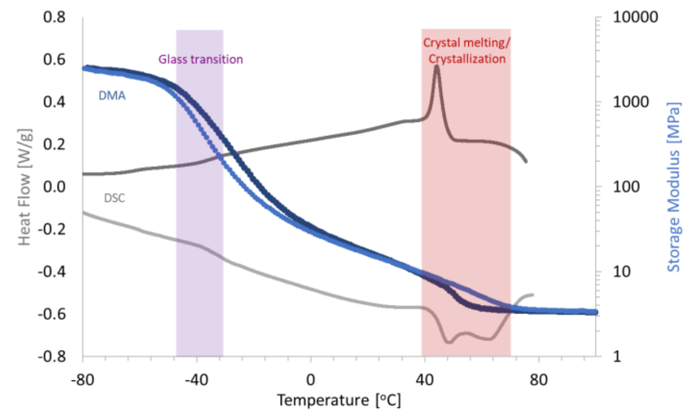


Full scale module sensitivity analysis

DuraMAT
Durable Module Materials Consortium



Cohesive zone models for encapsulant delamination



Material property characterization

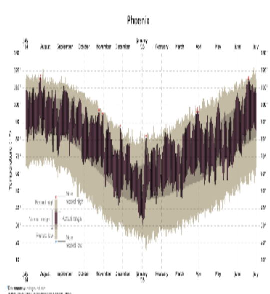
Future modeling efforts

- Physics which may be added to the finite element models:

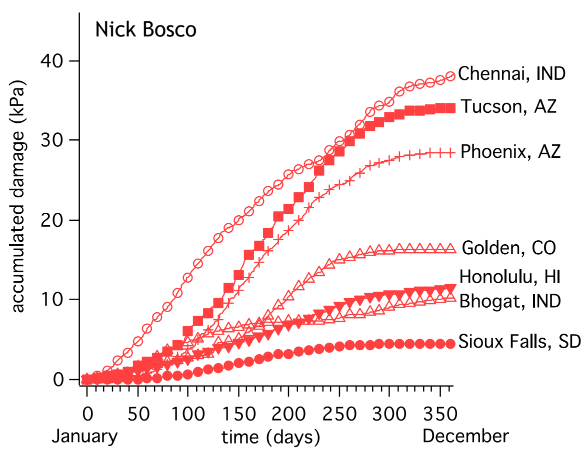
Laminate

$$\frac{\partial \varphi}{\partial t} = D\frac{\partial^2 \varphi}{\partial x^2} \text{ ??}$$

Moisture ingress modeling

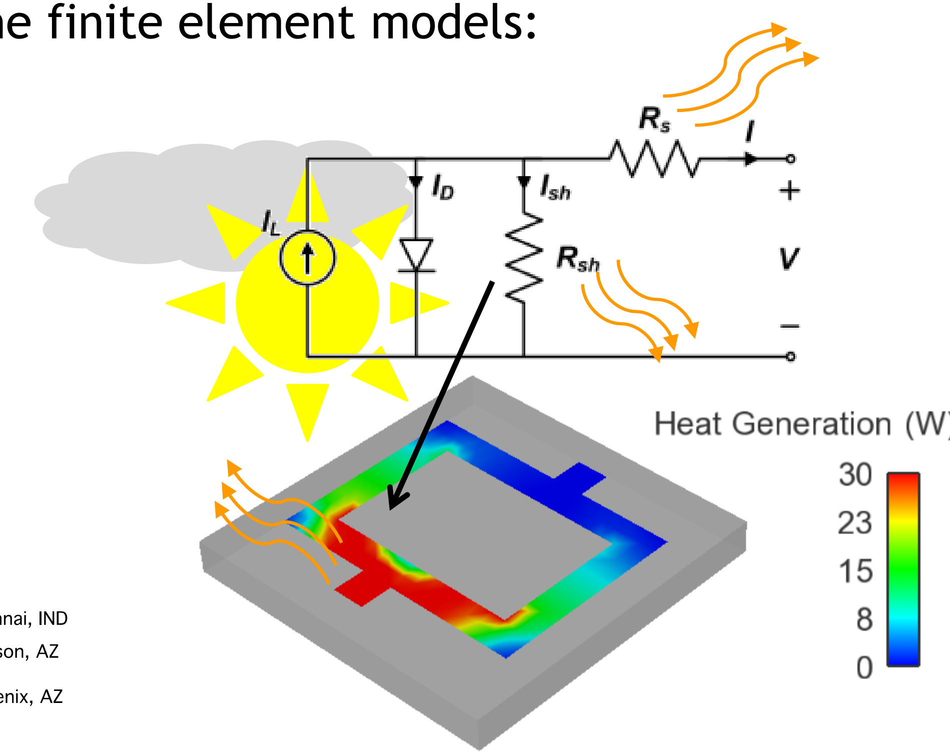


Cyclic Environmental Stressors



Damage rate vs. Geographical Location

Fatigue damage rate and lifetime prediction



Electrical-thermal (and mechanical) coupling

Summary and Conclusions

- Finite element modeling as applied to photovoltaic modules have a large application space including:
  - Module and cell design evaluation
  - Assessment of environmental effects
  - Evaluation of accelerated stress test protocols
- Development of module- and component-level models is in progress under the DuraMAT program
  - **The end goal is a predictive tool useful for capturing the physical phenomena affecting module lifetime**
  - Open research areas include characterizing and implementing:
    - Advanced material models
    - Coupled physical effects- electrical-thermal behavior, moisture, and potentially many more

- **Questions and comments?**