DuraMAT
Durable Module Materials Consortium

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Multi-Scale Modeling of Electrically Conductive Adhesive Interconnect Reliability

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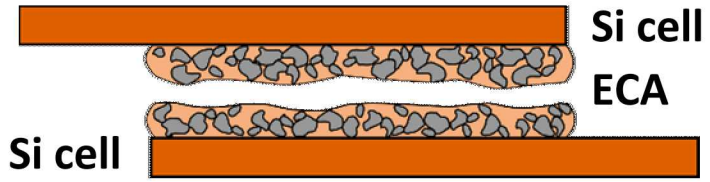
Motivation

Promising new module architectures have become available due to Electrically Conductive Adhesives (ECAs)

- Advantages such as reducing frontside metallization shading and removing soldering related stresses



ECAs use a conductive filler in a polymer matrix

Like any material, ECAs can degrade with exposure: But how?

- Novel material and novel module designs: conventional knowledge may not apply

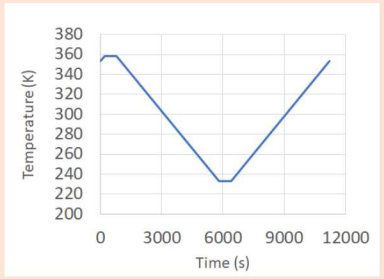
A shingled module:
An ECA-enabled architecture

Use a multi-scale modeling approach to elucidate the driving forces for ECA degradation in a shingled module

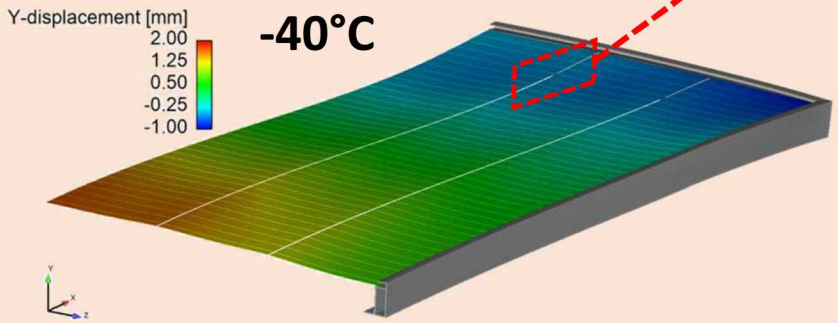
Multi-scale modeling approach

The **input** **[an environmental condition]** is propagated to the **output** **[forces on the ECA joint]** by passing information between computational models at different scales

Time (s)	Temp (°C)
0	80
200	85
800	85
5800	-40
6400	-40
11200	80



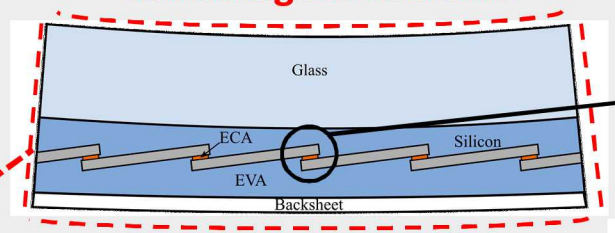
Thermal cycles: 85°C ↔ -40°C



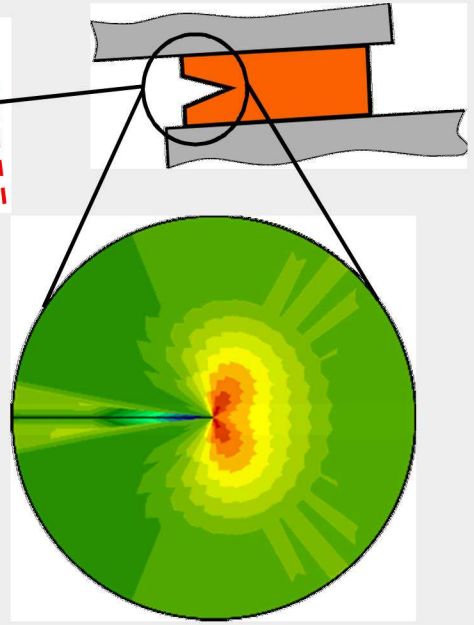
3D Full module model

Sandia National Laboratories

Cell string movements



2D, 5-cell fracture mechanics model



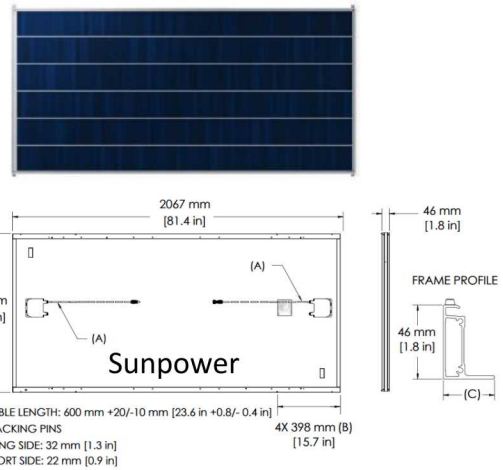
Debond driving force affecting an ECA joint

NREL NATIONAL RENEWABLE ENERGY LABORATORY

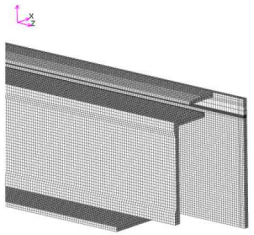
Ansys

3D Full module model

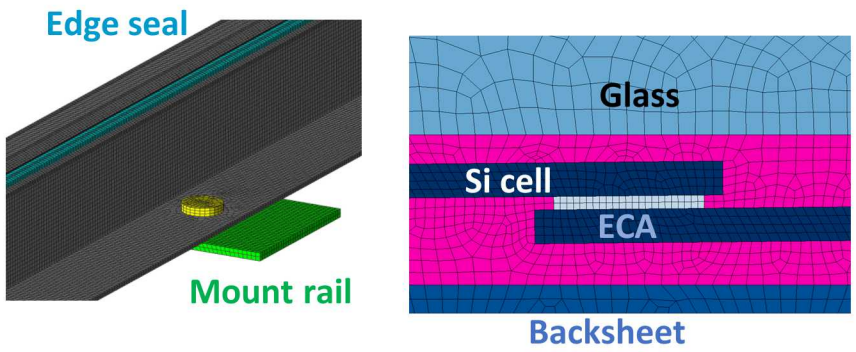
- Developed from datasheet information and a physical example
  - Frame, mounting, and assembly details as well as laminate and cell shingle detail
  - Thermal viscoelastic encapsulant and backsheet material models from measured data[1]
- Boundary conditions include mount points frame, edge adhesive
  - Informed by previous c-Si module mechanical analyses[2]



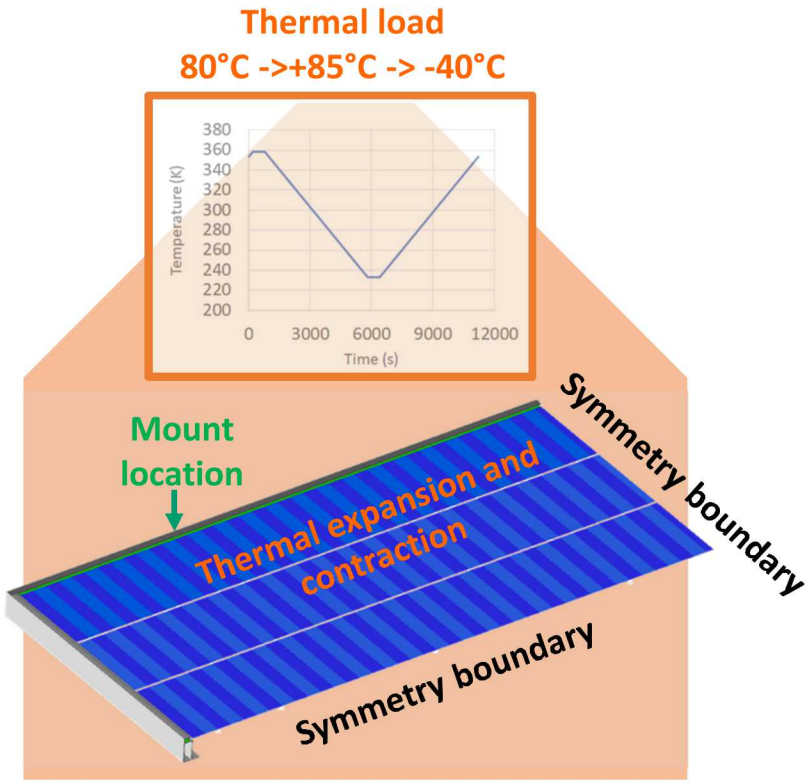
Geometry data



~8 million elements on quarter symmetric domain



Discretized model details



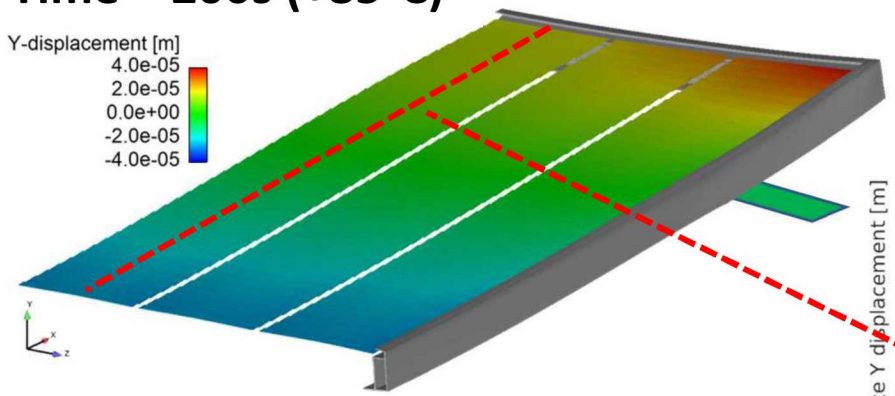
Simulation boundary conditions

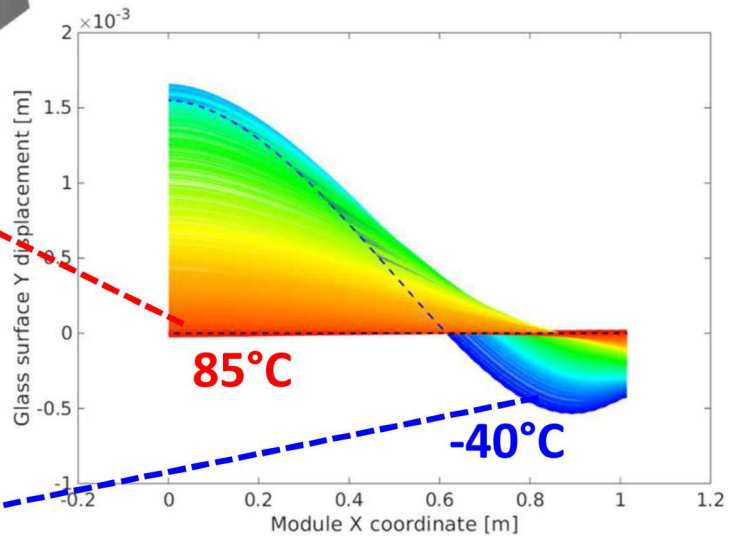
[1]N. Bosco, M. Springer and X. He, "Viscoelastic Material Characterization and Modeling of Photovoltaic Module Packaging Materials for Direct Finite-Element Method Input", *Journal of Photovoltaics, 2020.*

[2]J. Hartley, et al., "Effects of Photovoltaic Module Materials and Design on Module Deformation Under Load", *Journal of Photovoltaics, 2020*

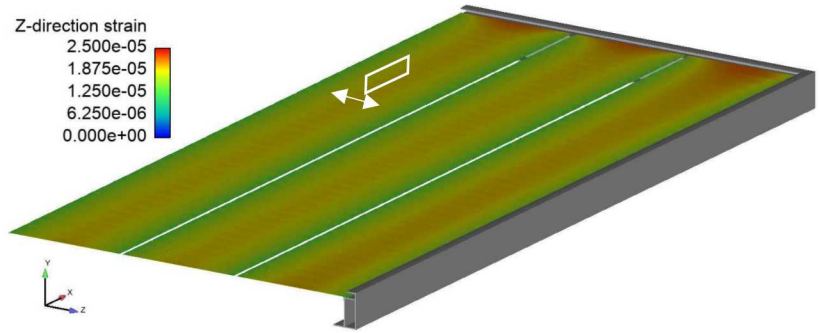
3D Full module model results

Time = 200s (+85°C)

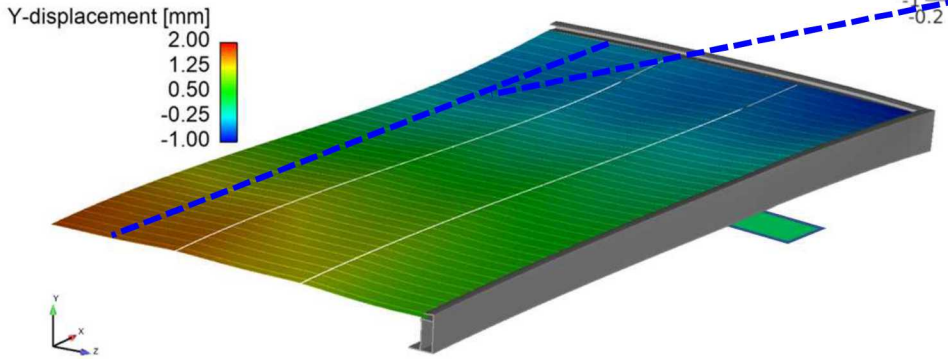




Time = 200s (+85°C)

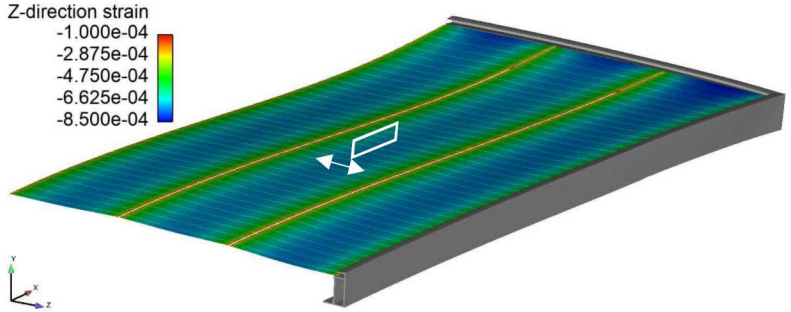


Time = 5800s (-40°C)



Cell string curvatures vs. temperature and time

Time = 5800s (-40°C)

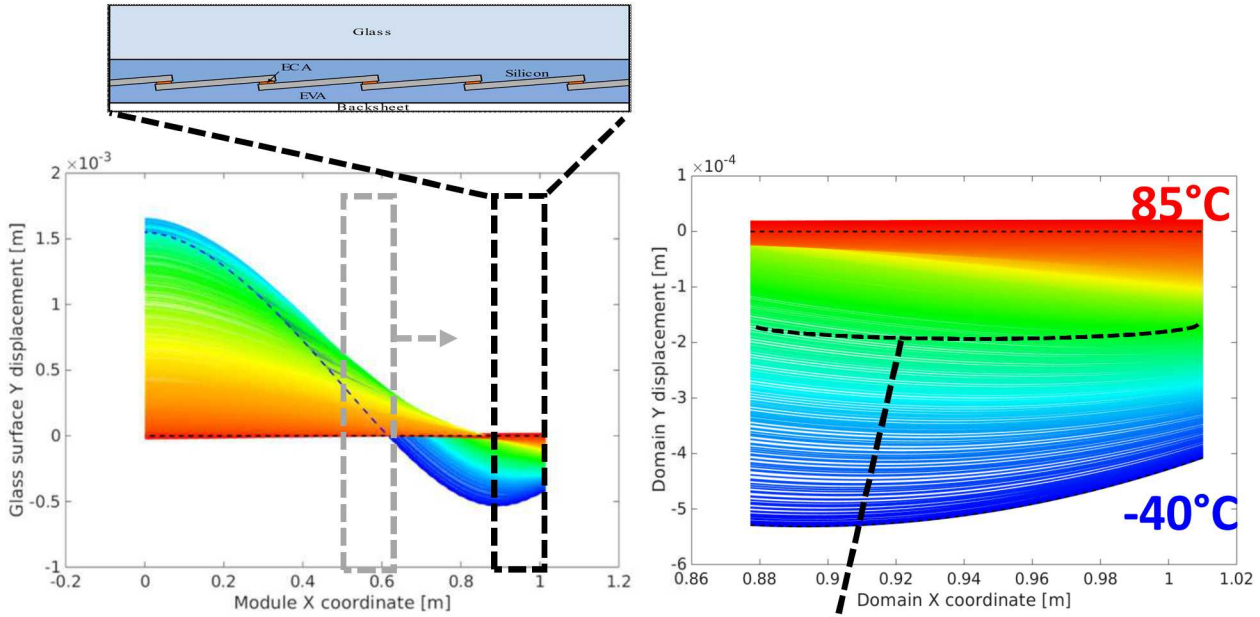


Simulated module displacements (quarter symmetric)

Confirmation of near-constant strain along cell widths

3D Full module to 2D model handoff details

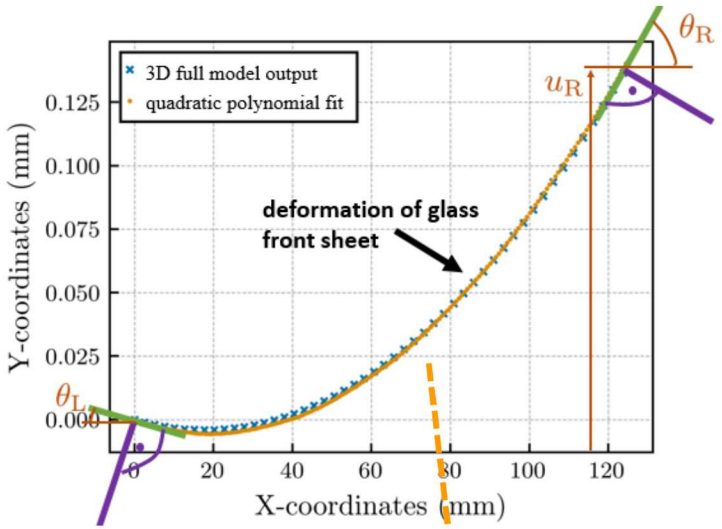
- 2D model: 5-cells, glass, encapsulant, and backsheet (same dimensions as full module model)



$$y = C_0 + C_1 x + C_2 x^2$$

```
for each row of cells
    for each 5-cell domain
        for all times and temps
```

Quantify each 5-cell domain curvature



Polynomial fit

$$y = C_0 + C_1 x + C_2 x^2$$

Derivative

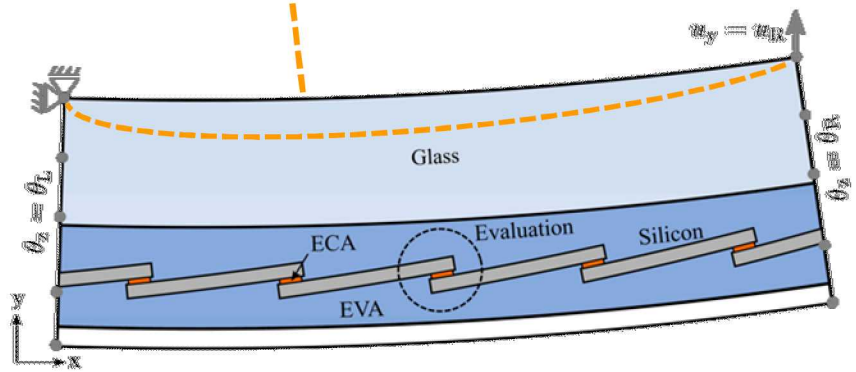
$$y' = C_1 + 2C_2 x$$

Boundary conditions

$$\theta = \arctan(y')$$
$$u_R = u_y$$

Submodel edges

Assumed to remain straight throughout the simulation

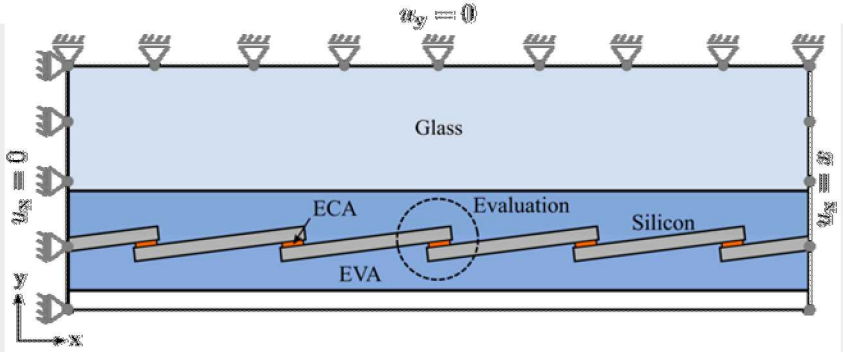


Apply full module domains to 2D model

Which 3D model boundary conditions should be used?

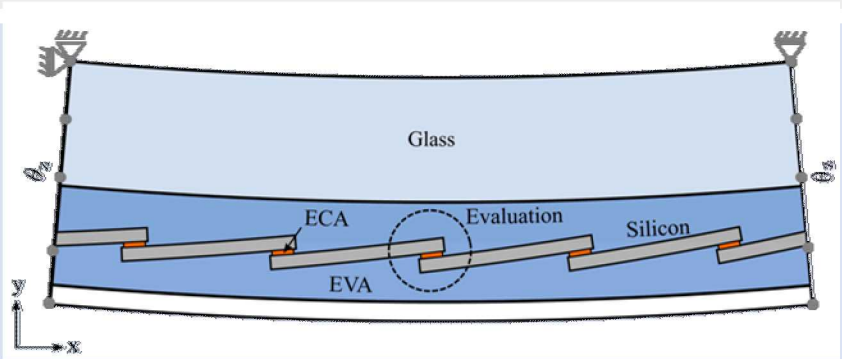
- Consider the extreme boundary conditions the 2D model could assume

Flat



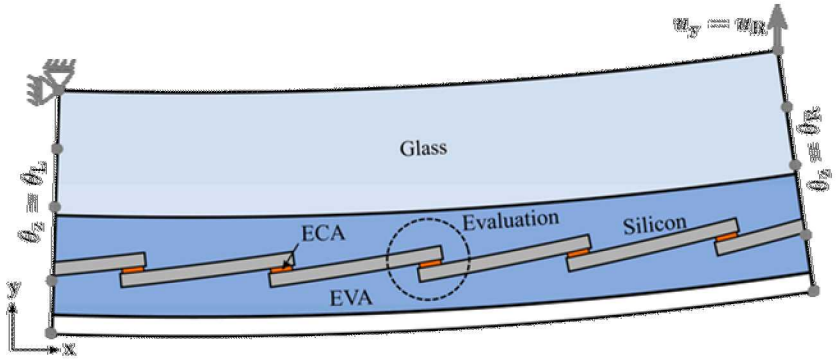
- Top surface remains flat and domain sides must stay rectangular

Free



- Constraints for rigid body movement and rotation. Domain sides are symmetric but otherwise free.

Full module derived



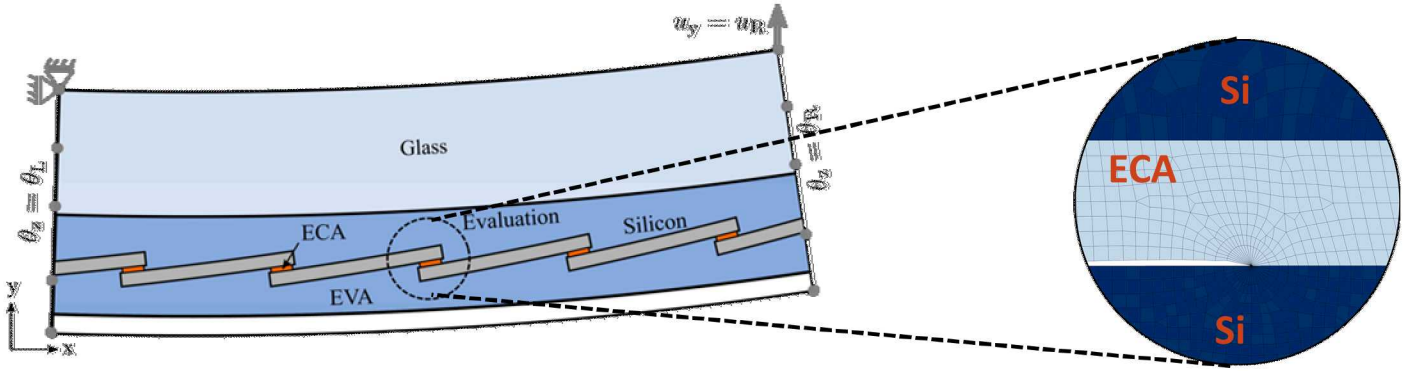
- Most realistic boundary condition from full module model

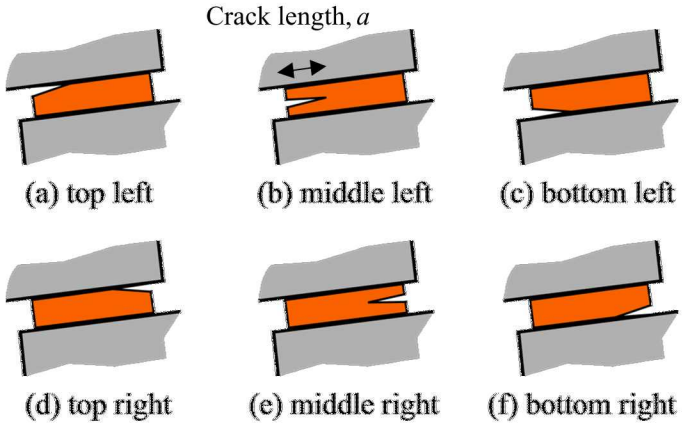
$$y = C_0 + C_1 x + C_2 x^2$$

- Can choose flattest and most curved states, i.e. $C_{2\ min}$ and $C_{2\ max}$

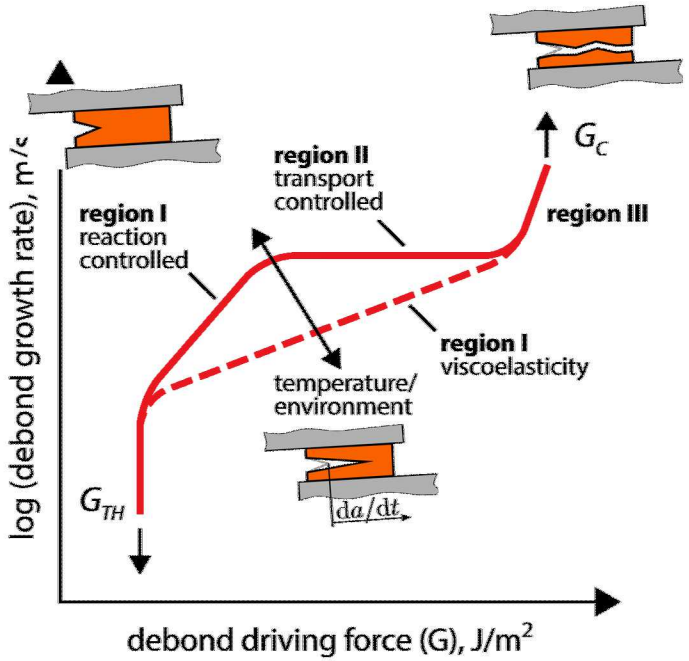
2D model details and features

- Fracture mechanics model includes assumed crack lengths and positions
- **Input:** Boundary curvatures and temperature vs. time
- **Output:** Debond driving force in modes I and II vs. crack position and length



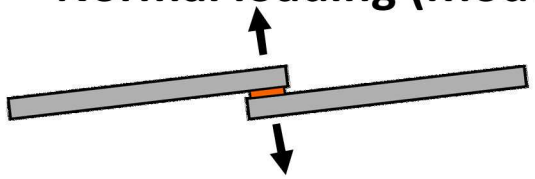


Assumed crack positions and length

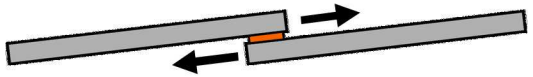


G_c= critical strain energy release rate (a material property)

Normal loading (Mode I)

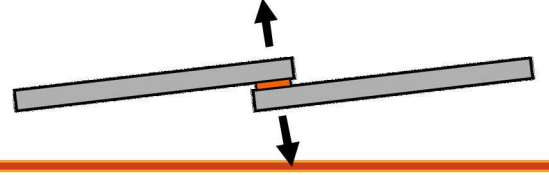


Shear loading (Mode II)

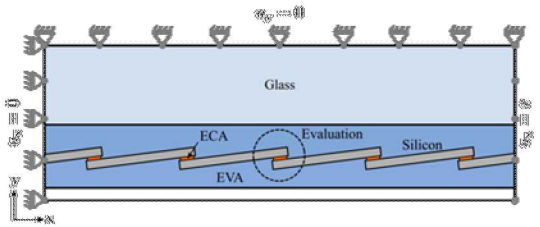


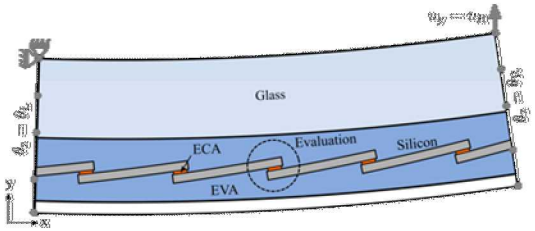
Model predicts if cracks will be stable, grow, or fracture

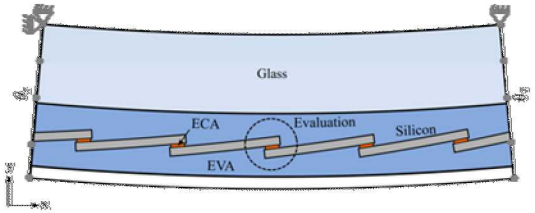
Submodel results: Mode I

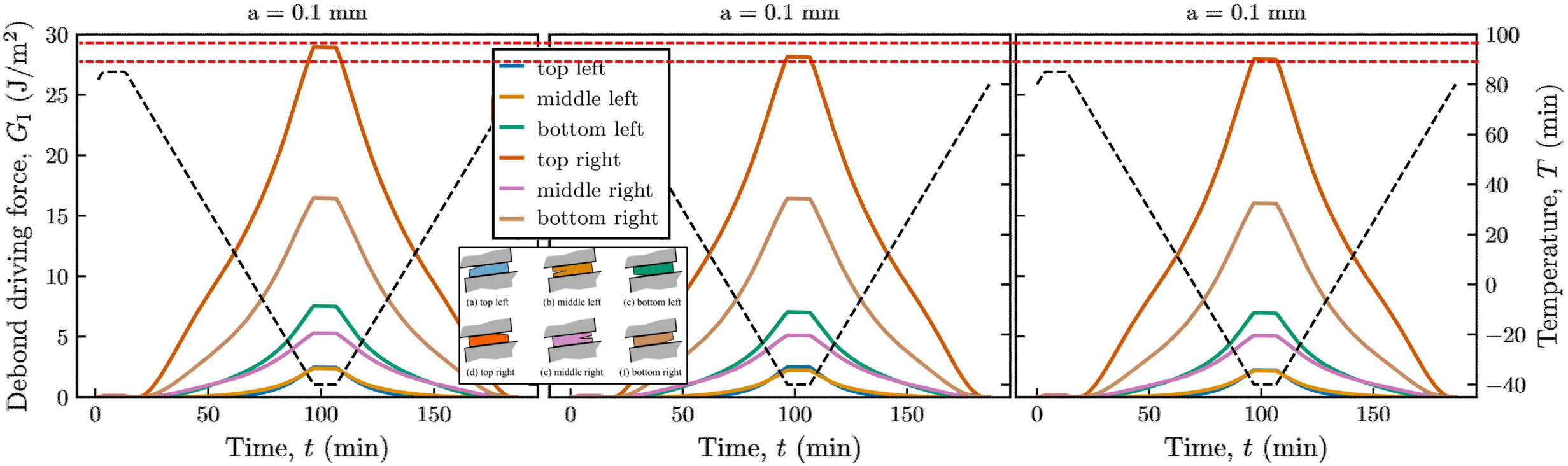


flat > **Full module derived** (Most curved, C_{2max}) > **free**

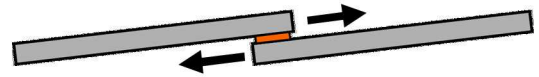




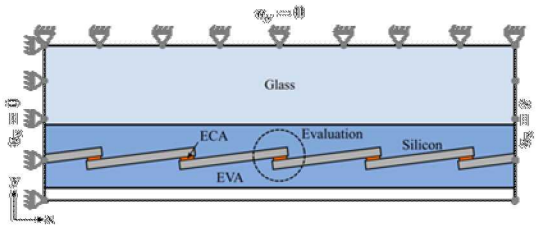


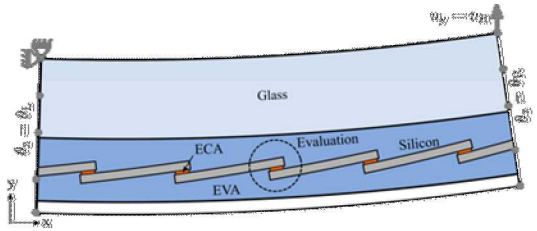


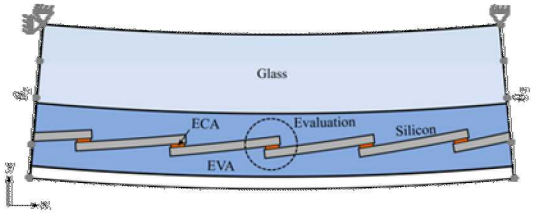
Submodel results: Mode II

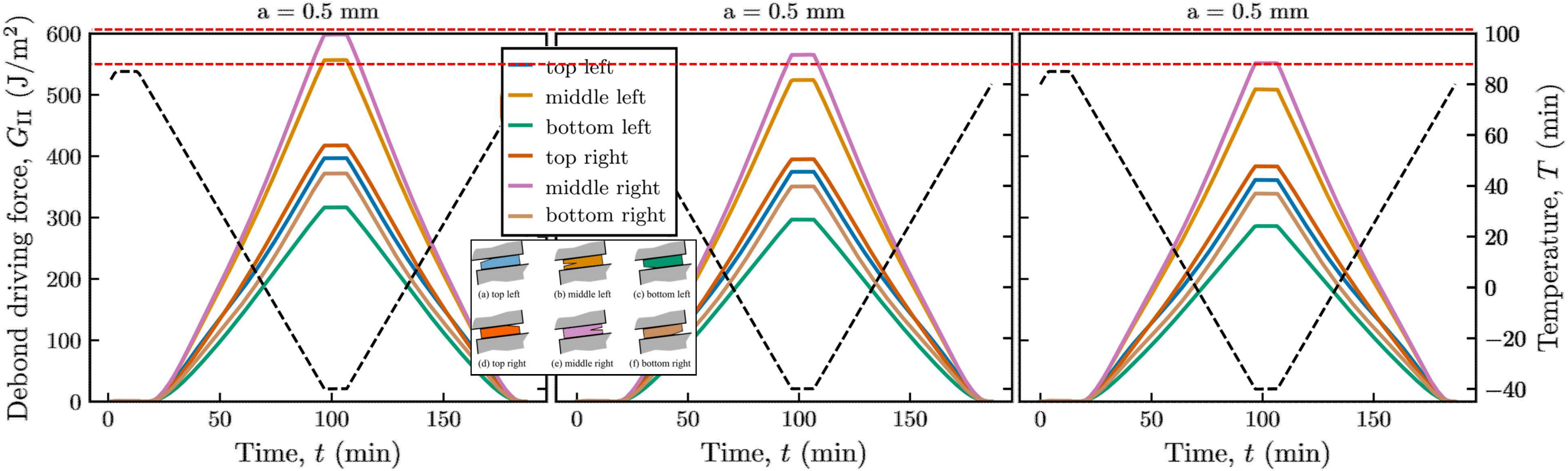


flat > **Full module derived** (Most curved, C_{2max}) > **free**



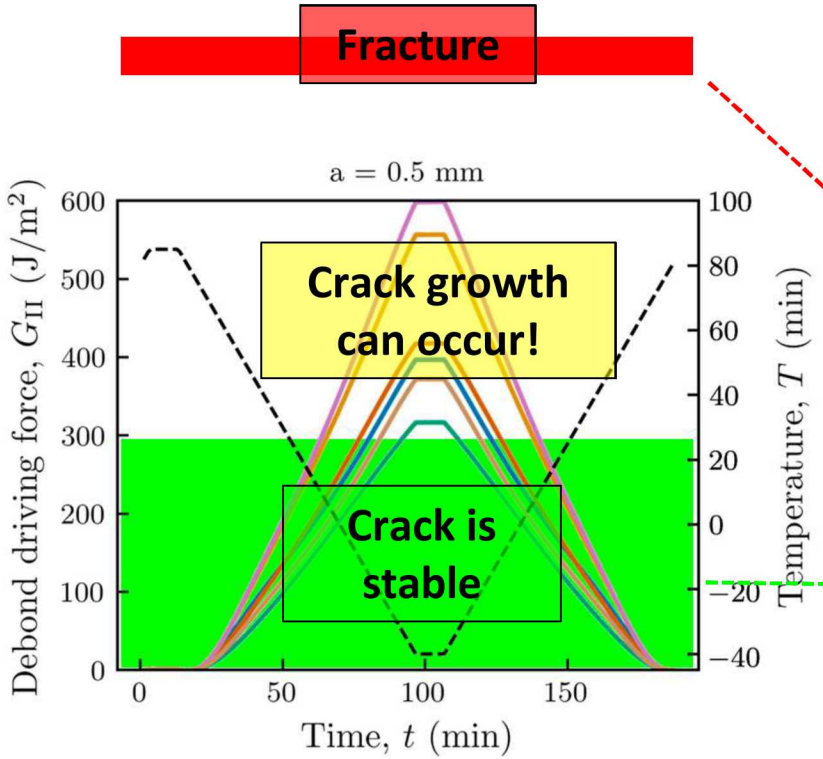




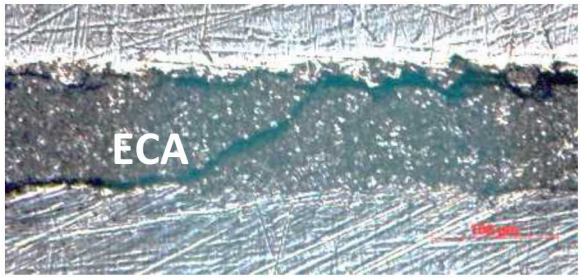


Key results

- Recall that critical debond driving force is a measurable material property: Strain energy release rate, *G*
- **Comparing modeled values for debond driving force to thresholds tells us if degradation is expected**



Model predicted debond driving forces vs. measured criteria



Moisture affected threshold values[3]

mode II	**mode I**
$G_c(45C) > 800$ J/m^2	$G_c(45C) < 100$ J/m^2
$G_{th}(45C) < 300$ J/m^2	$G_{th}(45C) < 20$ J/m^2

Critical values for ECA strain energy release rate (a.k.a. allowable debond driving force)

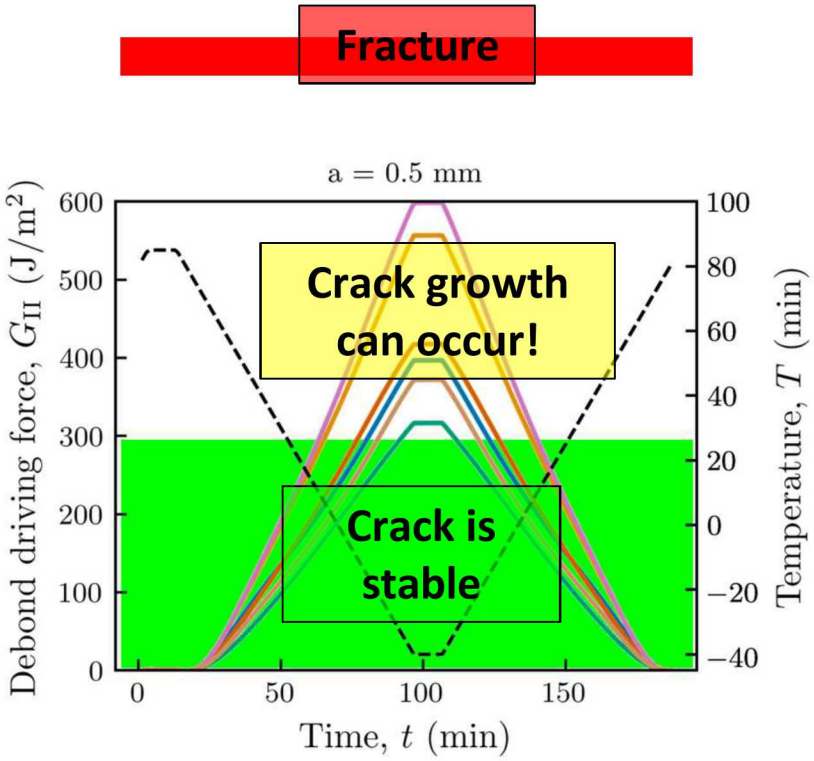
[3]N. Bosco, J. Tracy, and R. Dauskardt, "Environmental Influence on Module Delamination Rate," *IEEE Journal of Photovoltaics,* vol. PP, pp. 1-7, 12/13 2018, doi: 10.1109/JPHOTOV.2018.2877436.

Summary and conclusions

- **We've developed a method for calculating the debond driving force affecting an ECA joint *inside a full module* for arbitrary environments**
  - Demonstrated for an IEC thermal cycle
  - Demonstrated that 2D modeling assumptions are conservative

This modeling methodology enables:

- **A material design criteria to guarantee joint survival**
- **Accelerated test design criteria to exactly replicate real ECA joint stresses**



Model predicted debond driving forces vs. measured criteria

Backup

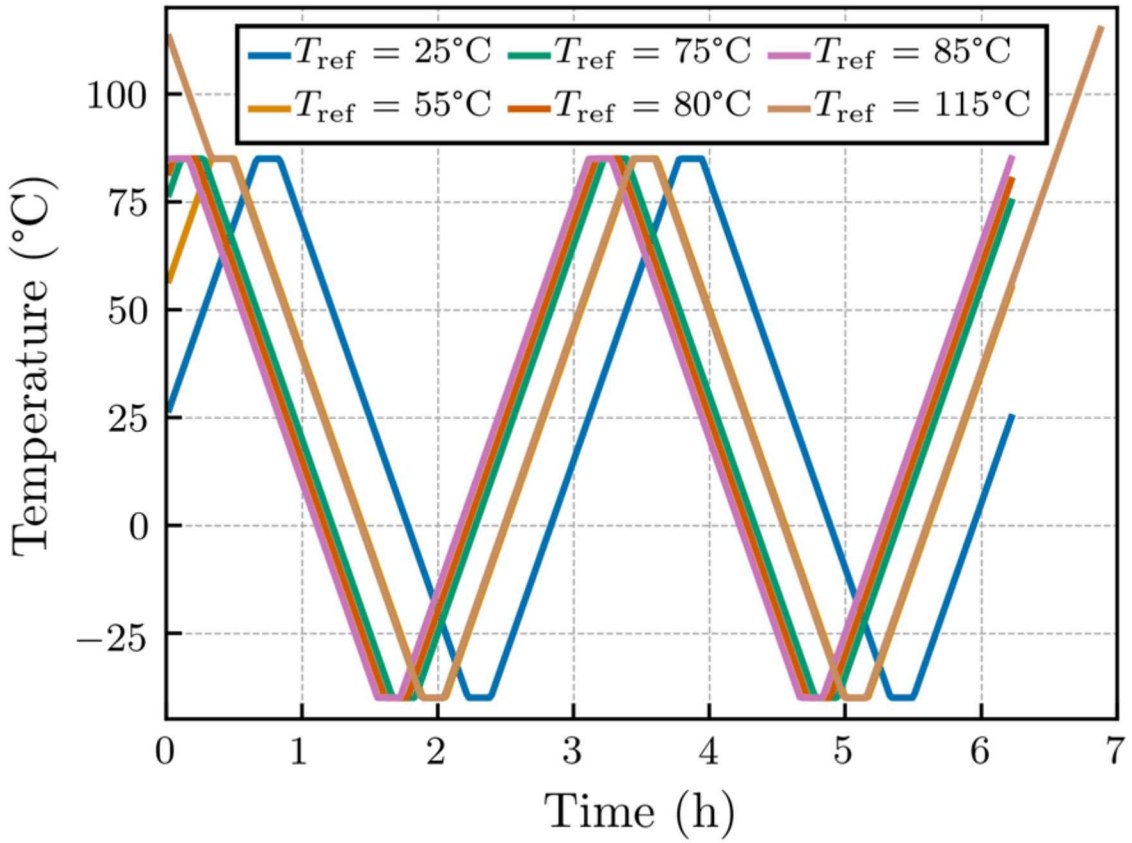
Reference Temperature Selection

minimum energy approach - arbitrary stress-free temperature

Simulations to determine simulation starting point.

minimum strain energy found to exist at ~80 C

thermal cycles with different reference temperatures



total strain energy minimum