Multi-Scale Modeling of Photovoltaic Module Electrically Conductive Adhesive Interconnects for Reliability Testing

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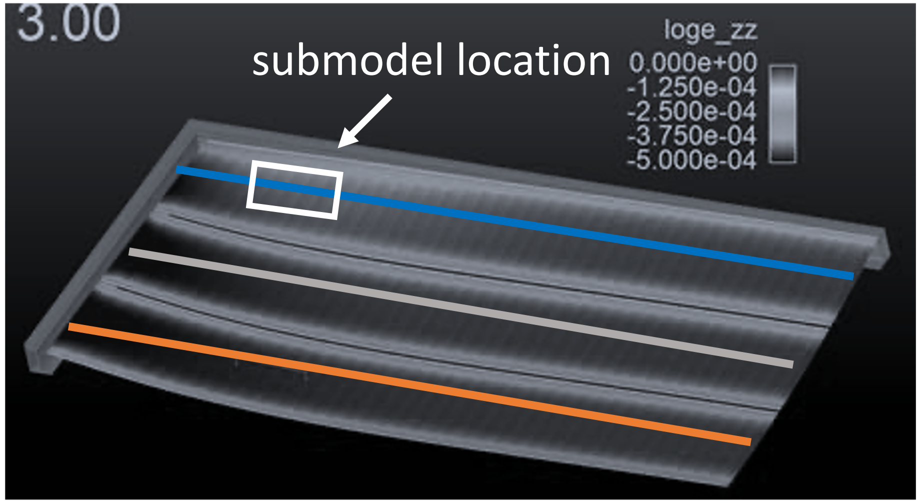
goal and approach

Elucidate the driving force for ECA *degradation* in shingled PV modules and how it is developed.

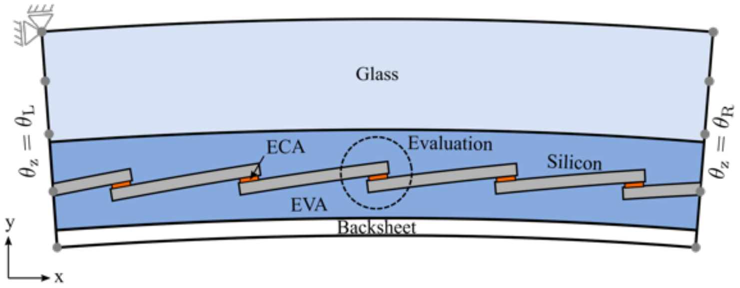
Employ a 3D model of a complete shingled cell module to inform a more detailed submodel.
This multi-scale approach allows accurate simulations of small-scale phenomenon.

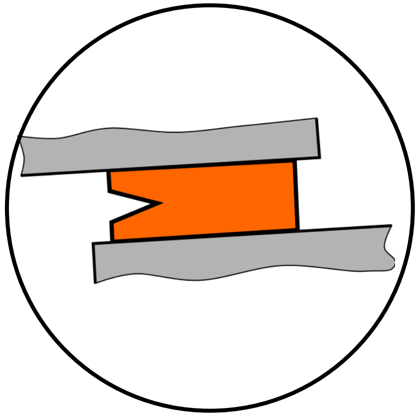
full 3D module model



input: module loading conditions
output: module-level deflection

2D module model



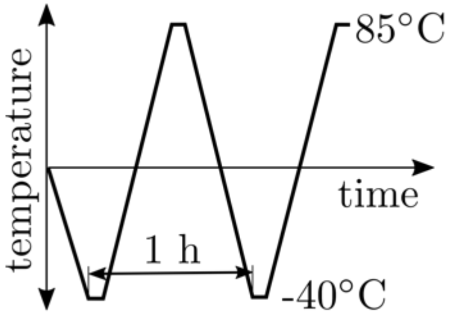


input: module-level deflection
output: interconnect-level response

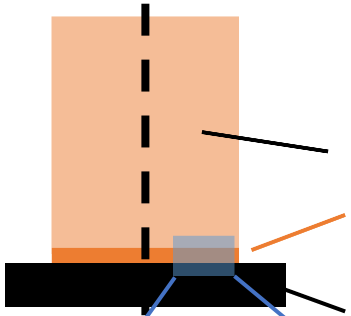
motivation

Cracking and debonding of an ECA marketed for PV interconnection found through accelerated thermal cycling

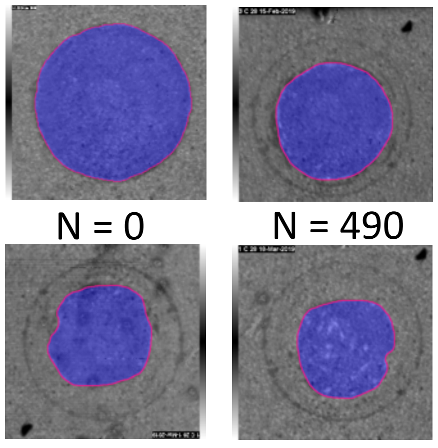
Thermal Cycling Test Vehicle



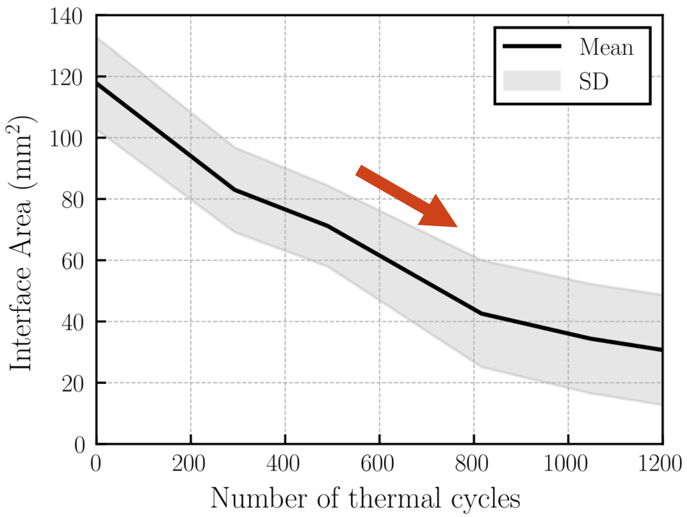
Schematic



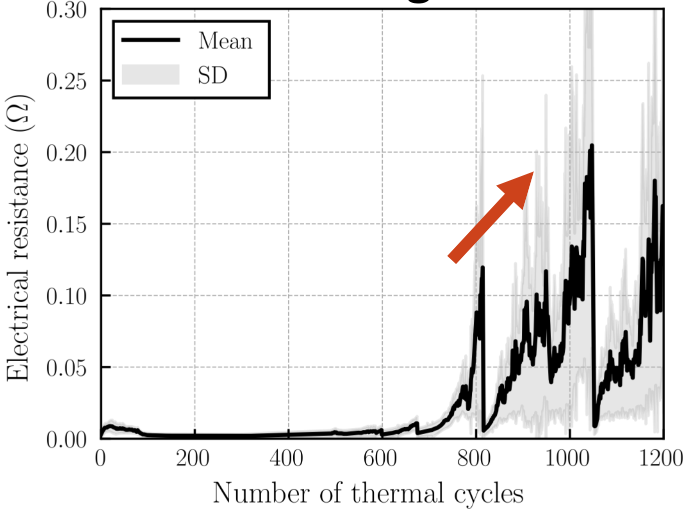
interface area



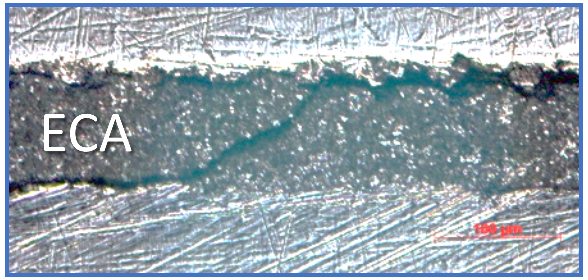
mechanical degradation



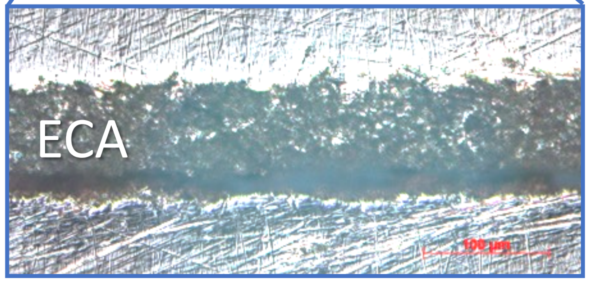
electrical degradation



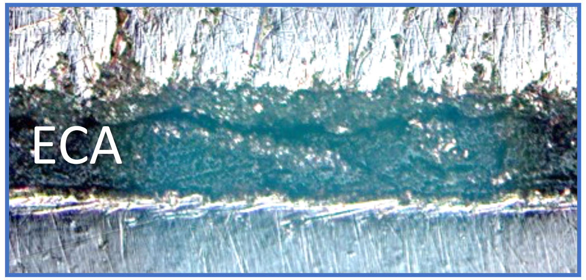
Mixed failure mode



Adhesive failure mode



Cohesive failure mode

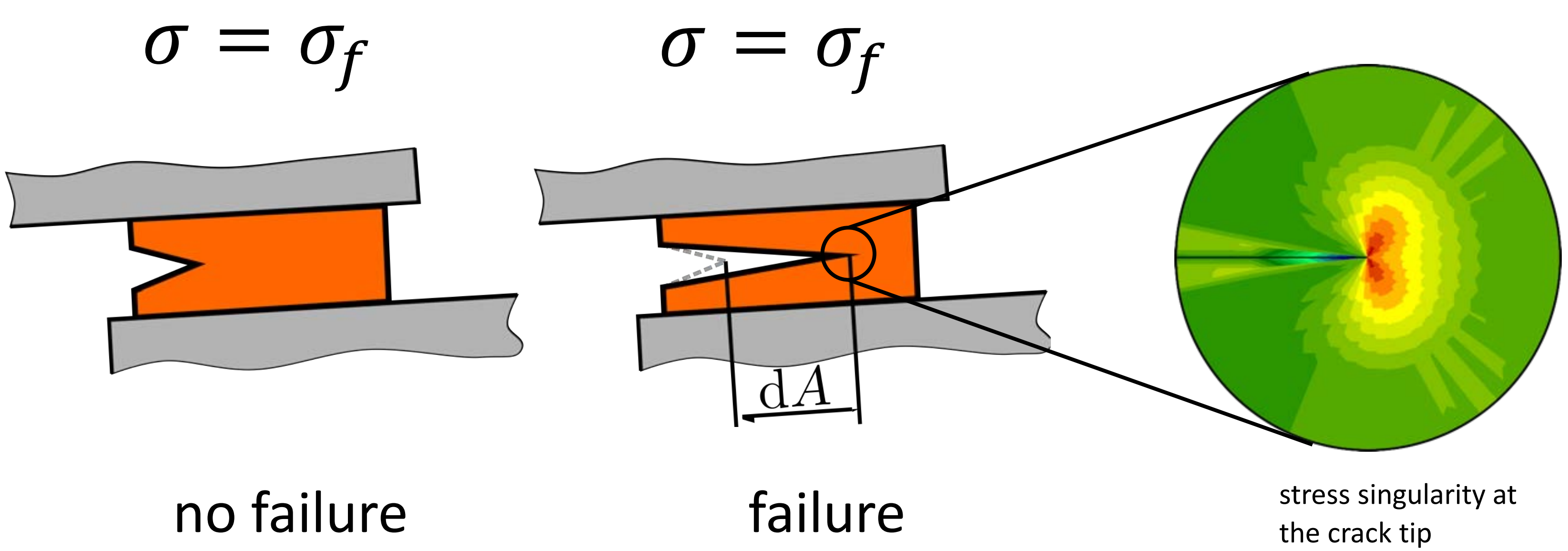


N. Bosco and M. Springer, "Towards a Unified Constitutive Model for the Degradation of Electrically Conductive Adhesives," in *Metallization and Interconnection Workshop*, Konstanz, DE, 2019.

approach

Evaluation of the strain energy release rate, *G*

A **maximum stress theory** for interconnect failure is too general to inform degradation behavior



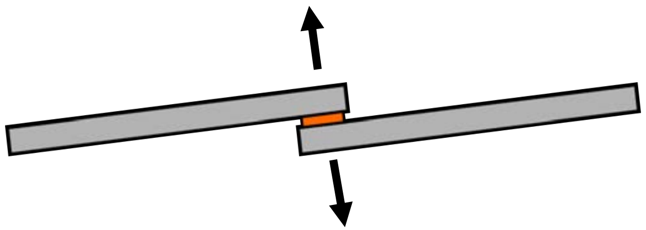
The **strain energy release rate**, *G,* accounts for both loading and crack specific geometry

Provides a specific metric (driving force) capable of predicting degradation behavior

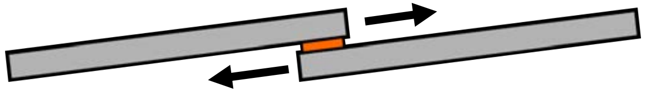
approach

We evaluate the **driving force, *G*,** for two modes of crack opening:

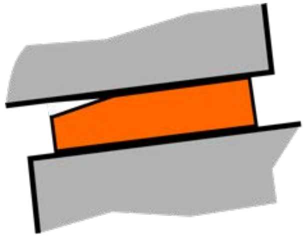
Normal loading (Mode I)



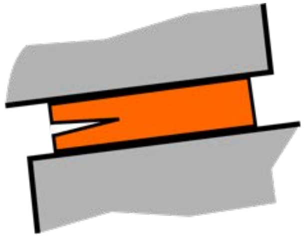
Shear loading (Mode II)



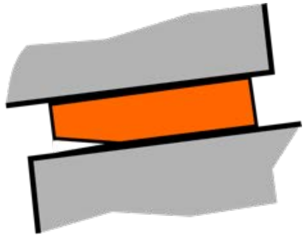
and six different crack locations within the interconnect



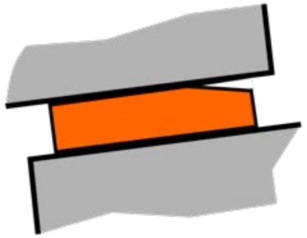
(a) top left



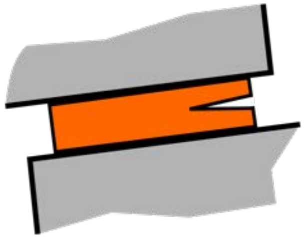
(b) middle left



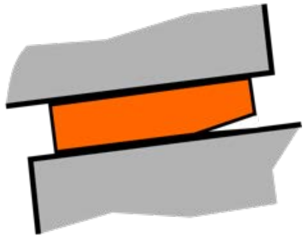
(c) bottom left



(d) top right



(e) middle right

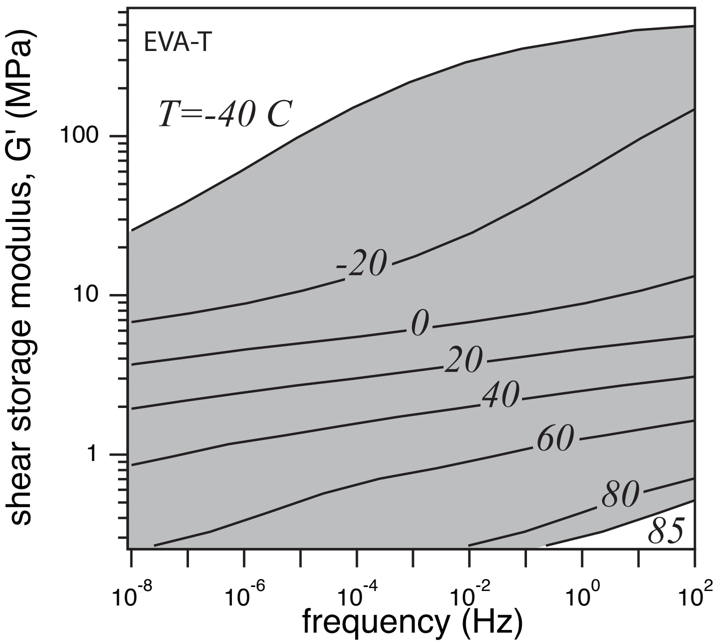


(f) bottom right

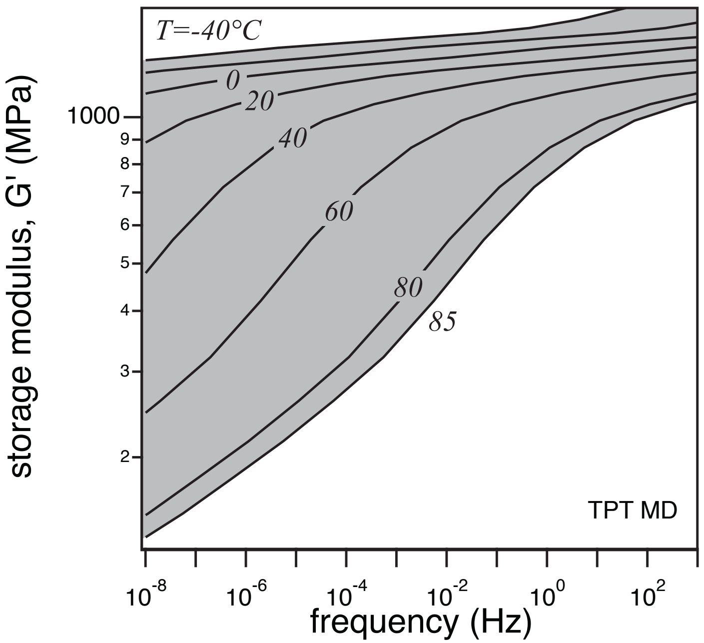
approach

Material models

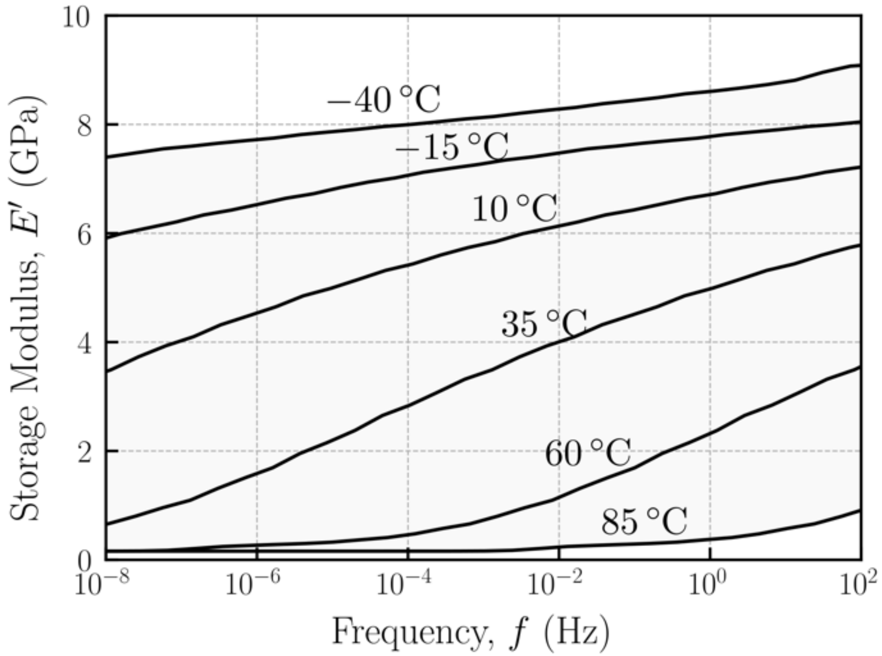
EVA encapsulant



TPT backsheet



ECA



M. Springer and N. Bosco, "Linear viscoelastic characterization of electrically conductive adhesives used as interconnect in photovoltaic modules," *Progress in Photovoltaics: Research and Applications,* vol. n/a, no. n/a, doi: 10.1002/pip.3257.

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

preliminary simulations

minimum energy approach - arbitrary stress-free temperature

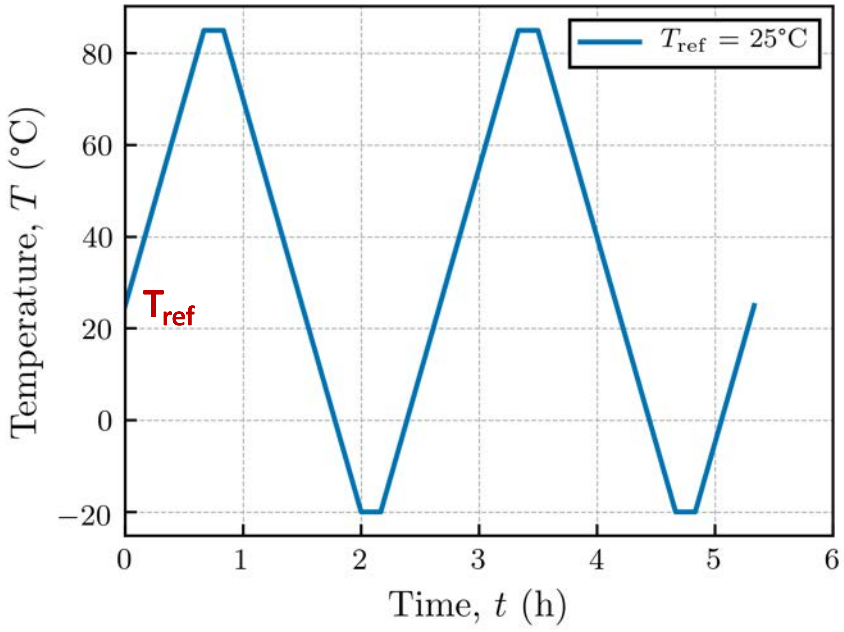
Example stress-free temperature: 25°C

Loading conditions: 2 thermal cycles (Tref -> 85°C -> -20°C -> Tref) x 2

Total strain energy = Elastic strain energy + Viscoelastic dissipation energy

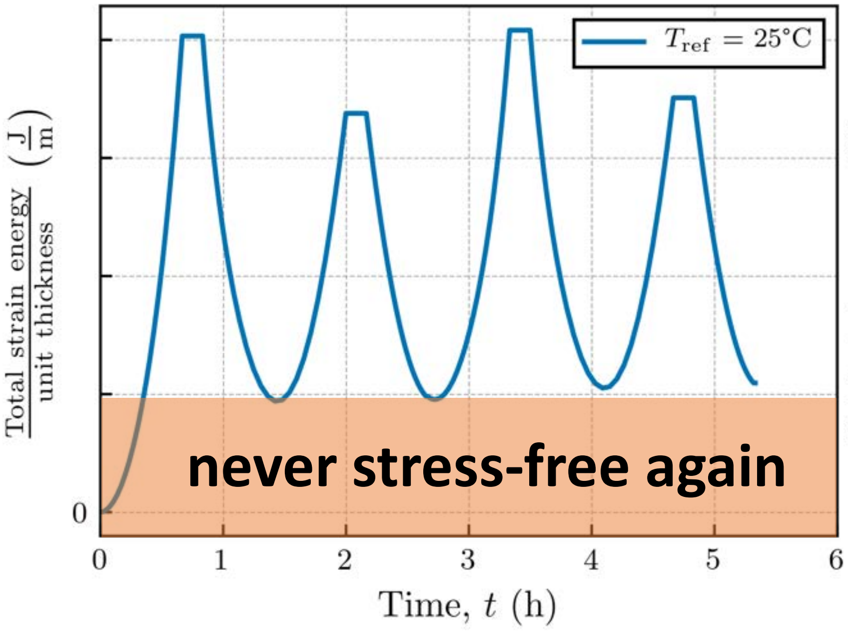
thermal cycling

over time

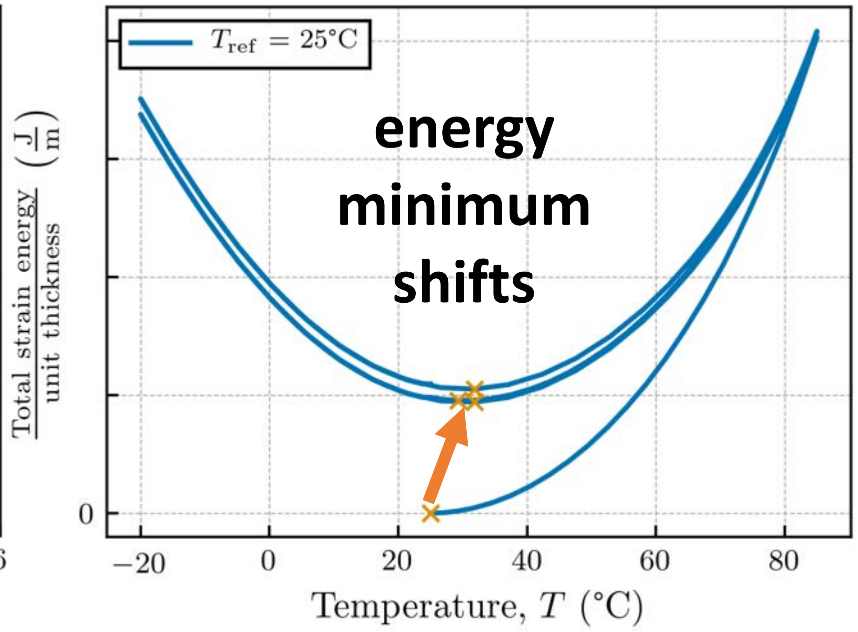


total strain energy

over time



over temperature



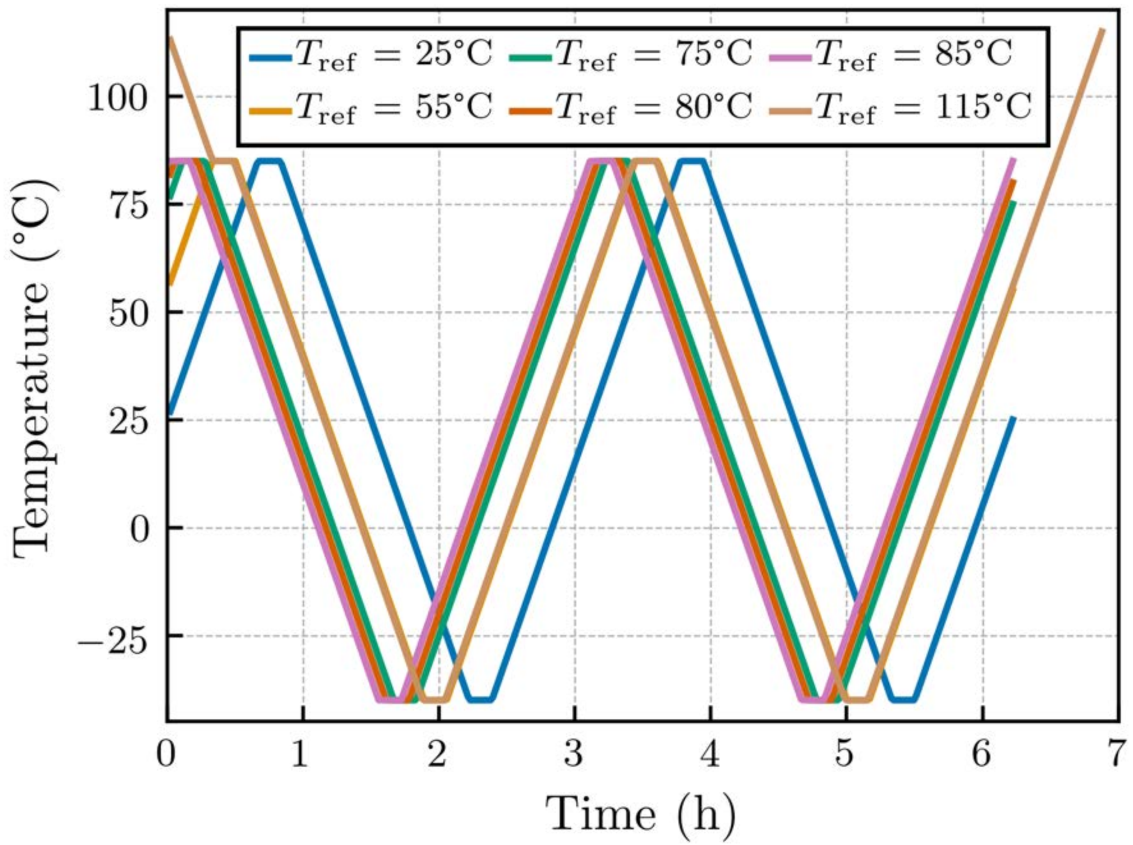
preliminary simulations

minimum energy approach - arbitrary stress-free temperature

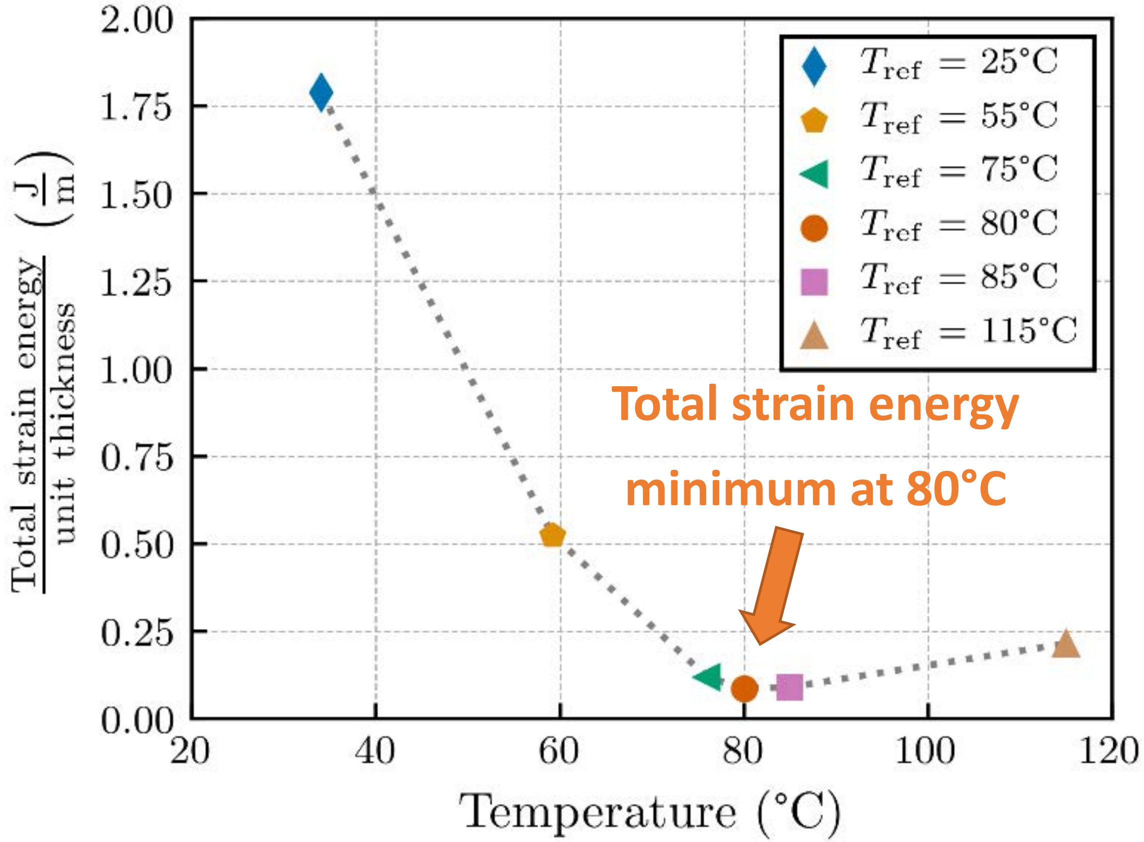
Simulations to determine simulation starting point.

minimum strain energy found to exist at ~80 C

thermal cycles with different reference temperatures



total strain energy minimum

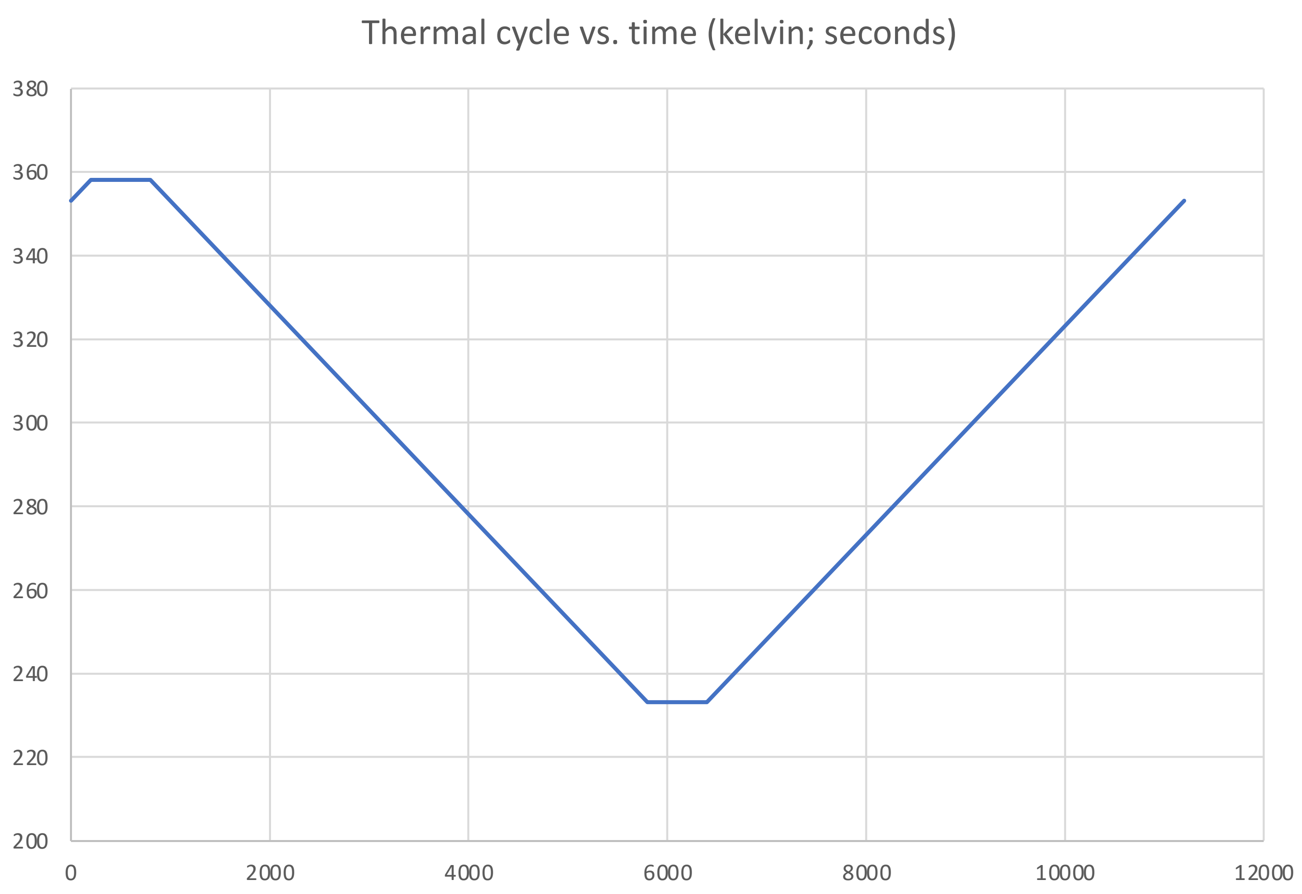


simulation

A standard accelerated thermal cycle is applied to the 3D full sized module model

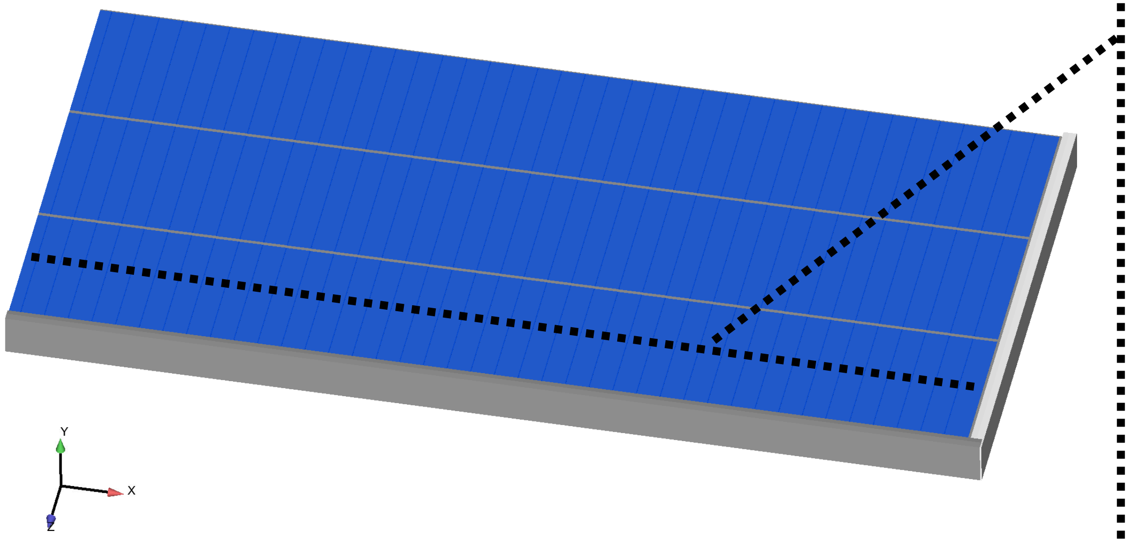
The cycle is started at the minimum energy temperature

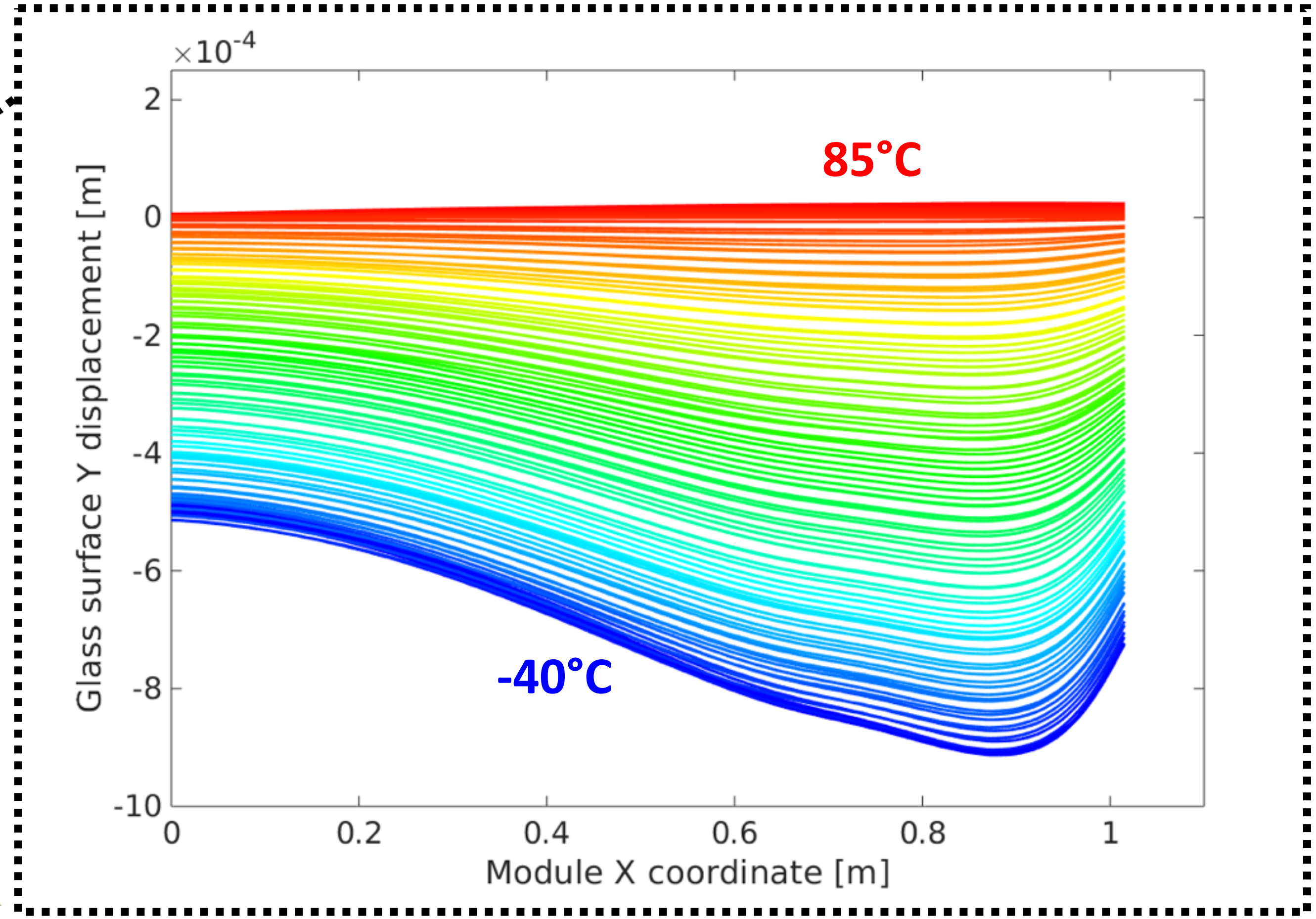
Time (s)	Temp (C)
0	80
200	85
800	85
5800	-40
6400	-40
11200	80



3D simulation results

out of plane deflection of outer most string

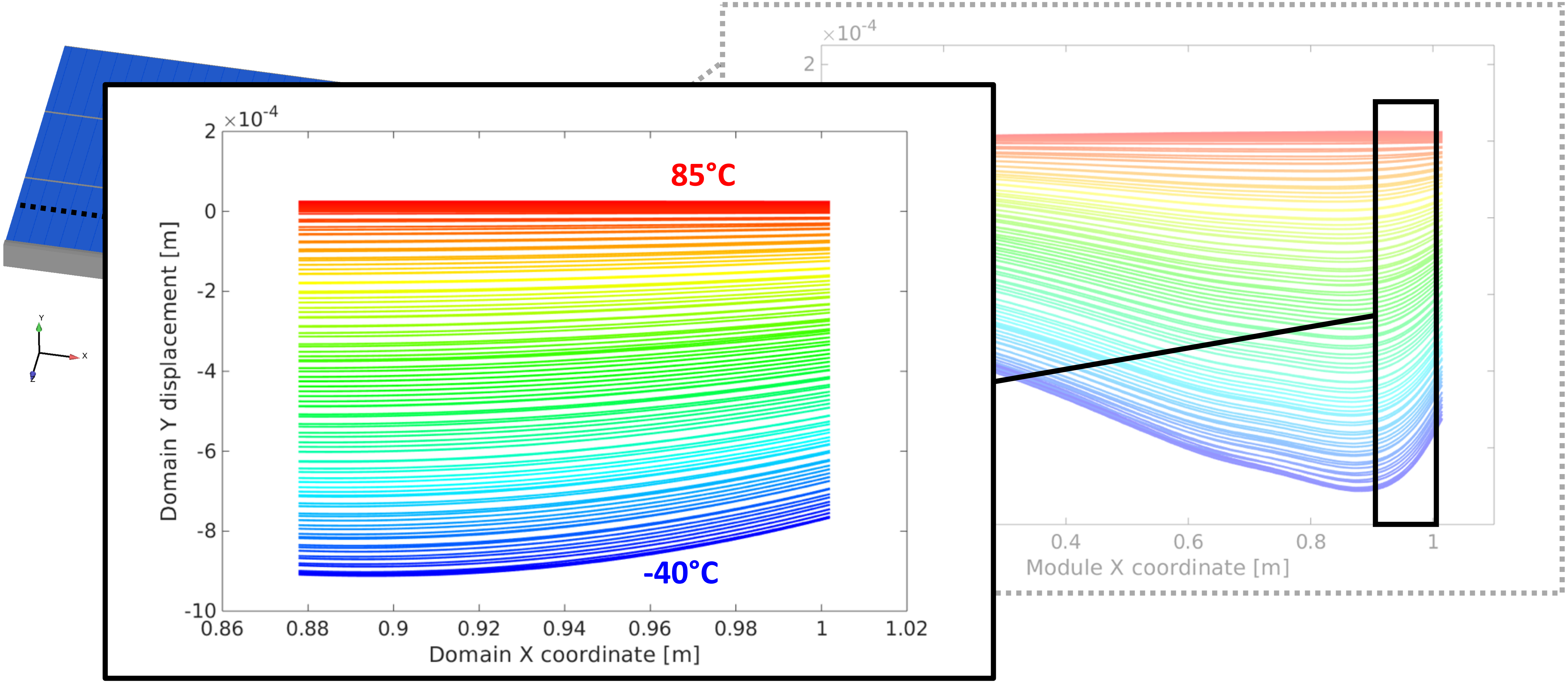




Full module curvatures during a thermal cycle, over frame row (host for most curved domain)

3D simulation results

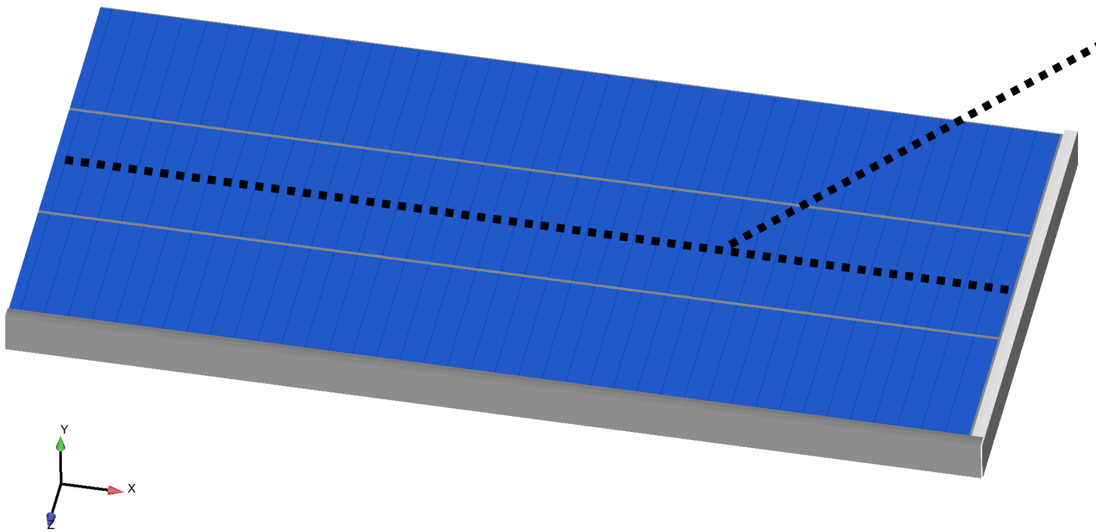
out of plane deflection of outer most string

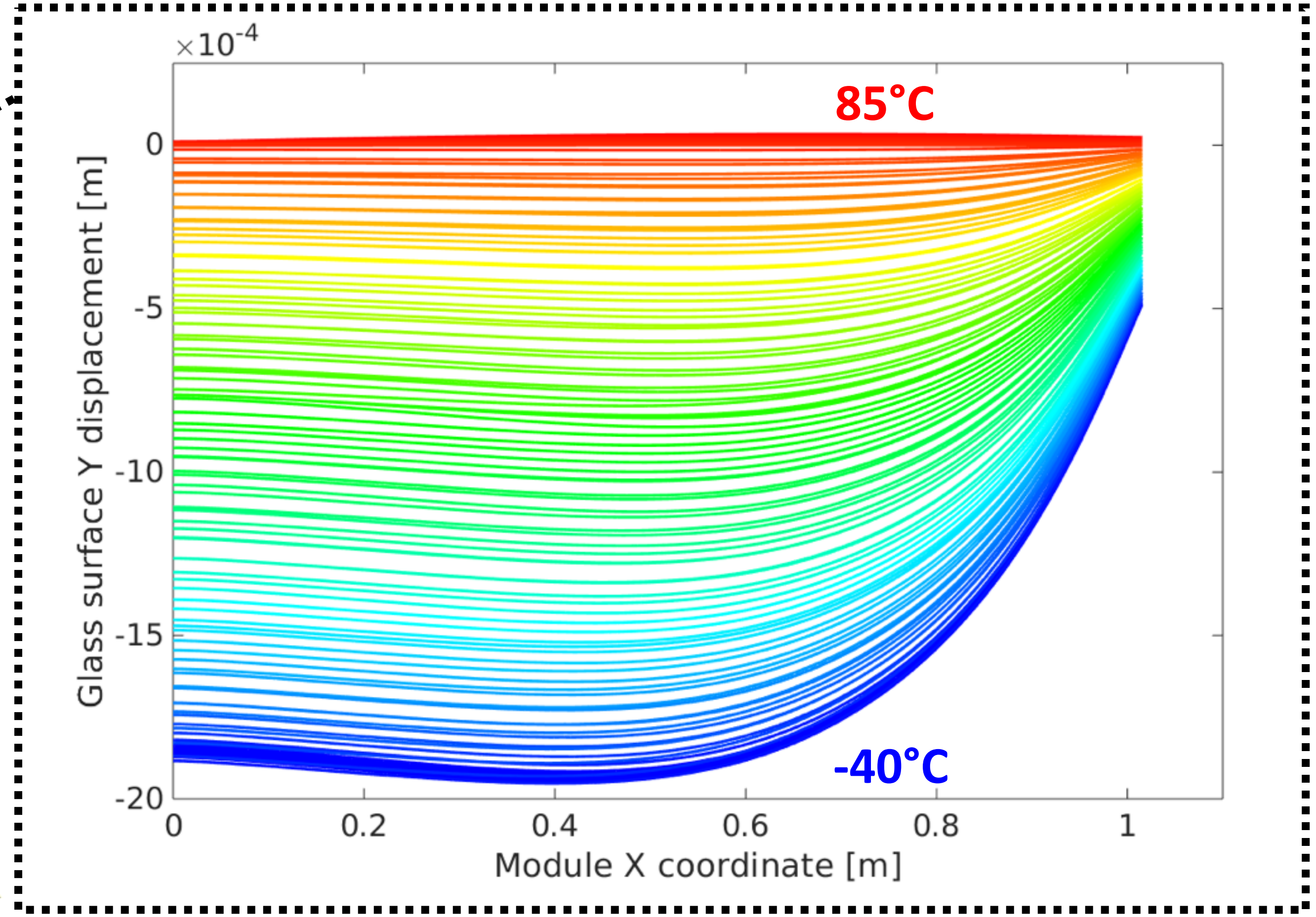


Most curved 5-cell domain over a thermal cycle

3D simulation results

out of plane deflection of adjacent string

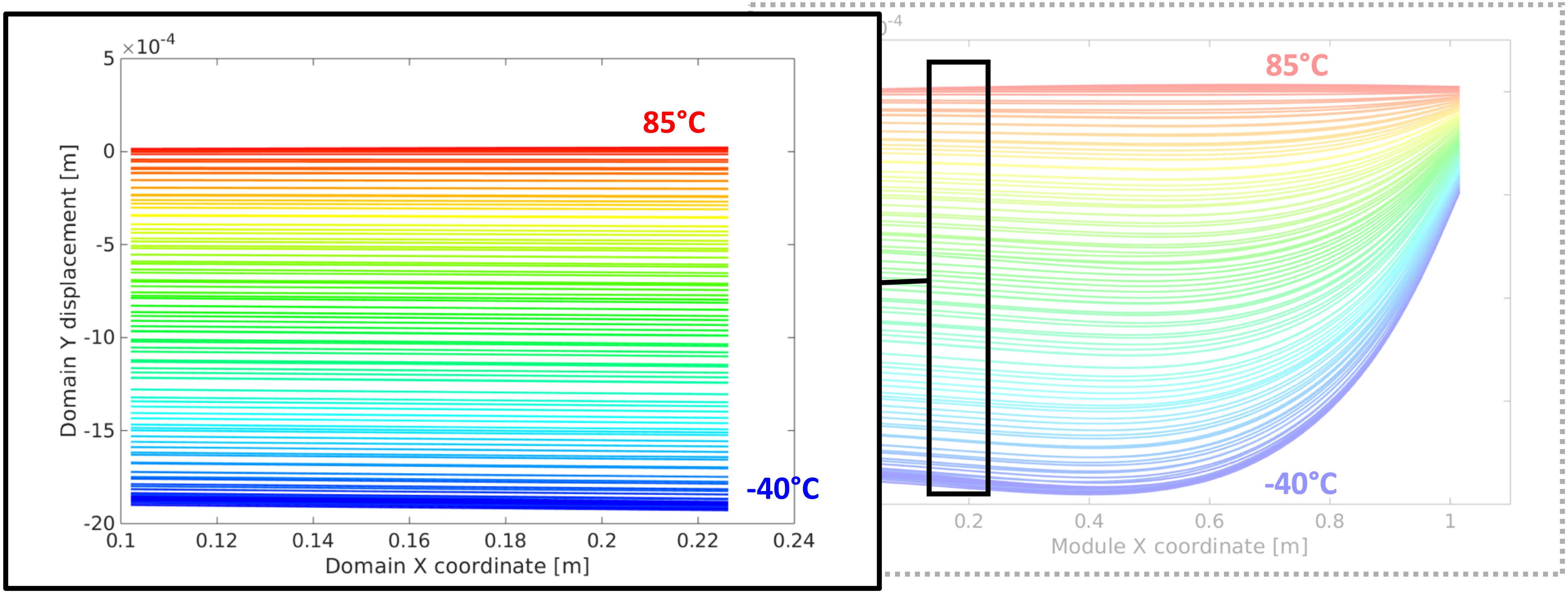




Full module curvatures during a thermal cycle, over 2nd row (host for flattest domain)

3D simulation results

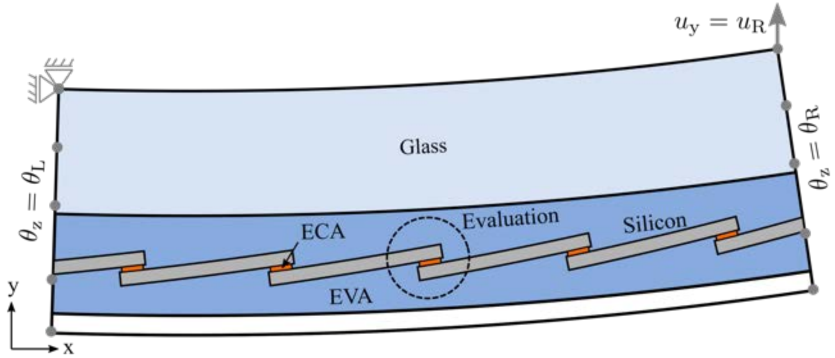
out of plane deflection of adjacent string



Flattest 5-cell domain over a thermal cycle

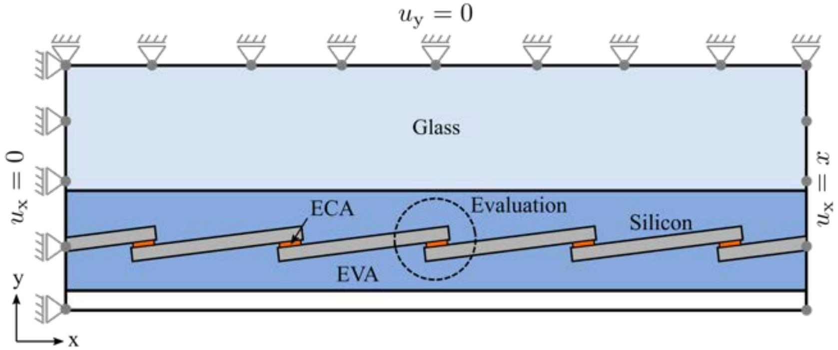
2D simulations
boundary conditions

rotation



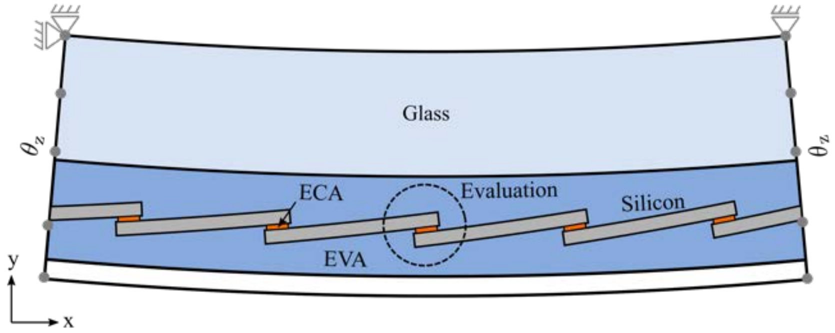
- rigid body movement constrained at top left corner
- left and right surface rotation constrained to 3D full size model output
- top right corner y displacement applied from 3D full size model output

flat



- left and right surface displacement constrained in x direction
- top surface displacement constrained in y direction

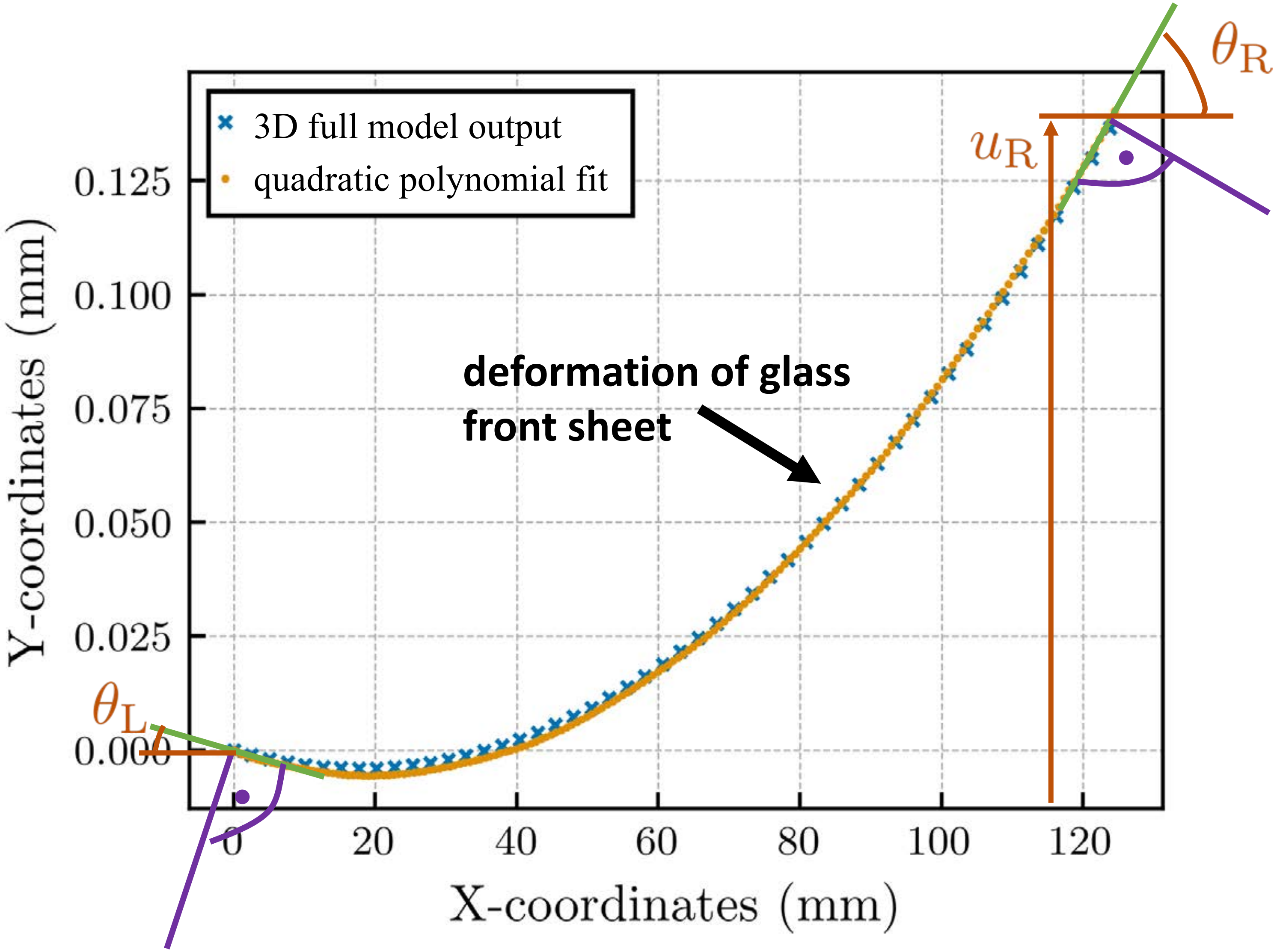
free



- rigid body movement constrained at top left corner
- y displacement constrained at top right corner to avoid model rotation.

2D simulations

boundary conditions



Polynomial fit

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

Derivative

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

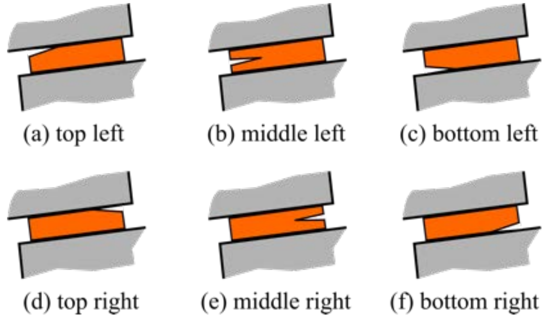
Boundary conditions

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

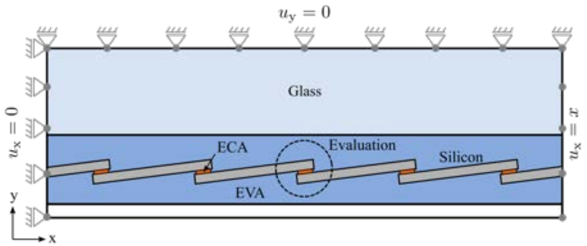
Submodel edges

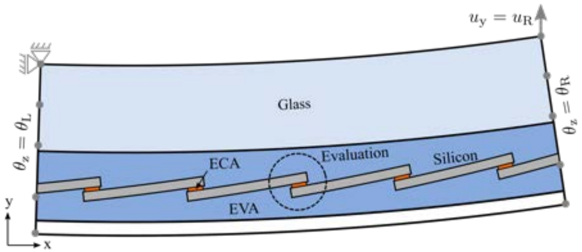
assumed to remain straight throughout the simulation

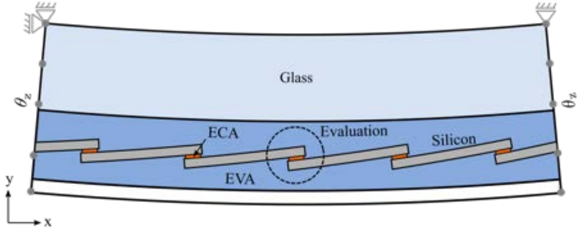
2D submodel results
mode I

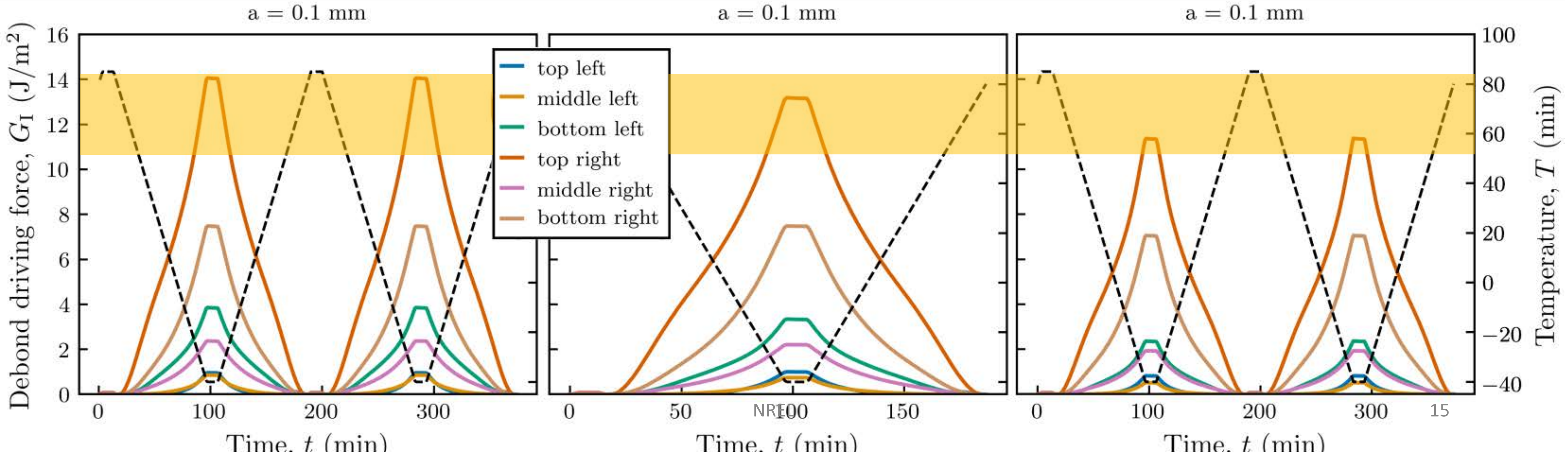


flat > **rotation** > **free**





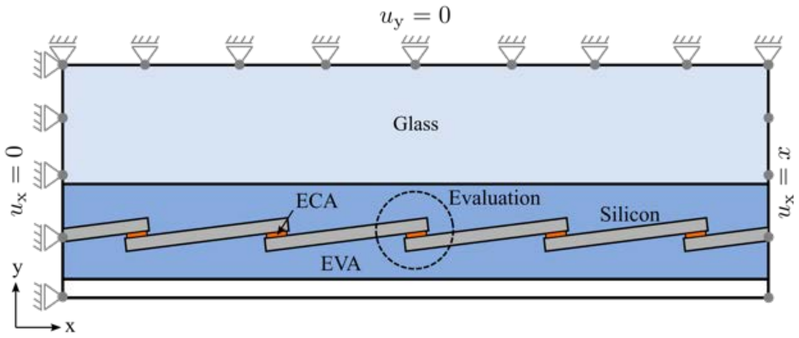


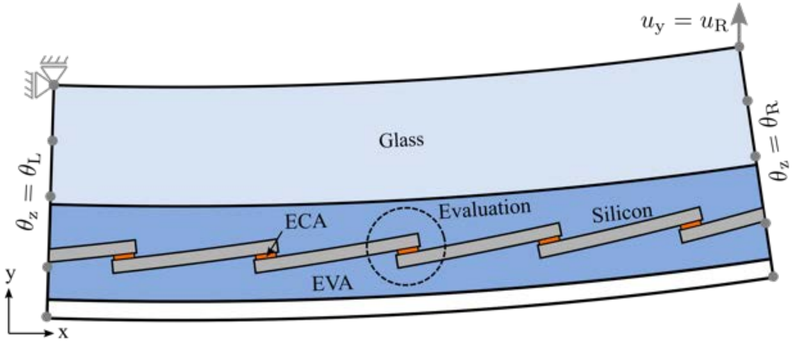


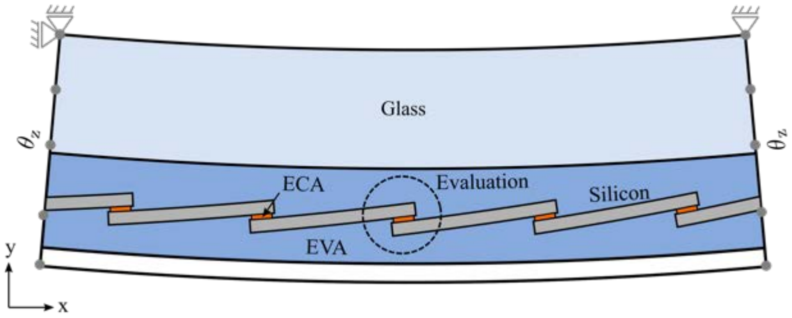
2D submodel results

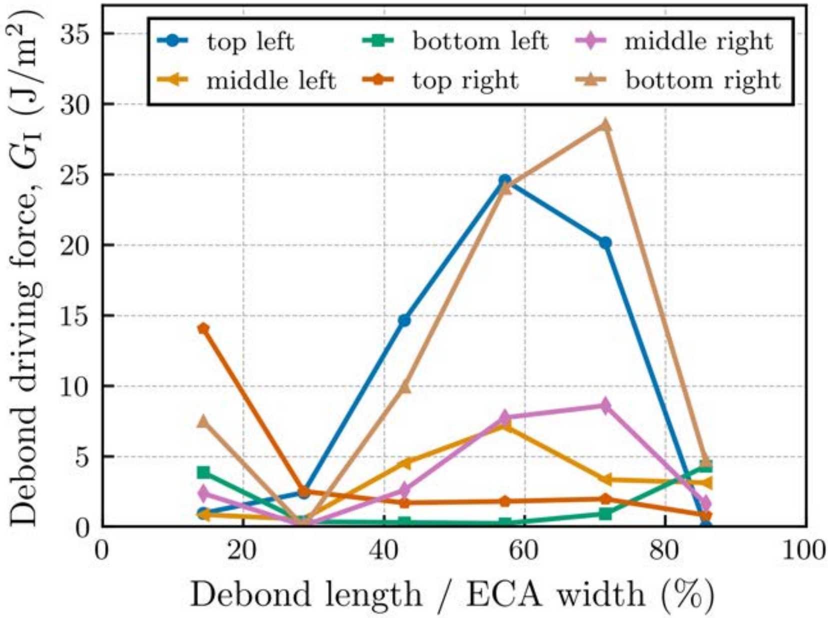
mode I

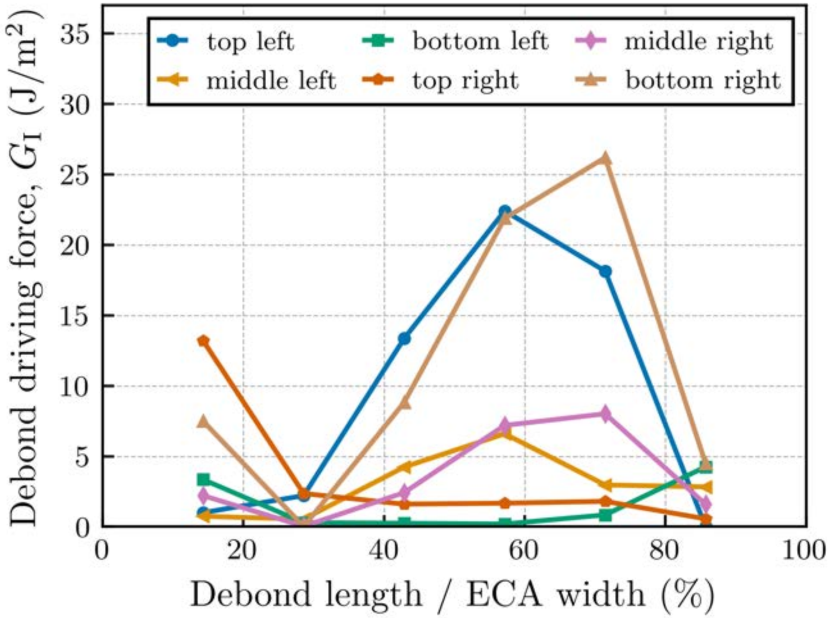
flat > **rotation** > **free**

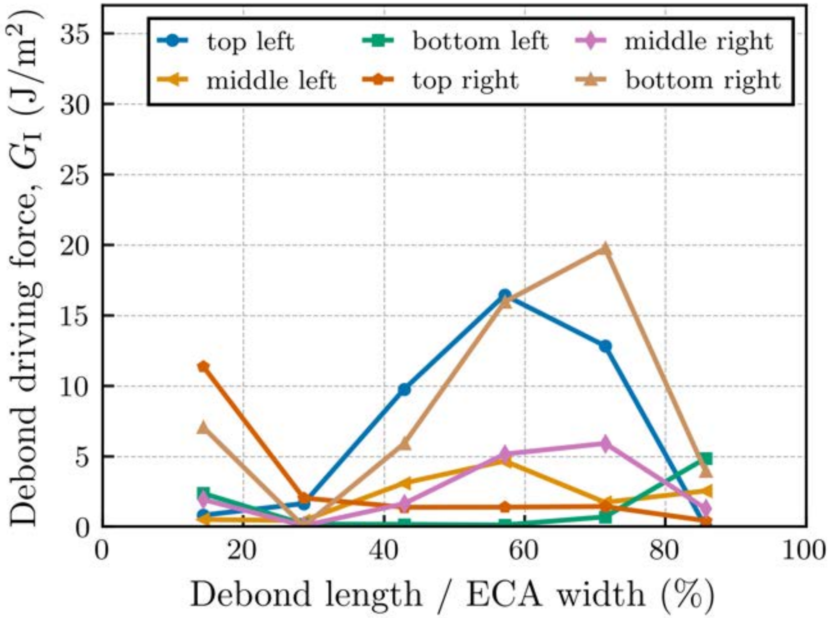






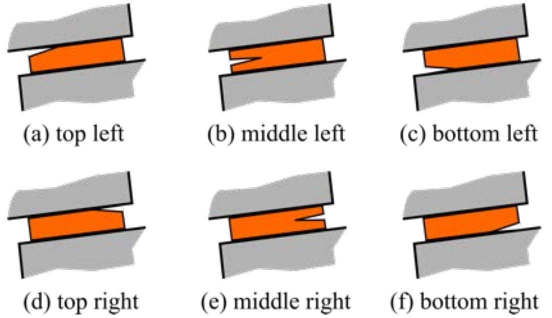


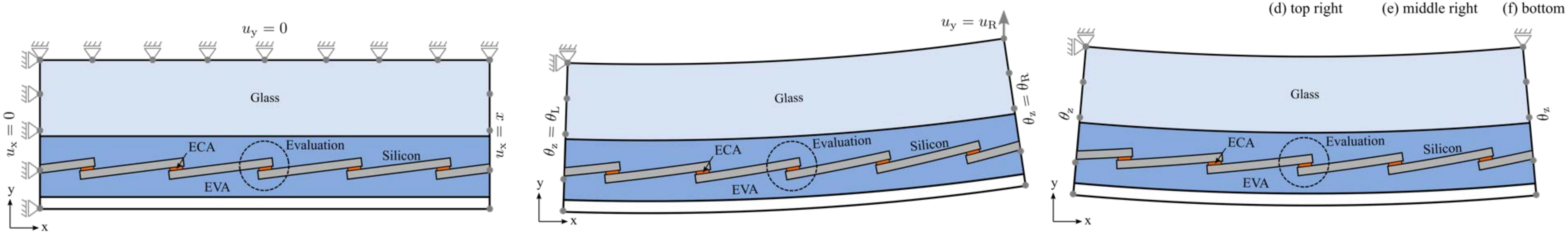


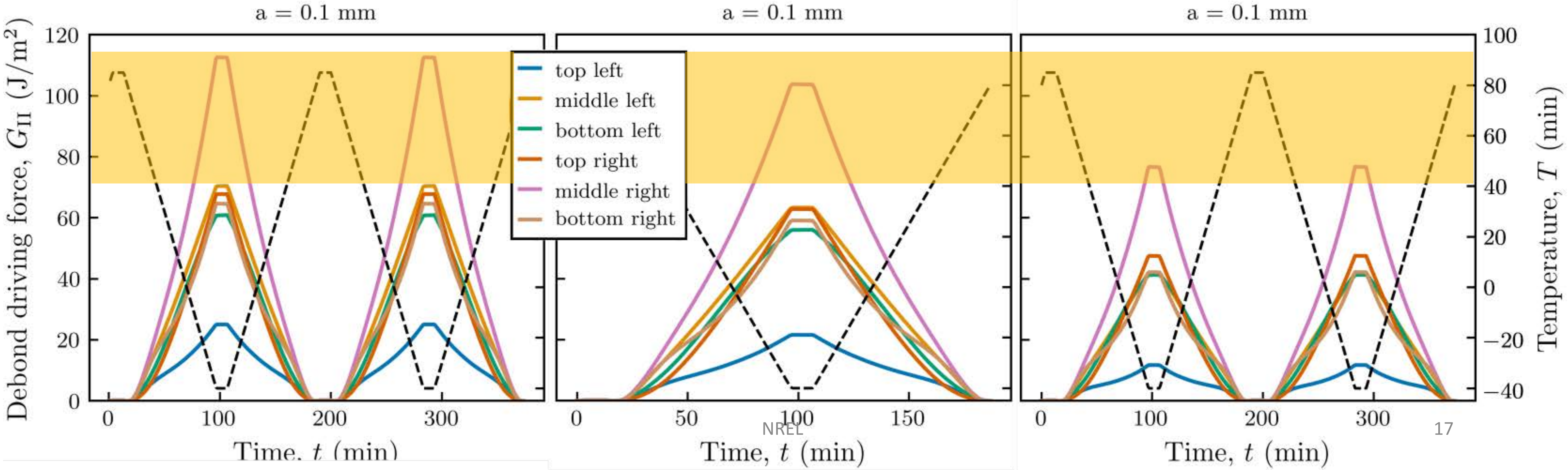


2D submodel results

mode II

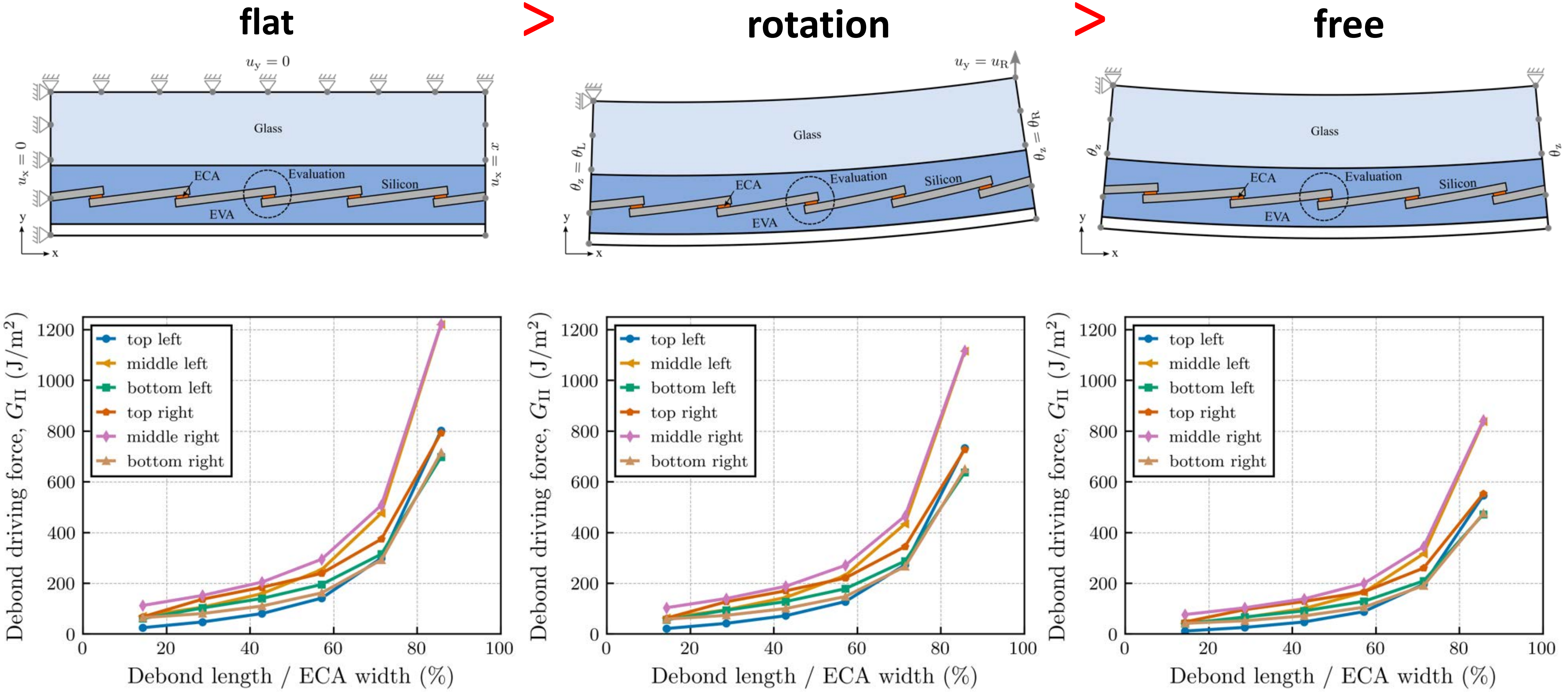






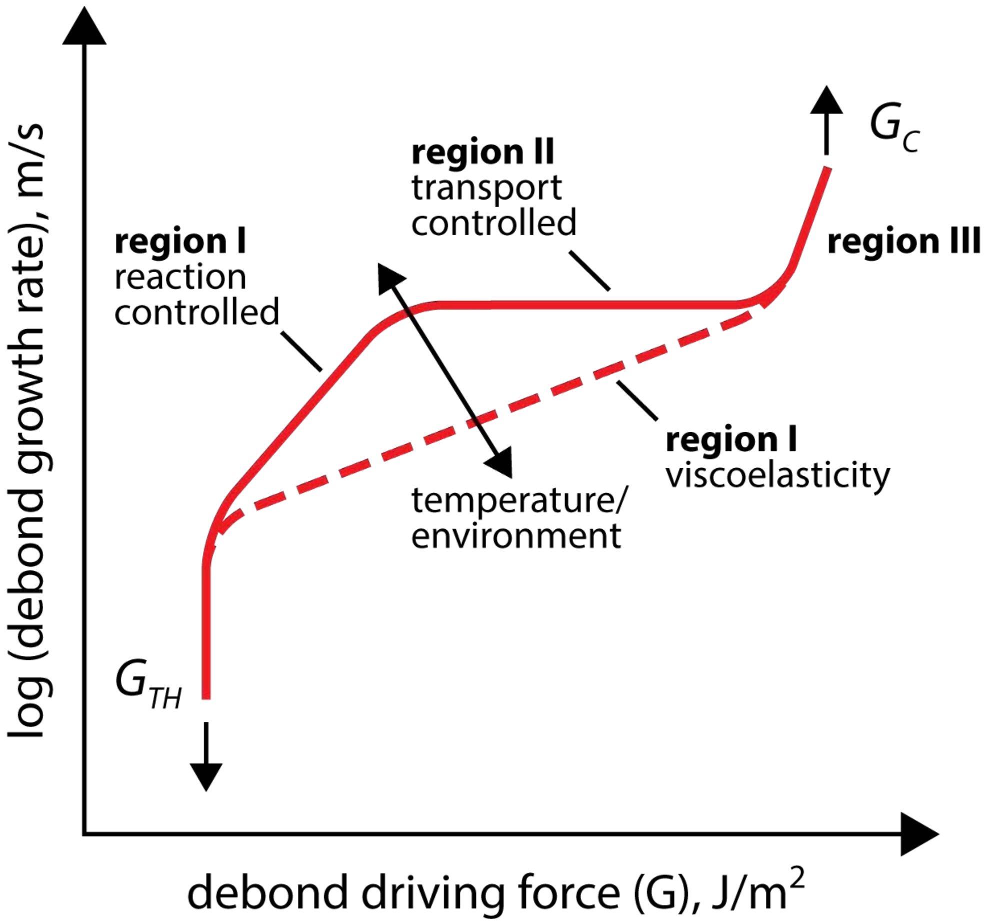
2D submodel results

mode II



Analysis

fracture criterion



mode I

G_c(-20C) > 500 J/m²

G_c(45C) > 450 J/m²

G_{th}(-20C) < 350 J/m²

mode II

G_c(-20C) > 800 J/m²

G_c(45C) > 1000 J/m²

G_{th}(-20C) < 500 J/m²

However, following extensive exposure to moisture:

mode I

G_c(45C) < 100 J/m²

G_{th}(45C) < 20 J/m²

mode II

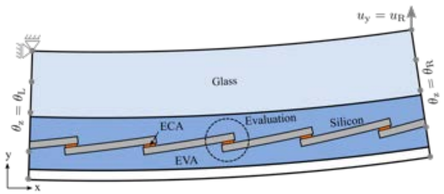
G_c(45C) > 800 J/m²

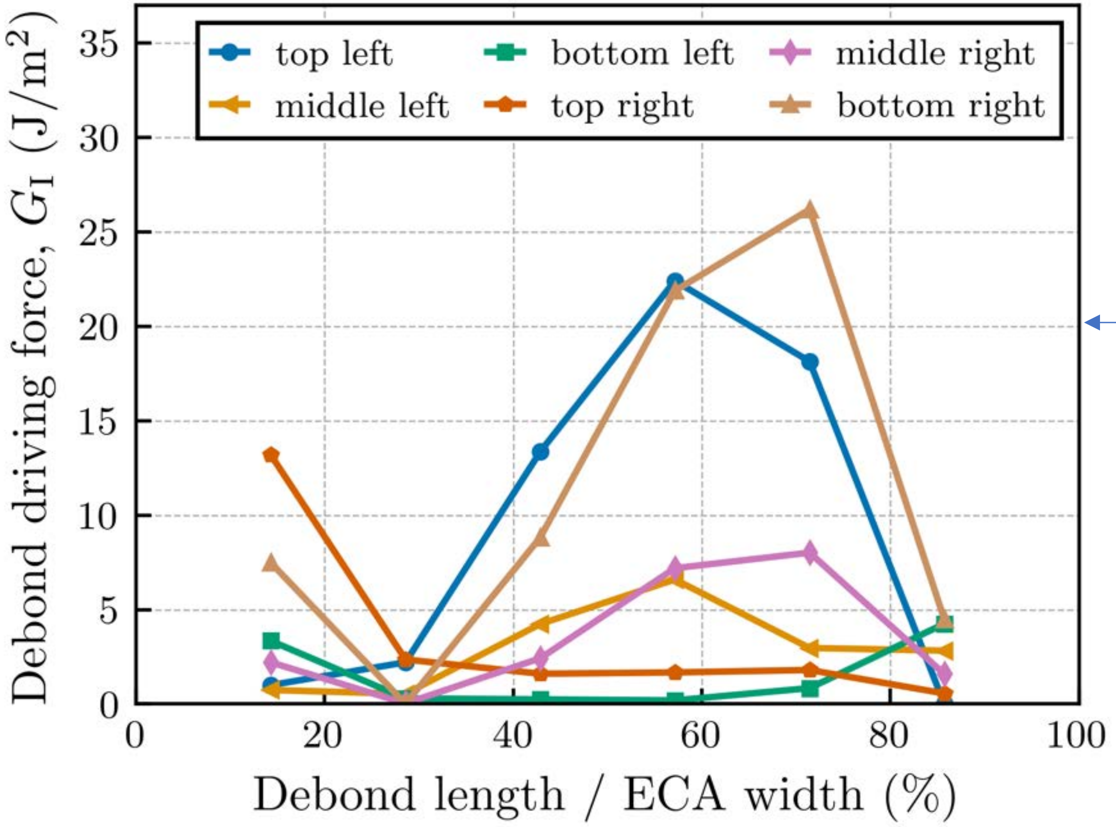
G_{th}(45C) < 300 J/m²

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.

Analysis
fracture criterion

rotation





$G_{th}(45C) < 20\ J/m^2$

mode I

$G_c(-20C)$ > 500 J/m^2

$G_c(45C)$ > 450 J/m^2

$G_{th}(-20C)$ < 350 J/m^2

moisture degraded

mode I

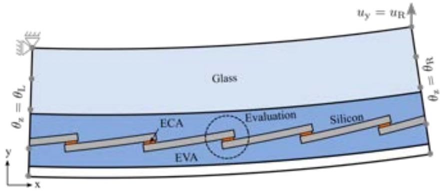
$G_c(45C) < 100\ J/m^2$

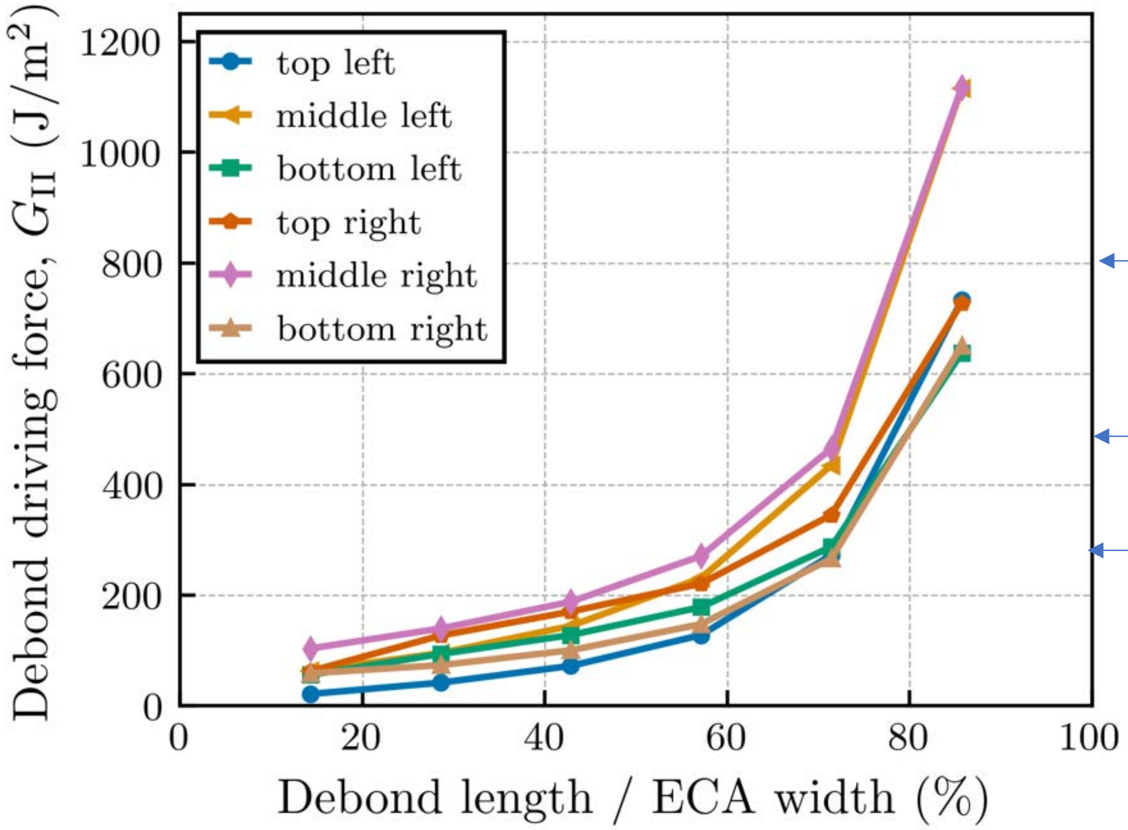
$G_{th}(45C) < 20\ J/m^2$

Analysis

fracture criterion

rotation





$G_c(-20C)$ > 800 J/m^2

$G_{th}(-20C)$ < 500 J/m^2

$G_{th}(45C)$ < 300 J/m^2

mode II

$G_c(-20C)$ > 800 J/m^2

$G_c(45C)$ > 1000 J/m^2

$G_{th}(-20C)$ < 500 J/m^2

moisture degraded

mode II

$G_c(45C)$ > 800 J/m^2

$G_{th}(45C)$ < 300 J/m^2

conclusions

We've demonstrated a multiscale modeling approach for ECA interconnect degradation

- developed a method to determined the minimum stress temperature
- this needs to be the starting point for any simulation
- likely similar for any glass/backsheet module construction

Demonstrated how the solutions for 2D submodel extrema bound the MSM result

When ECA defects become a large fraction of their width, critical and subcritical failure can be activated

Thank You

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