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Lamination Process Induced Residual Stress in Glass-Glass vs. Glass-Backsheet Modules

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49 IEEE PHOTOVOLTAIC SPECIALISTS CONFERENCE

U.S. DEPARTMENT OF ENERGY NNSA

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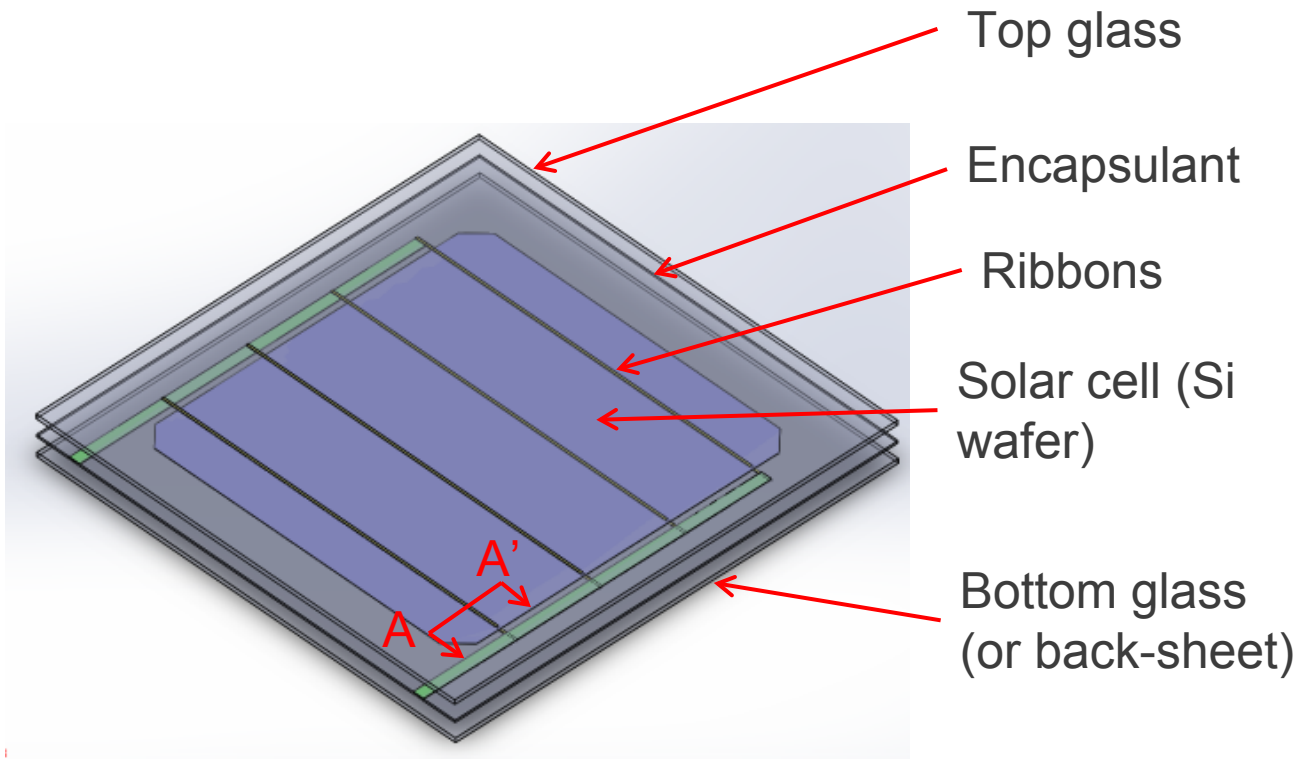
Outline

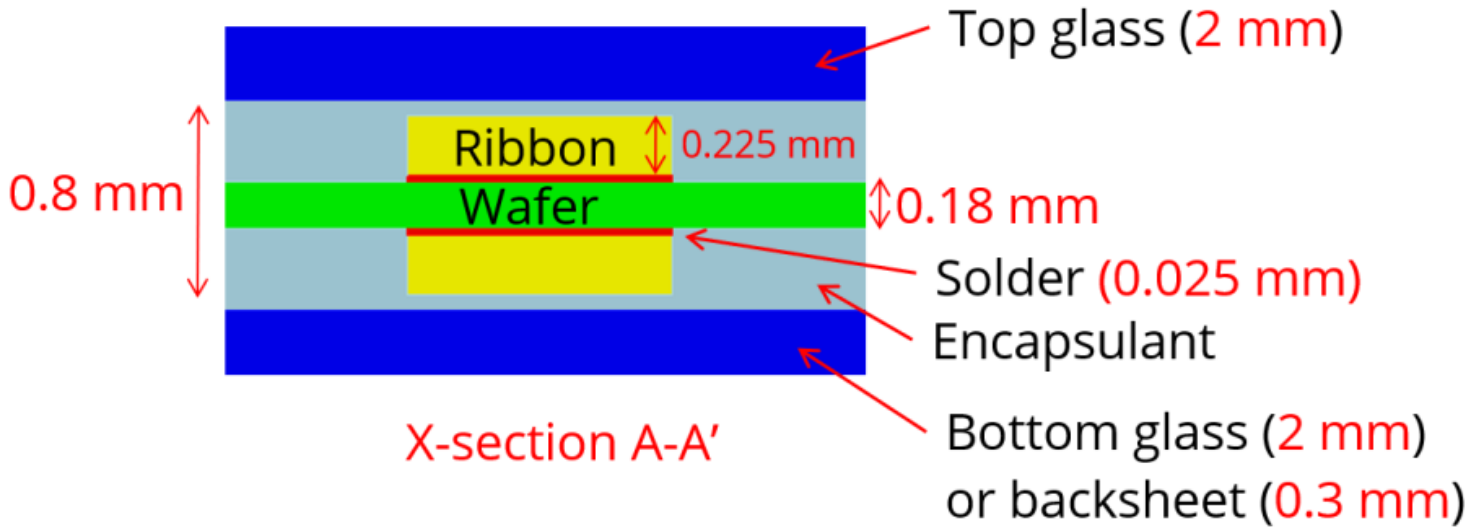
- Motivation
- Previous FEA studies and overview of simulations
- Photovoltaic module manufacturing process simulations
  - Lamination simulations of different module architectures
- Summary

Motivation

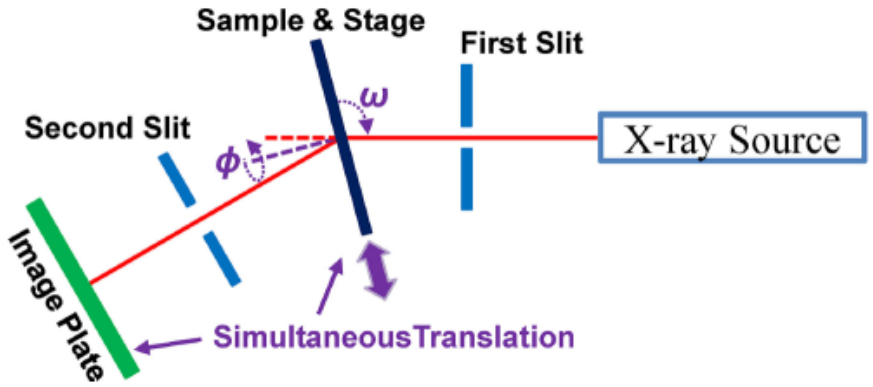
- Manufacturing-process-induced residual stress causes immediate to delayed cell breakage
  - Ribbon soldering – CTE mismatch
  - Lamination – temperature and pressure

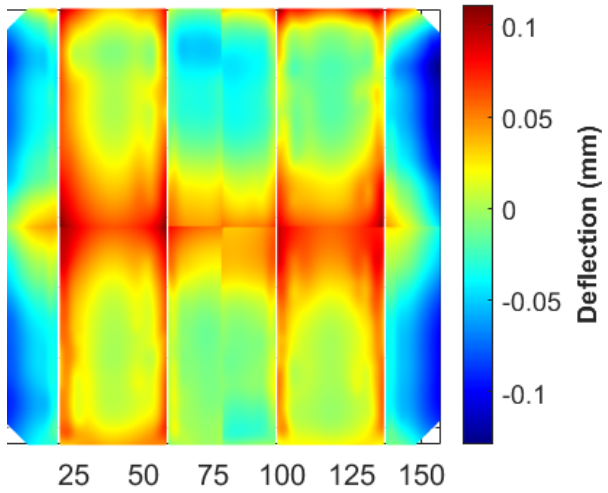
- Residual stress is function of
  - Module architecture
  - Module material

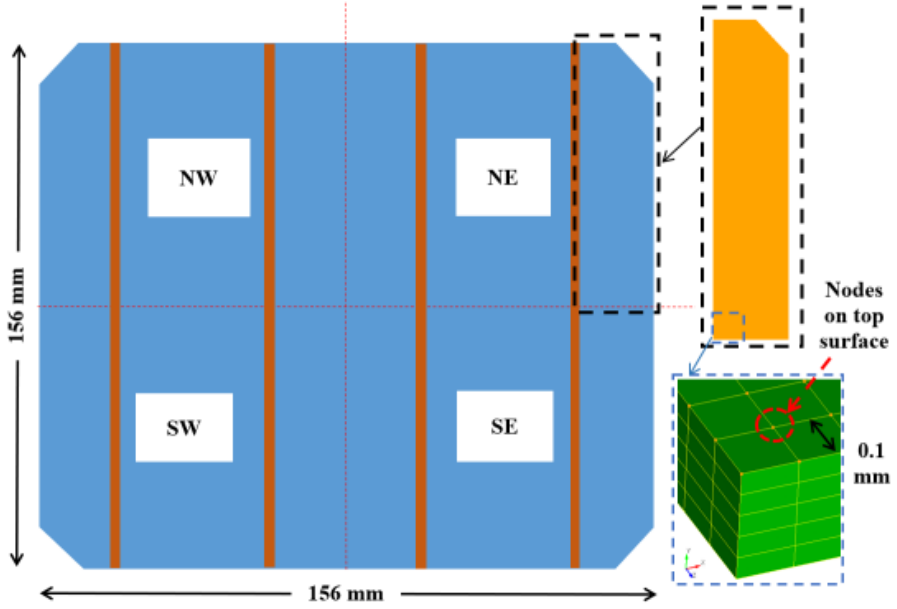




Cell Deflections Measured by X-ray Topography (XRT)







- X-ray is passed through wafer
- Satisfying Bragg condition wafer curvature is obtained
- From curvature deflection is determined

Module architectures
- Glass - glass
- Glass - backsheet

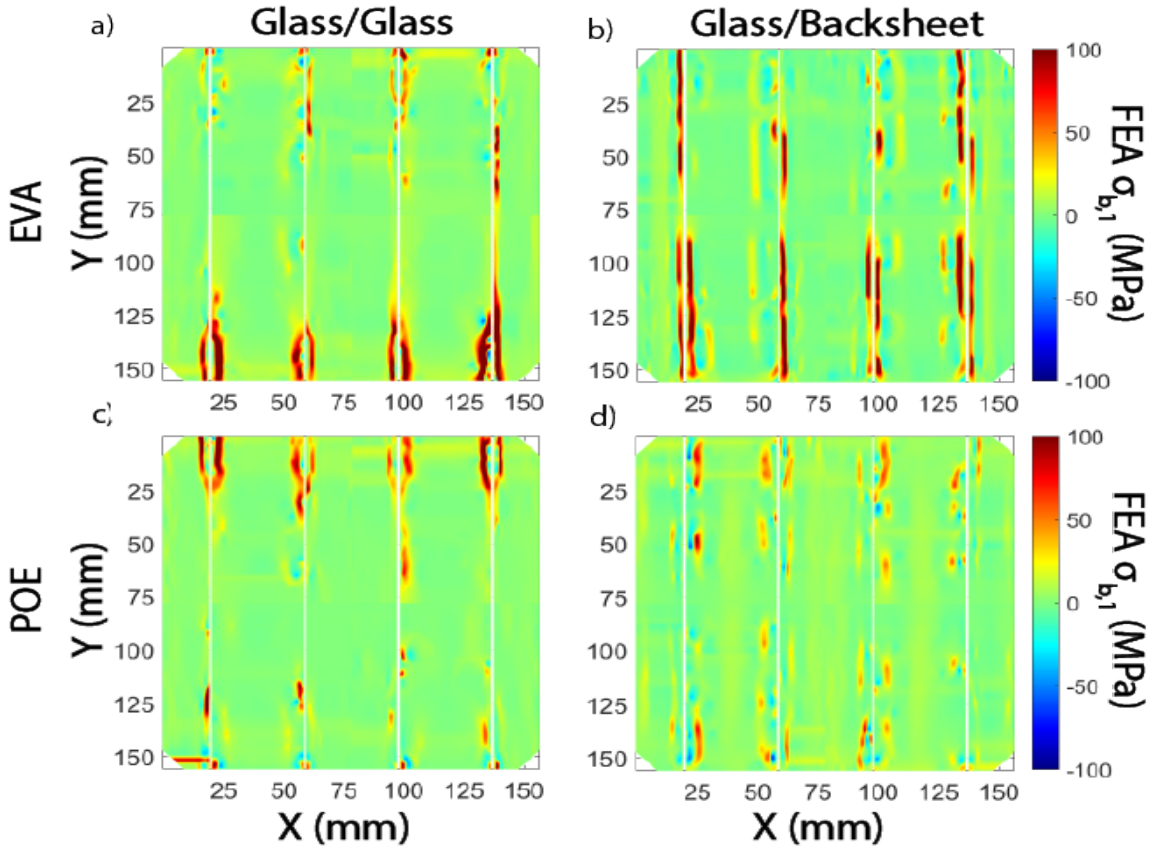
Module materials
- Ethylene vinyl acetate (EVA)
- Polyolefin (POE)

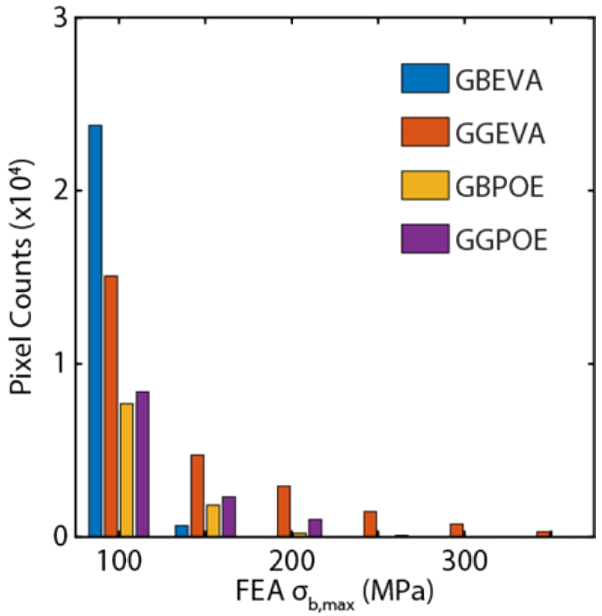
XRT performed by Arizona State University researchers [a]

[a] X. Meng et al., "Quantitative Mapping of Deflection and Stress on Encapsulated Silicon Solar Cells," in *IEEE Journal of Photovoltaics*, Jan. 2018

[b] **I. M. Slauch et al., "Manufacturing Induced Bending Stresses: Glass-Glass vs. Glass-Backsheet," 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), 2021, pp. 1943-1948, doi: 10.1109/PVSC43889.2021.9518938**

FEA using XRT Data as Boundary Condition





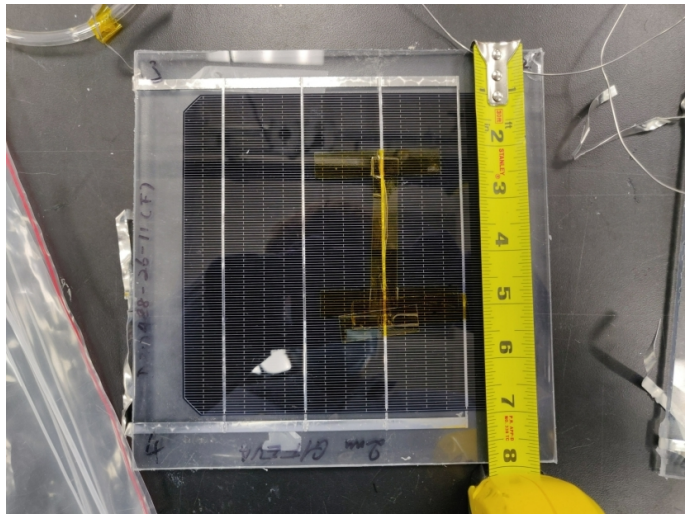
- Peak in-plane principal stress
  - Glass-glass > glass-backsheet
  - EVA > POE
- Glass-glass module architecture with EVA encapsulant had the largest residual stress

In-plane (2D) principal stress for different configurations [(a)]

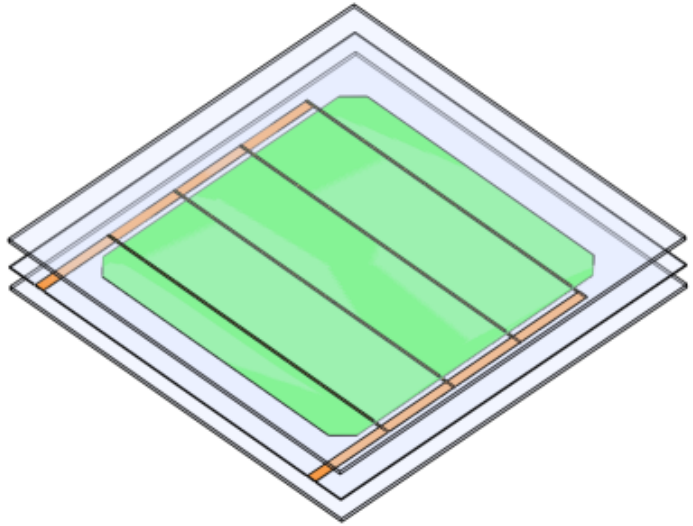
(a) I. M. Slauch et al., "Manufacturing Induced Bending Stresses: Glass-Glass vs. Glass-Backsheet," 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), 2021, pp. 1943-1948, doi: 10.1109/PVSC43889.2021.9518938

Overview of Simulations

- Experimentally measure solar cell deflection using X-ray
  - Cell deflection is the finger-print of the manufacturing process
  - Use cell deflection as boundary condition for simulation [(a)]
- Simulation of solar panel manufacturing process
  - Soldering of interconnect on solar cell
  - Lamination of the solar panel stack



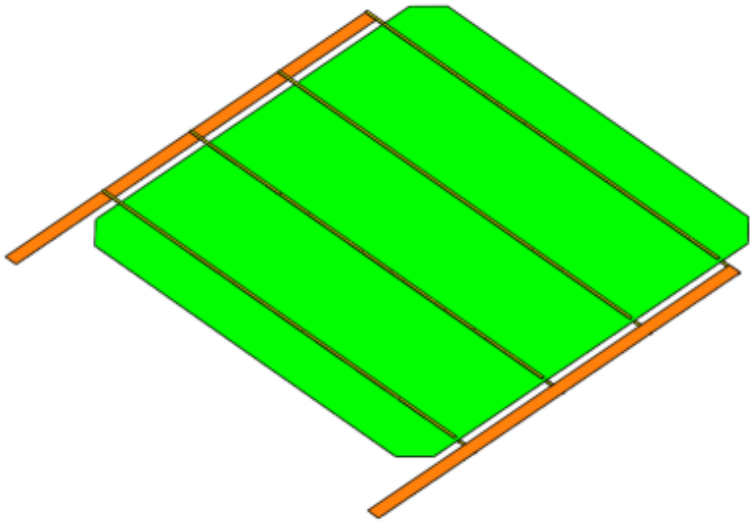
Mini-module reference image (ASU)

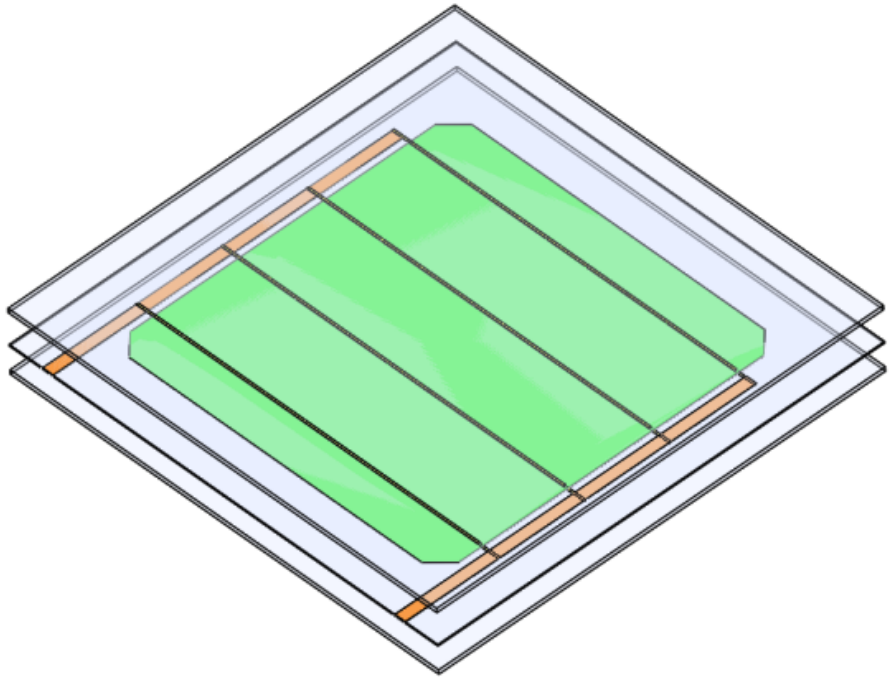


Forward predictive simulation of the manufacturing process is performed in current research

(a) I. M. Slauch et al., "Manufacturing Induced Bending Stresses: Glass-Glass vs. Glass-Backsheet," 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), 2021 pp. 1943-1948, doi: 10.1109/PVSC43889.2021.9518938

Solar Module Manufacturing Process: Soldering and Lamination





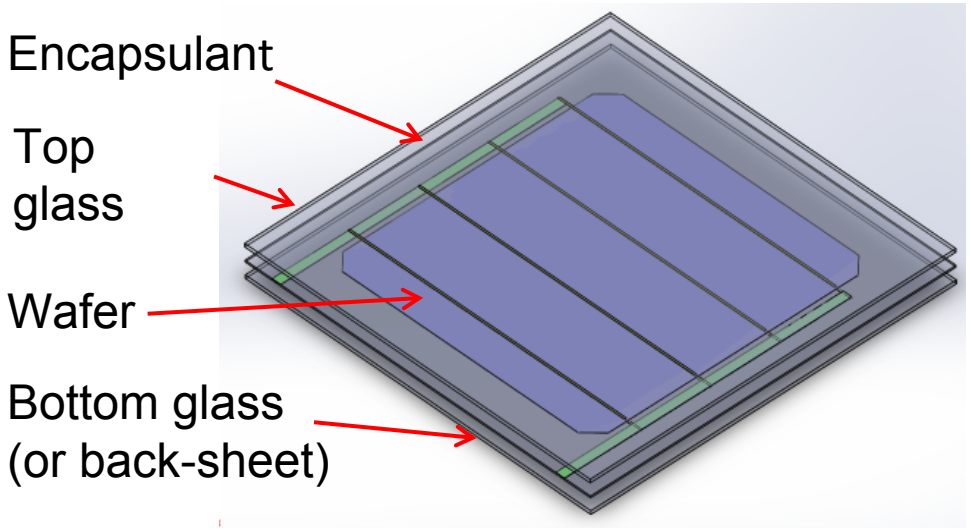
- In soldering and preheating steps encapsulant and glass/backsheet are not present in FE model
- Encapsulant and glass/backsheet are added in the lamination step

Ribbons soldered onto wafer → Laminate stack is preheated → Lamination pressure and temperature cool-down (encapsulation shrinkage)

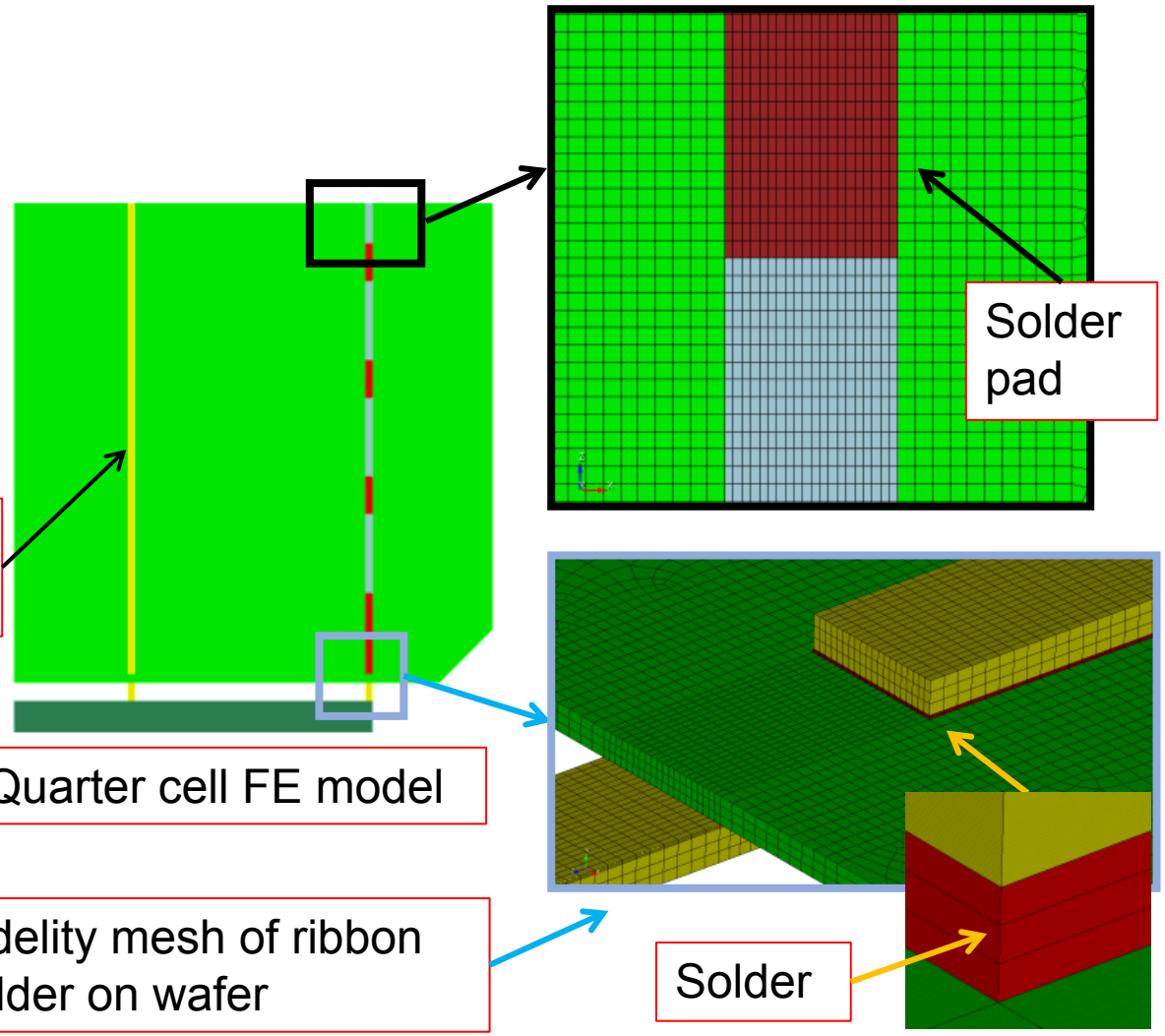
Module architecture (Glass-Glass vs Glass-Backsheet) only has influence at the lamination step

FEA of Module Manufacturing Process

Component	Material	Material model
Wafer	Mono c-Si	Elastic
Solder	Solder	Thermo-elastic plastic
Ribbon	Copper	Thermo-elastic plastic
Encapsulant	EVA	Viscoelastic[(a)]

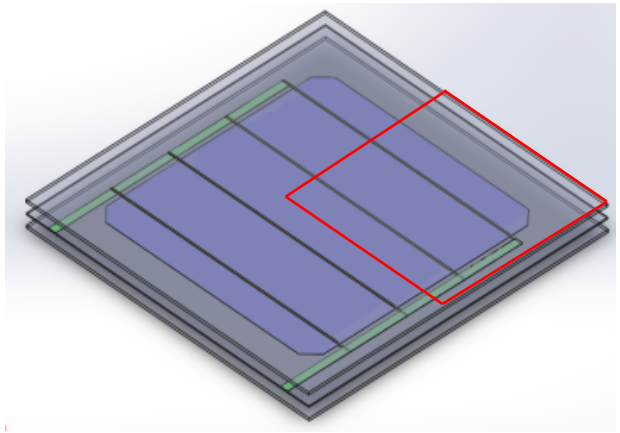


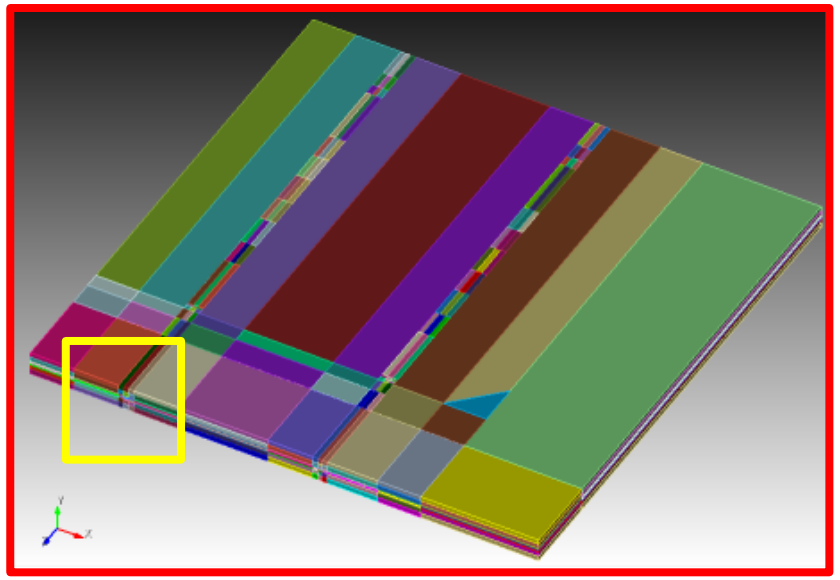
3D CAD of single-cell solar module



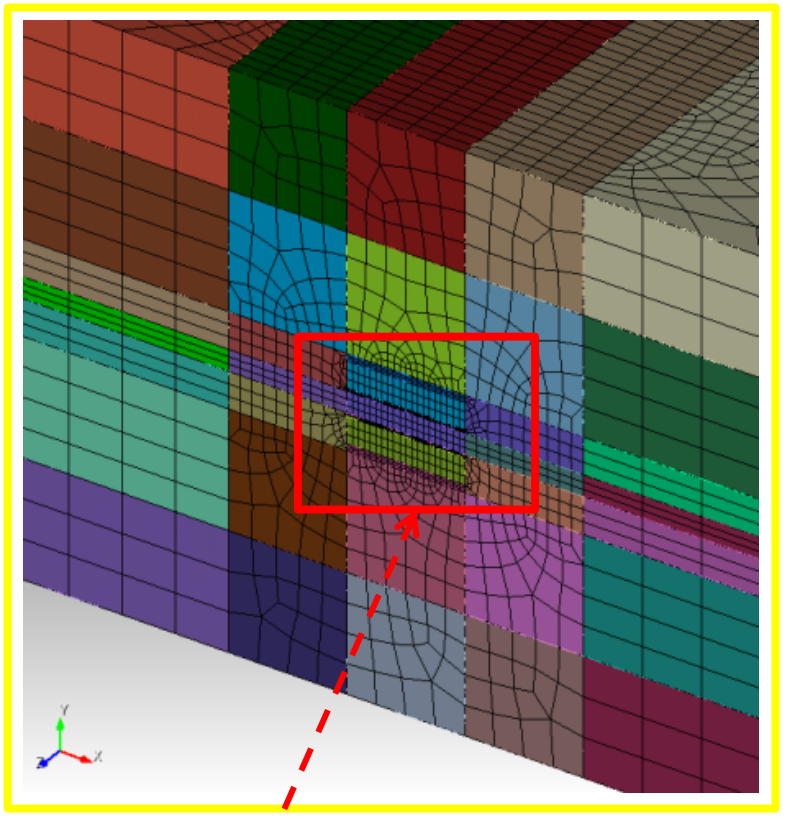
(a) N. Bosco, M. Springer, and X. He, "Viscoelastic Material Characterization and Modeling of Photovoltaic Module Packaging Materials for Direct Finite -Element Method Input," IEEE J. Photovoltaics, vol. 10, no. 5, pp. 1424–1440, Sep. 2020, doi: 10.1109/JPHOTOV.2020.3005086

Mesh Developed with Hex Elements

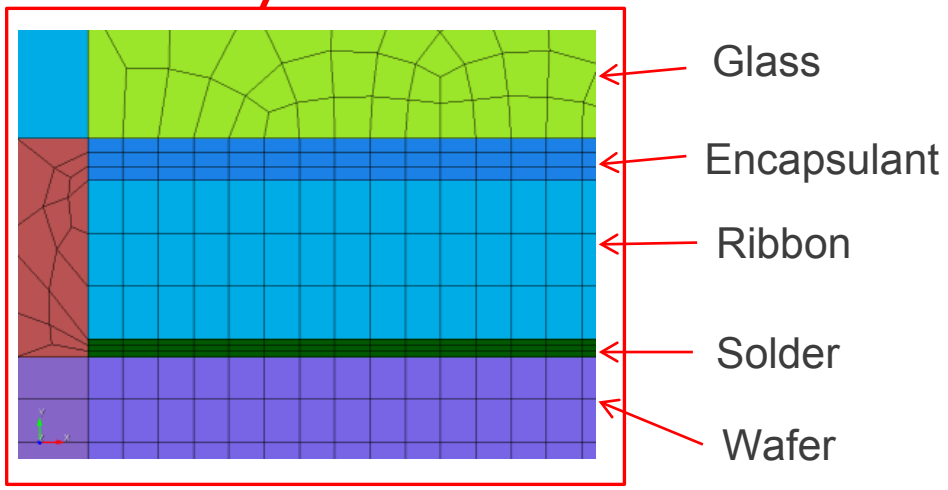




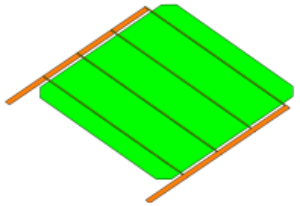
Minimodule quarter model



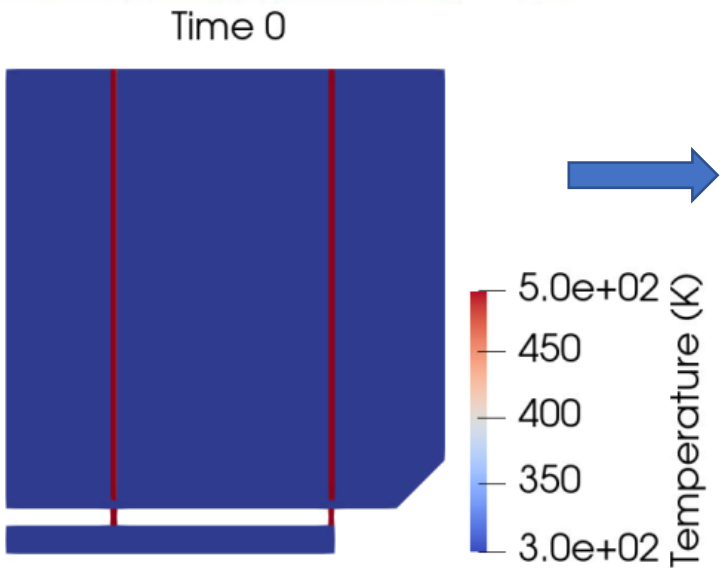
X-section of minimodule quarter model

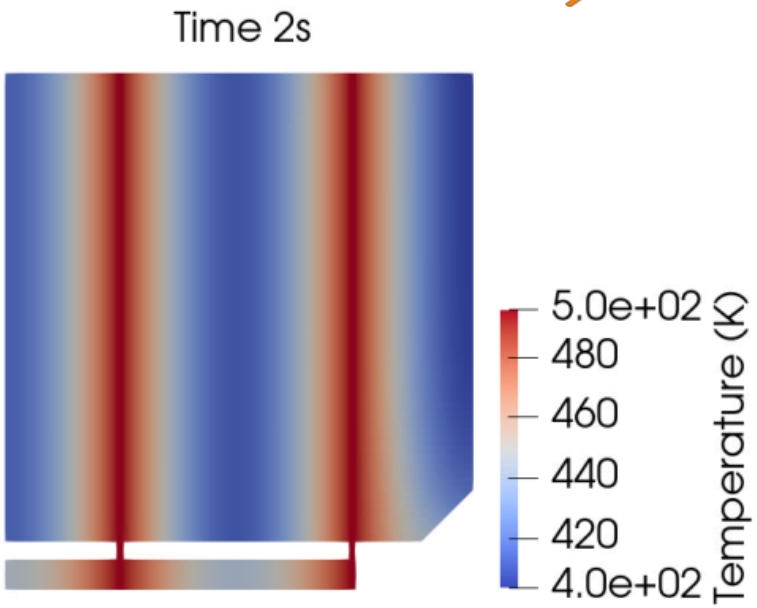


Soldering of Ribbons on Wafer



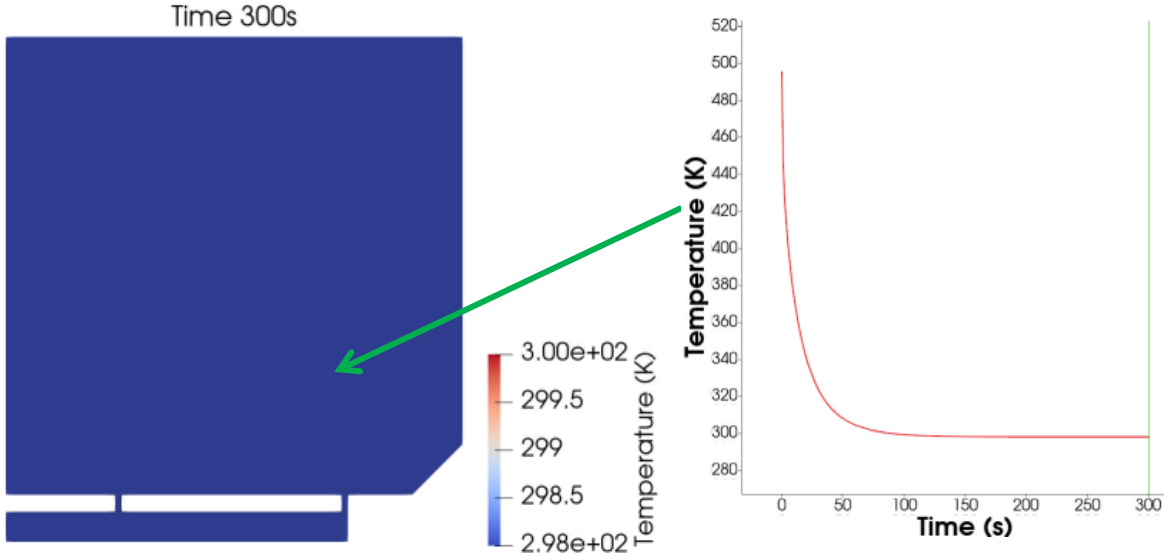
Solder and ribbon temperatures set at solder melting temperature (493 K)





Temperature distribution from thermal simulation (SIERRA ARIA code) after 2 seconds

Soldering cool-down simulation in ARIA (from 493 K to 298 K)



Thermal Boundary Conditions

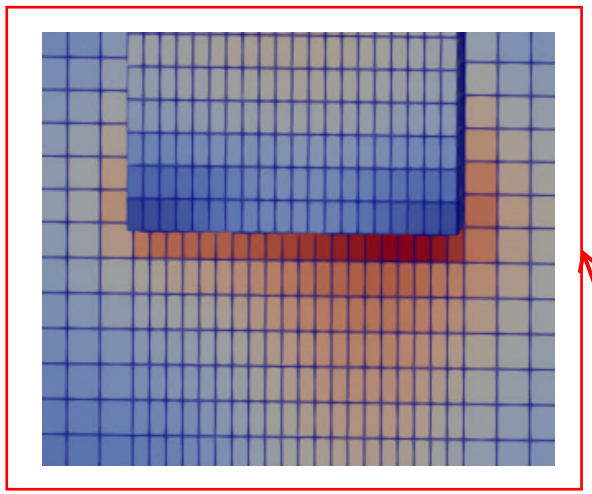
- Convective cooling coefficients (function of temperature)[a]
  a. 1 – 3 W/m^2/K for downward horizontal surface
  b. 2 – 7 W/m^2/K for upward horizontal surface
  c. 100 – 147 W/m^2/K for vertical surfaces
- Radiative cooling

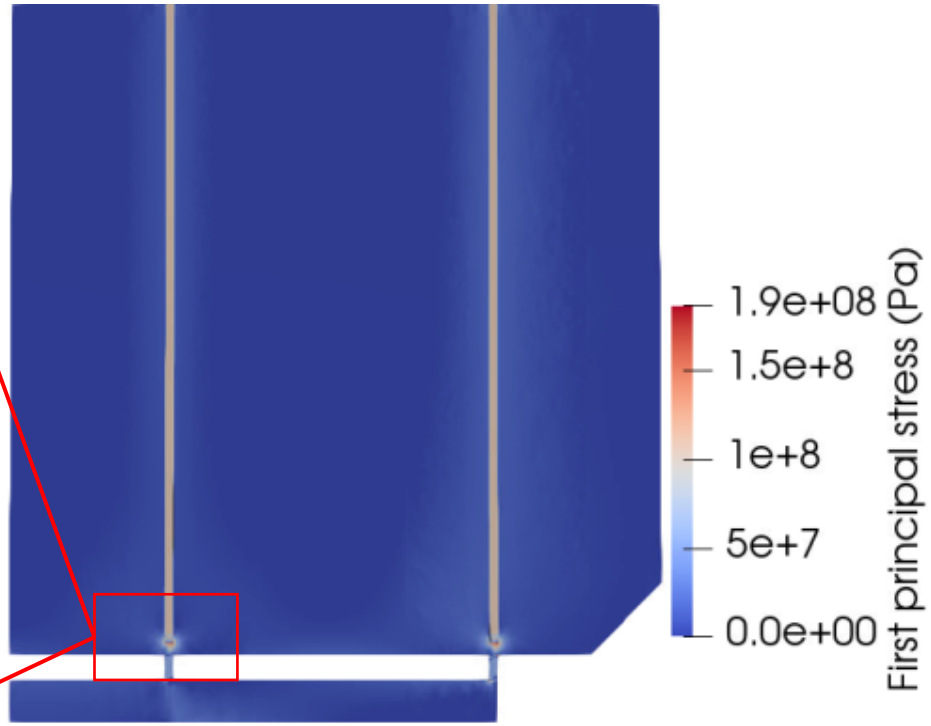
Specific heat vs temperature function used to account for latent heat of solidification of solder

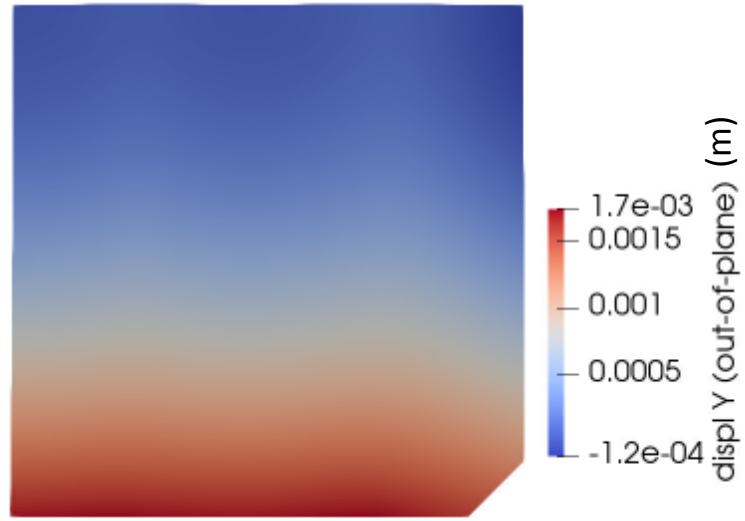
(a) Introduction to heat transfer by Incropera, Dewitt, Bergman and Lavine, 5th edition

Post-soldering Stress and Deflection

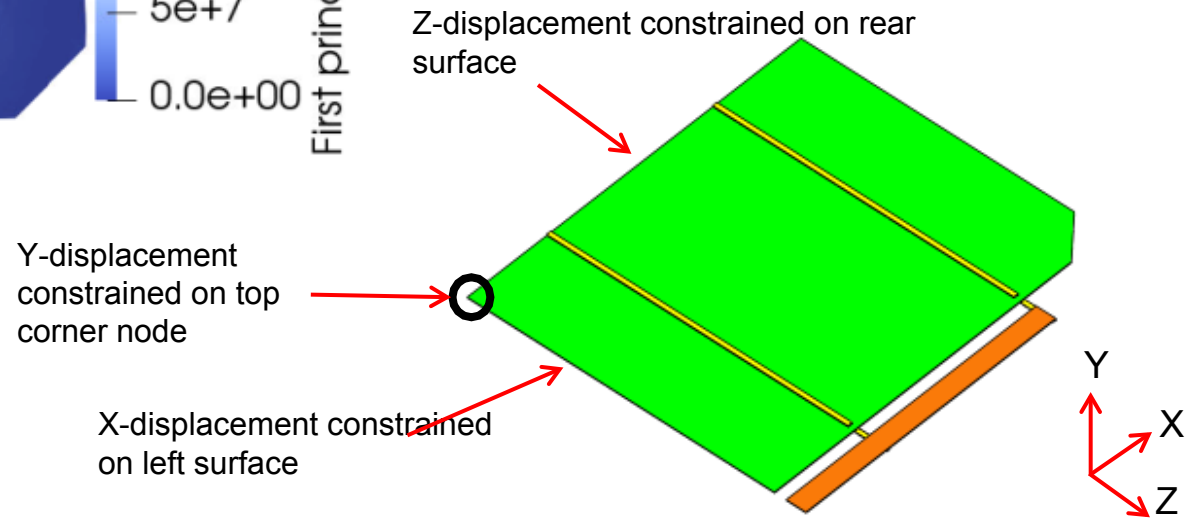
Solid mechanics simulation performed in SIERRA ADAGIO code using temperature distribution determined from thermal simulation





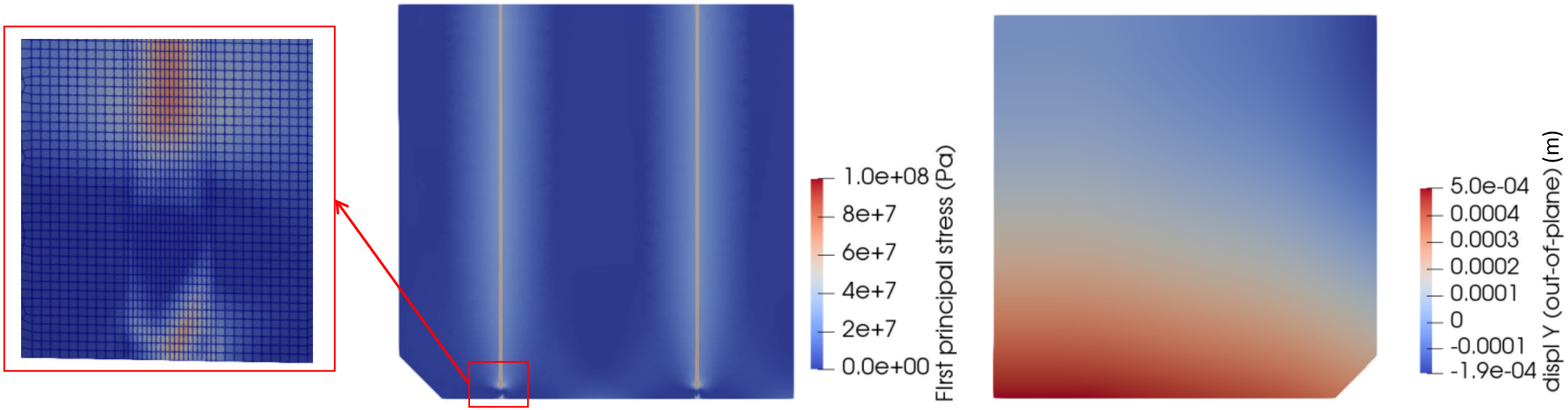


- High stress regions on cell near the edge of the solder
- 1.7 mm maximum displacement of cell



Boundary conditions in solder cool-down simulation

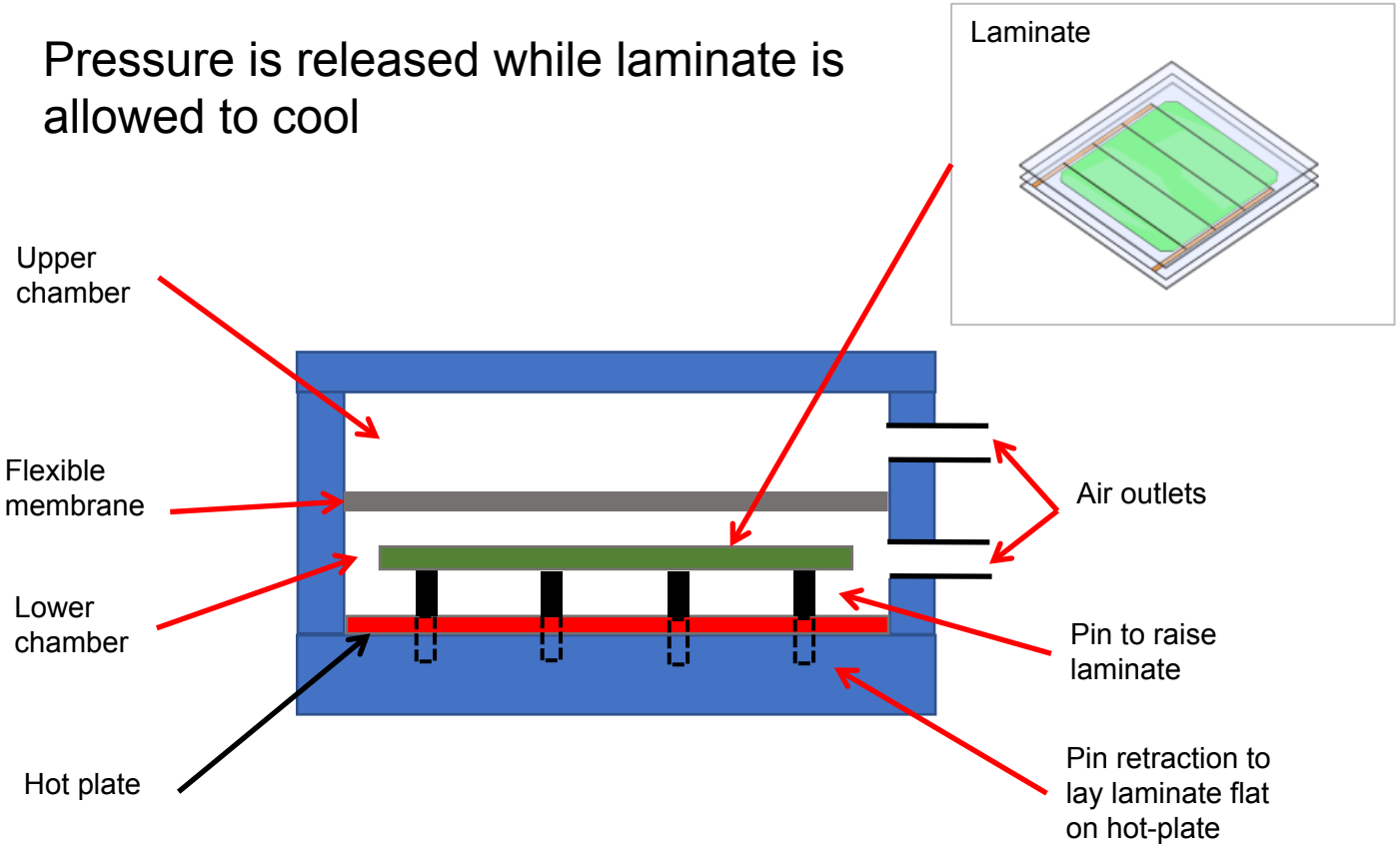
Reduced Post-soldering Stress after Preheating to 150 ^{0}C

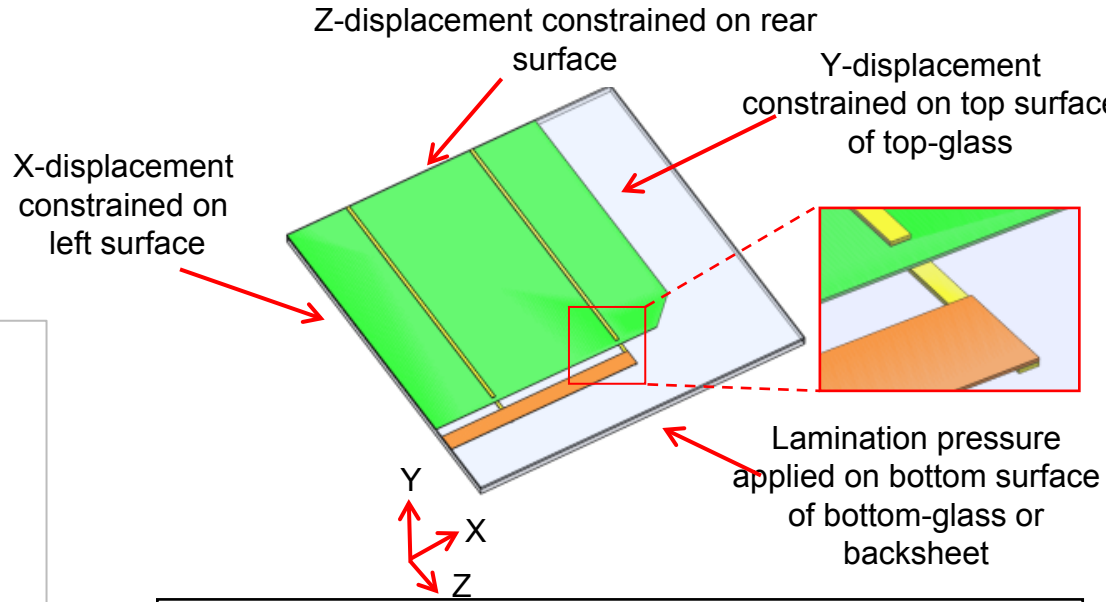


Preheating reduces the post-soldering stress as well as the cell deflection

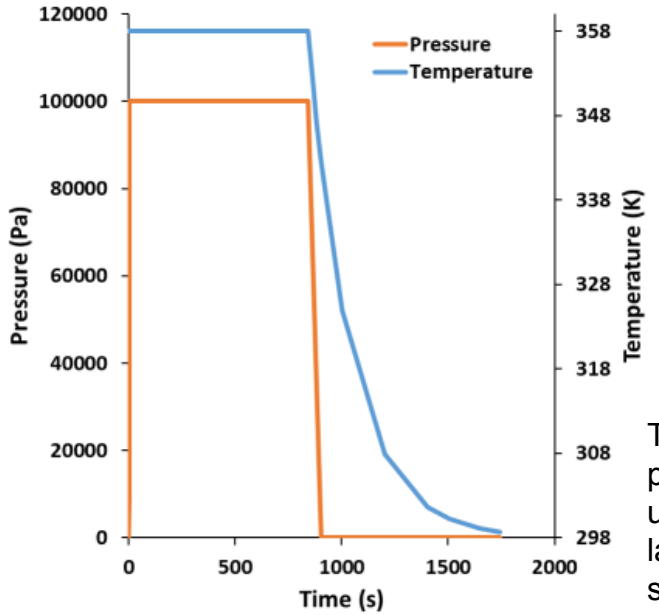
Lamination of Solar Module

- Lamination temperature (150 ^{0}C) and pressure (100 kPa) are maintained for EVA encapsulation curing for 14 min
- Pressure is released while laminate is allowed to cool



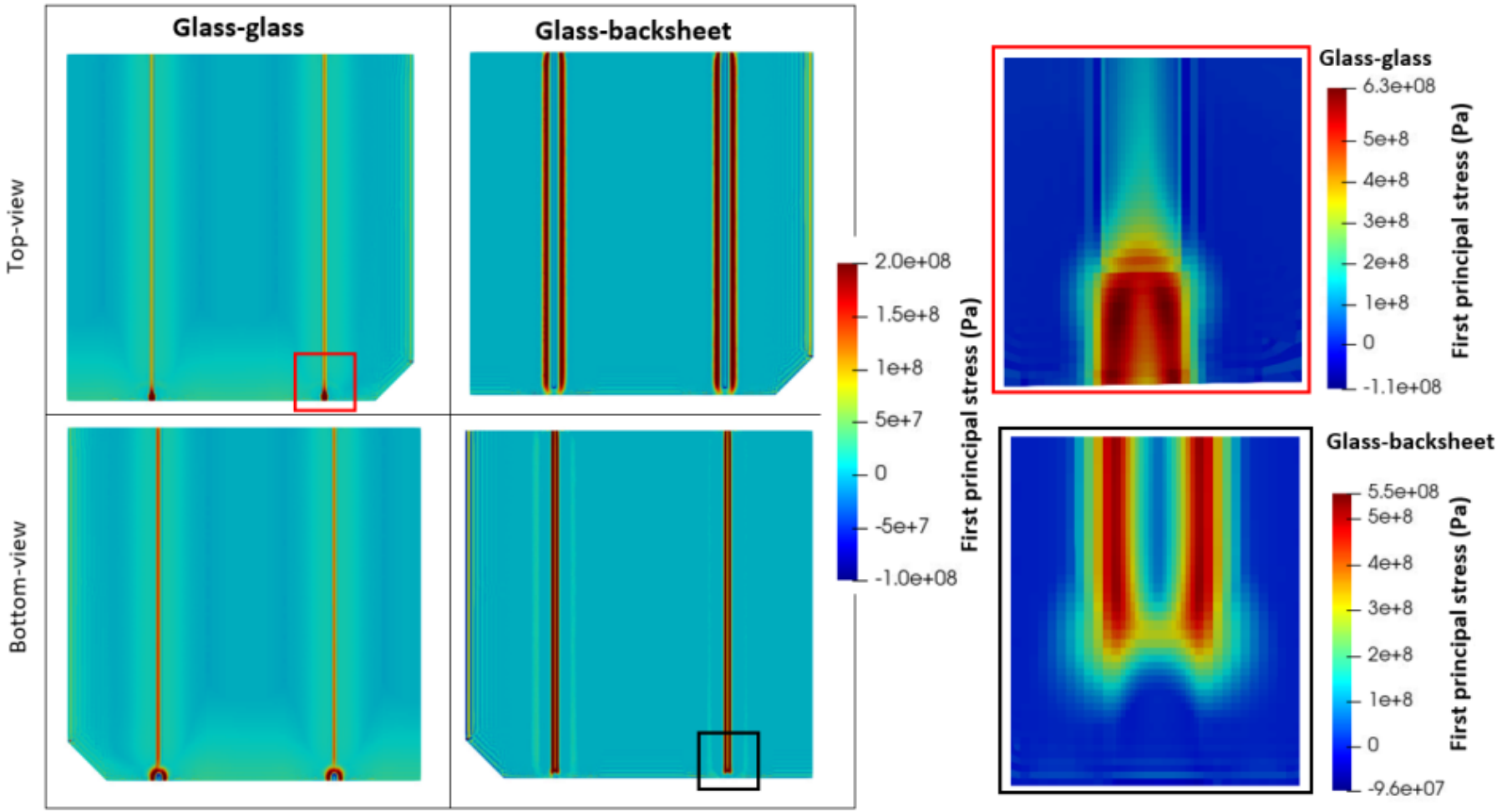


Boundary conditions used in lamination simulation

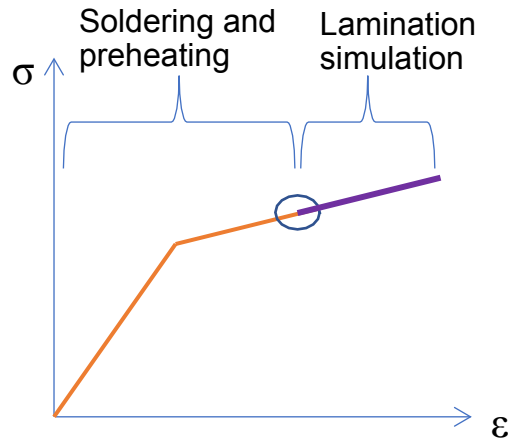


Temperature and pressure profiles used for lamination simulation

Lamination simulation : Glass-glass vs Glass-backsheet (EVA encapsulation [a])



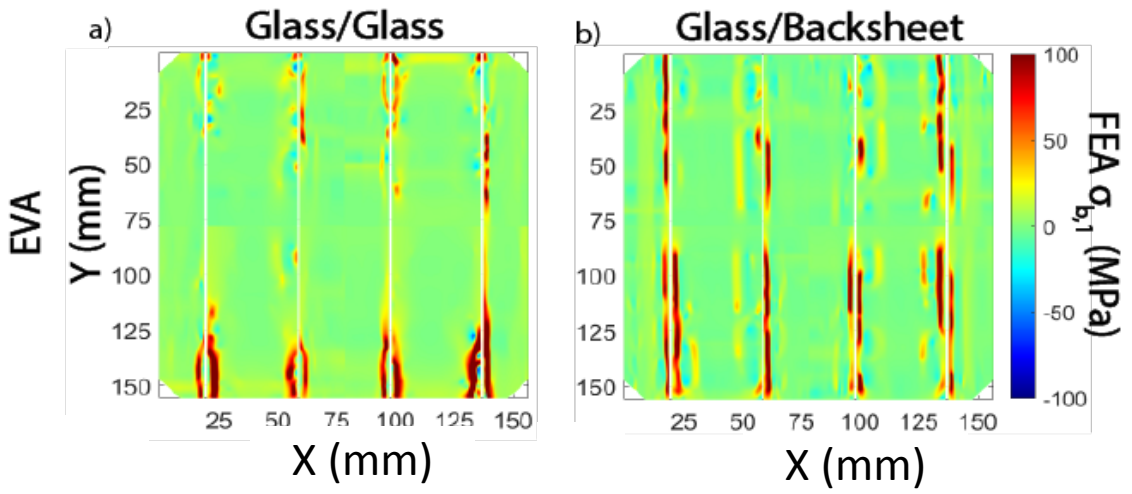
- Lamination stimulation performed assuming initial stress free condition
- Maximum of first principal stress
  - GG – 623 MPa
  - GB – 554 Mpa
- Maximum stress location
  - GG - end of top ribbon
  - GB - along ribbon's foot-print on cell's back side

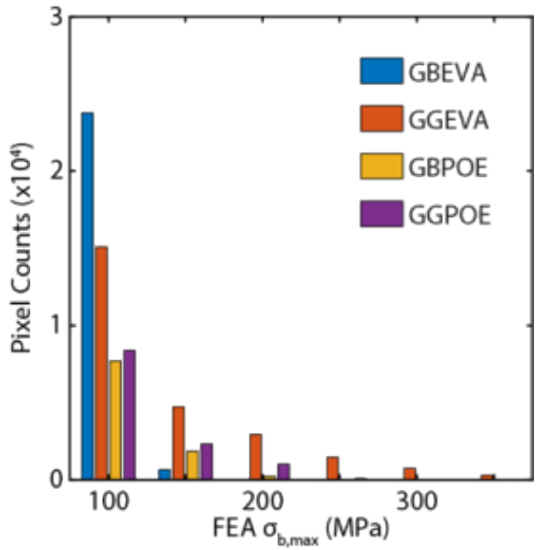


Ongoing work: lamination simulation with stress and state history

(a) N. Bosco, M. Springer, and X. He, "Viscoelastic Material Characterization and Modeling of Photovoltaic Module Packaging Materials for Direct Finite-Element Method Input," IEEE J. Photovoltaics, vol. 10, no. 5, pp. 1424–1440, Sep. 2020 , doi: 10.1109/JPHOTOV.2020.3005086

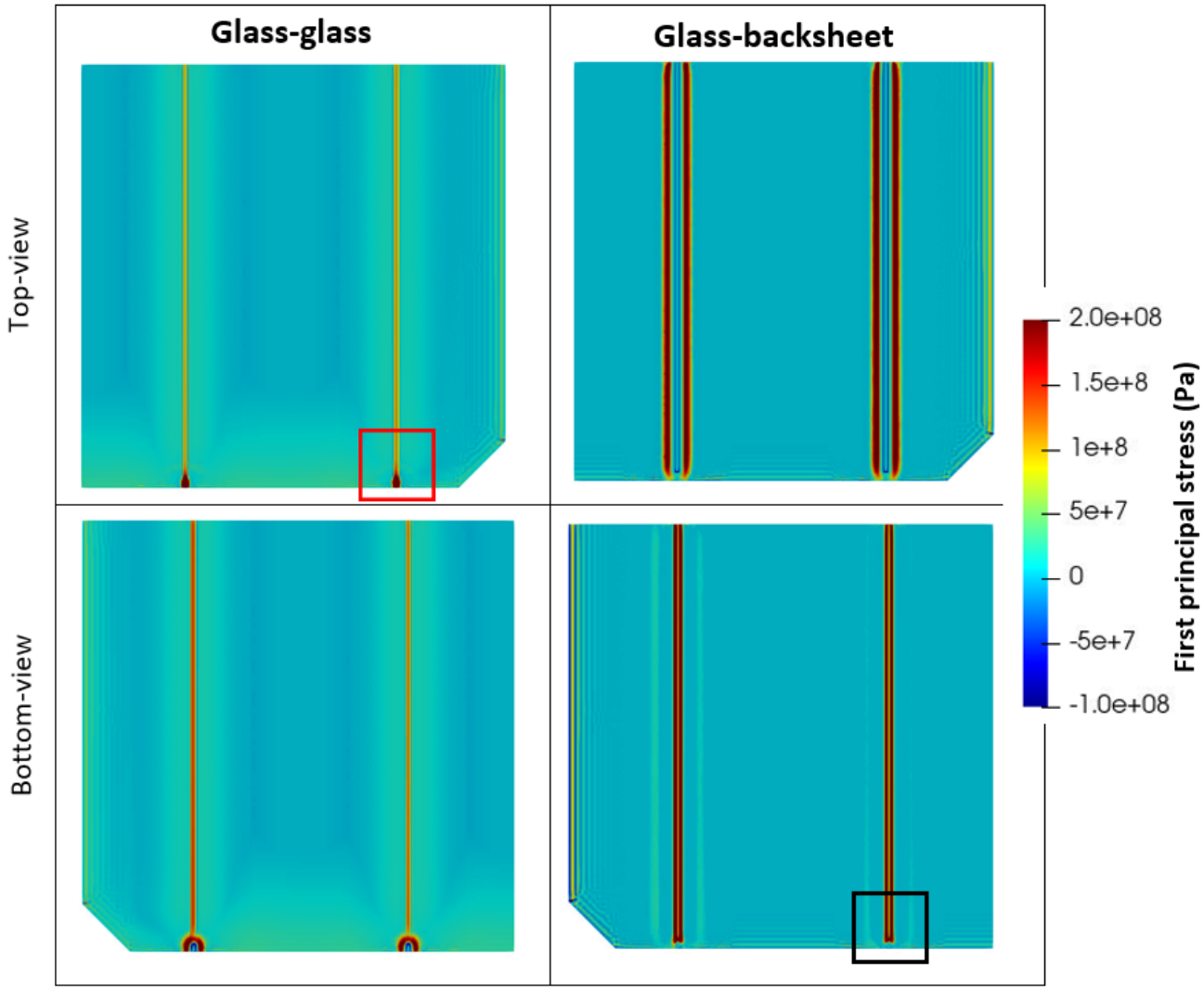
Lamination FEA Result Comparison with Previous FEA Study [a]





Lamination simulation results agree with previous FEA studies [a] :

a. Trend of GG > GB
b. Maximum stress locations



[a] I. M. Slauch et al., "Manufacturing Induced Bending Stresses: Glass-Glass vs. Glass-Backsheet," 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), 2021, pp. 1943-1948, doi: 10.1109/PVSC43889.2021.9518938

Summary

- PV module manufacturing process simulated with:
  - High fidelity mesh
  - Advanced constitutive models
- Comparison among soldering, preheating and lamination simulations (stand-alone) indicated lamination step is dominant in imparting cell residual stress
- Lamination simulation result agreed with previous FEA result
  - Trend of module architectures (GG > GB)
  - Location of peak stress
- Ongoing works:
  - Lamination simulation with stress and material state history
  - Manufacturing simulation with POE encapsulation

Acknowledgements

- SNL researchers: James Hartley, Matthew Phillips, Ashley Maes, Christine Roberts (encapsulant master curve generation and parameter determination for universal polymer model used in simulation)
- ASU researchers: Mariana Bertoni, Rico Meier, Ian Slauch

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