Mapping process model results to fracture model initial conditions for adhesive bonding

Andrew Bergan[1], Thammaia Sreekantamurthy[2], James Ratcliffe[1], and Nelson De Carvalho[1]

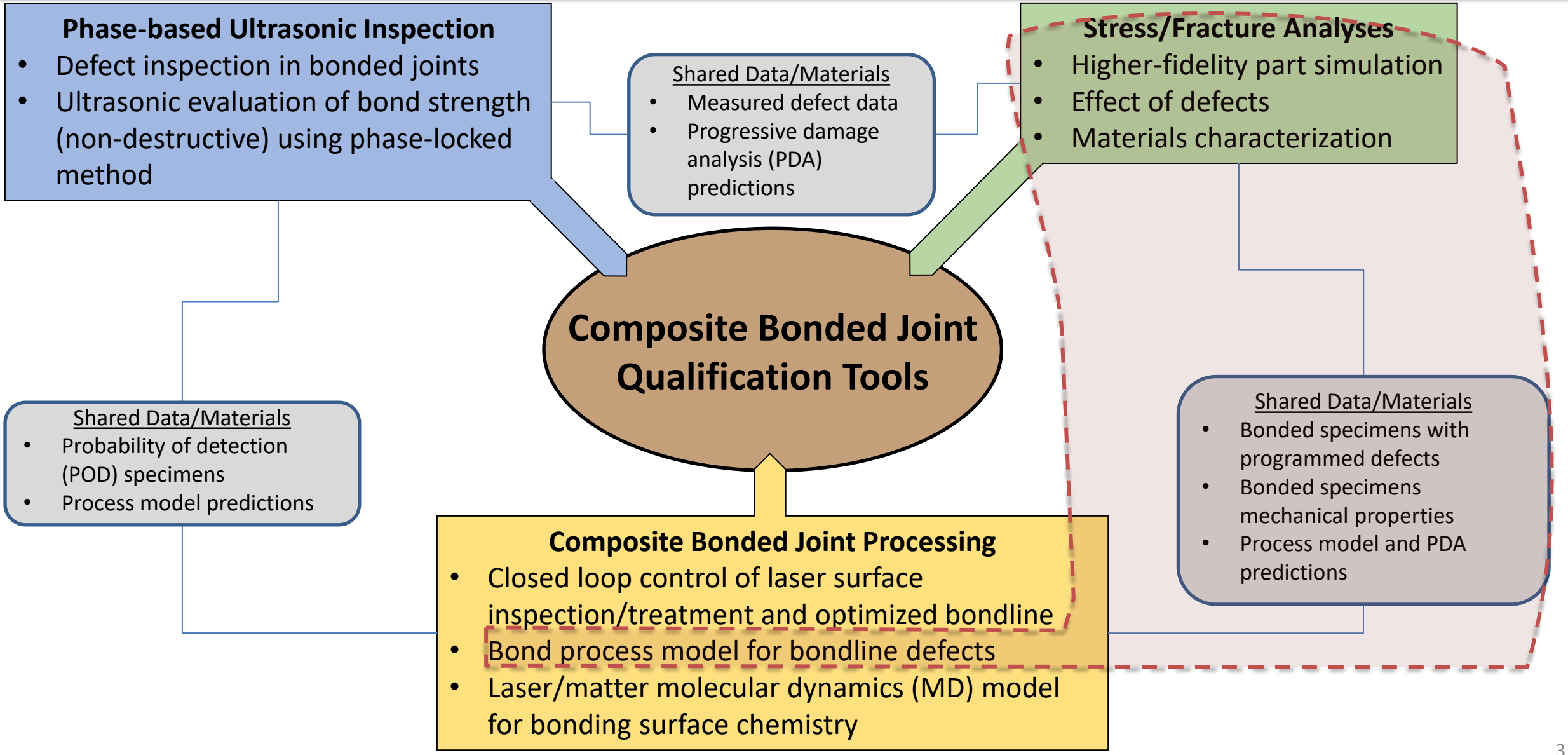
[1] Durability, Damage Tolerance, and Reliability Branch, NASA Langley Research Center, Hampton, VA 23681
[2] Analytical Mechanics Associates, Hampton, VA 23666

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Outline

- Background and motivation
- Approach
- Direct mapping
- Functional mapping
- Summary

NASA Transformational Tools & Technologies (TTT) Project: Composite Bonding Effort



Overview

Problem:

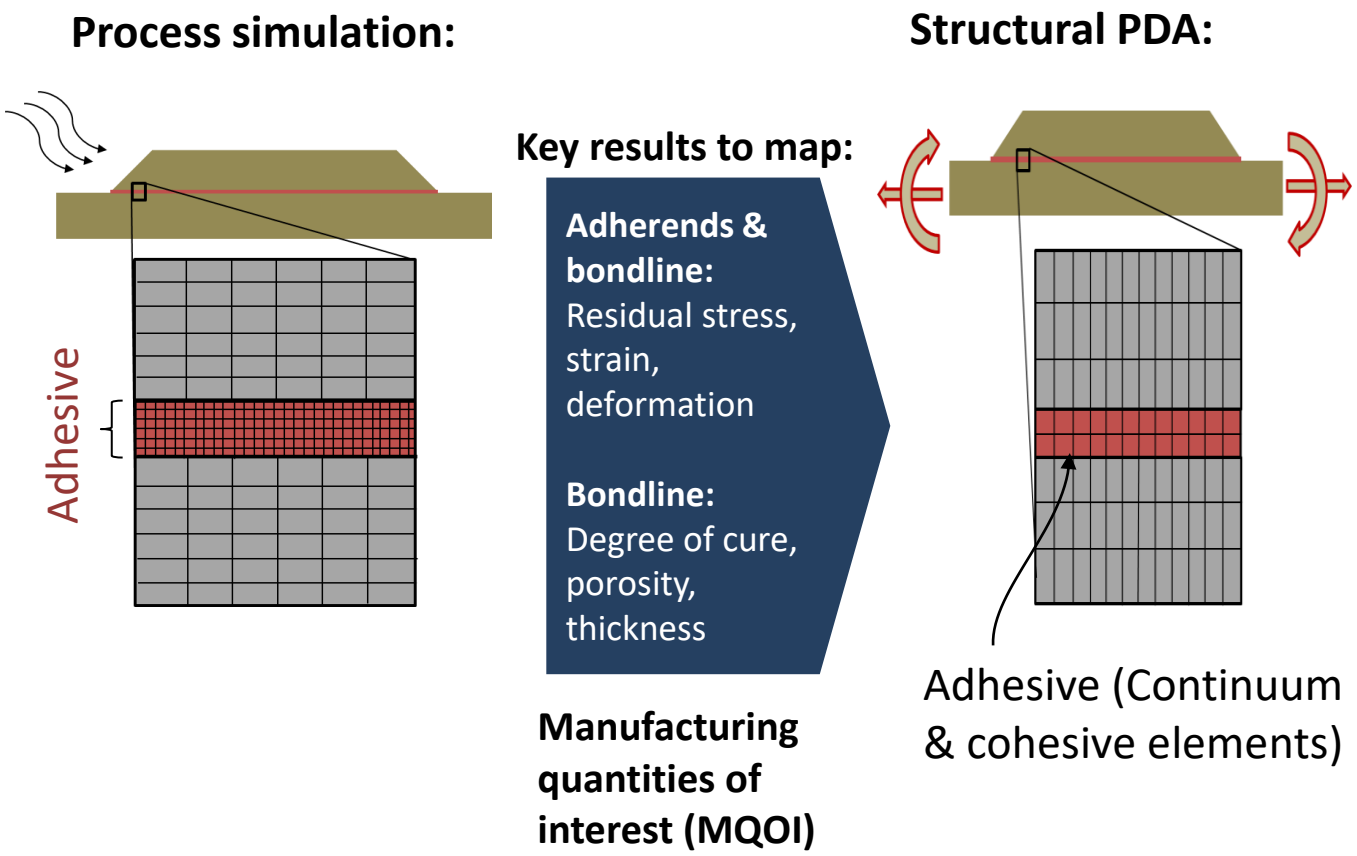
- Secondary bonding process often produces spatially varying features
- Tools are needed for consideration of bonding process outcomes in structural analysis
- Bonding process-to-performance assessment based on empiricism and heuristics

Objective:

- Develop tools to map process model results to fracture model initial conditions → predict the relationship between process and structural performance

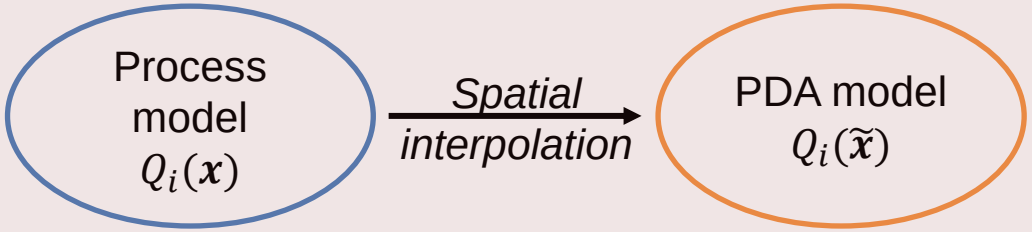
Challenges:

- Discretization requirements and simulation techniques differ
- Characterization testing requirements



Two Approaches for Mapping

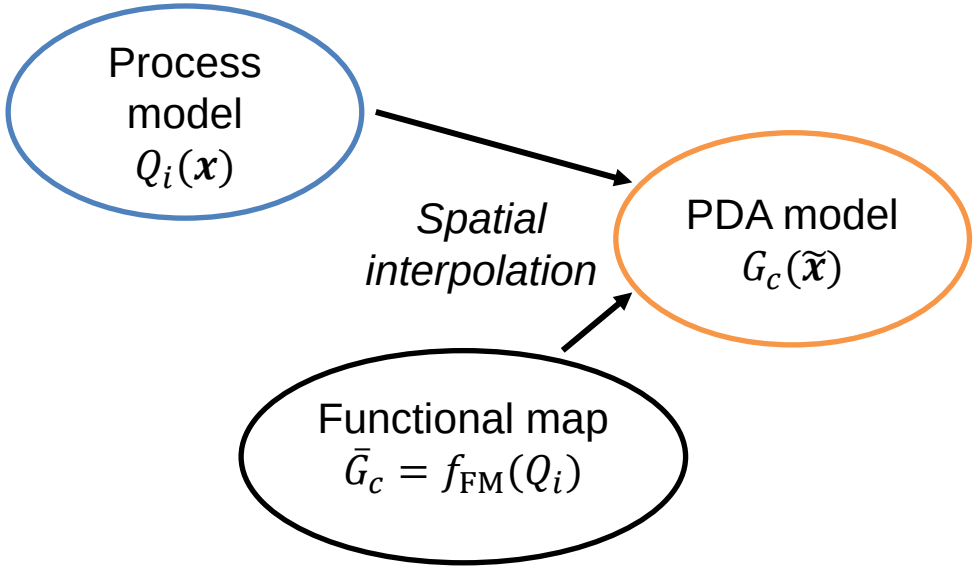
Direct mapping



- Process simulation and PDA use the same representation of the MQOI, Q_i
- Applies to adherends and bondline:
  - Residual stress
  - Residual strain
  - Residual deformation

- Mapping addresses differences in discretization → map from process model mesh onto PDA mesh

Functional mapping



- A functional relationship is assumed between the MQOI and fracture toughness (f_{FM}), determined by test or simulation
- Applies to bondline:
  - Degree of cure
  - Porosity
  - Thickness

Direct Mapping

Process model (COMPRO[1]) reports equivalent non-mechanical strains, ε_{eqnms}, [Integrated Computational Methods for Composite Materials (ICM2), Lockheed Martin, 2018]:

$$\varepsilon_{eqnms} = \varepsilon_{tot,cure} - C^{-1}\sigma_{cure}$$

$\varepsilon_{tot,cure}$ and σ_{cure} are the total strains and residual stresses at the end of the cure simulation

ε_{eqnms} is equivalent to Abaqus[1] output variable `THE` if cure is modeled as a thermal cooldown $\alpha\Delta T$

In subsequent mechanical analysis, ε_{eqnms} is taken as the initial free strain

Stress is calculated as:
$\sigma = C(\varepsilon - \varepsilon_{eqnms})$

Abaqus implementation:

- Python script handles mesh interpolation (next chart)
- ε_{eqnms} read in as state variables
- Set ε_{eqnms} as thermal strains
- Set $\Delta T = 1$ in first step
- Solve static step with rigid body motion constrained

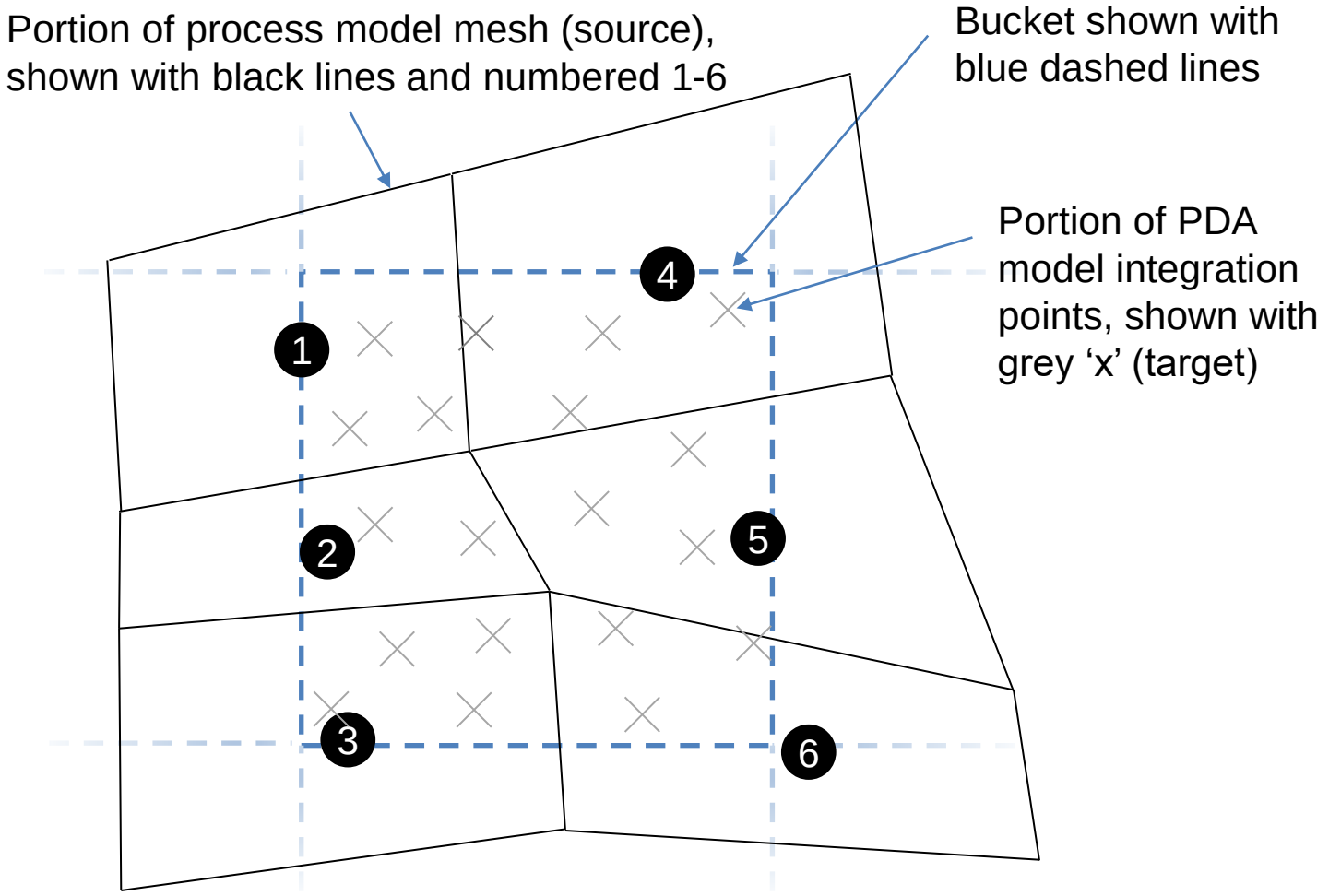
(examples completed so far model cure as a thermal cooldown $\alpha\Delta T$)

[1]`Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the software, material, or test hardware. The use of vendor and manufacturer names does not imply an endorsement by the National Aeronautics and Space Administration (NASA) nor does it imply that the specified material or equipment is the best available.

Direct Mapping

Use the source mesh shape functions to interpolate source results at target mesh integration point locations

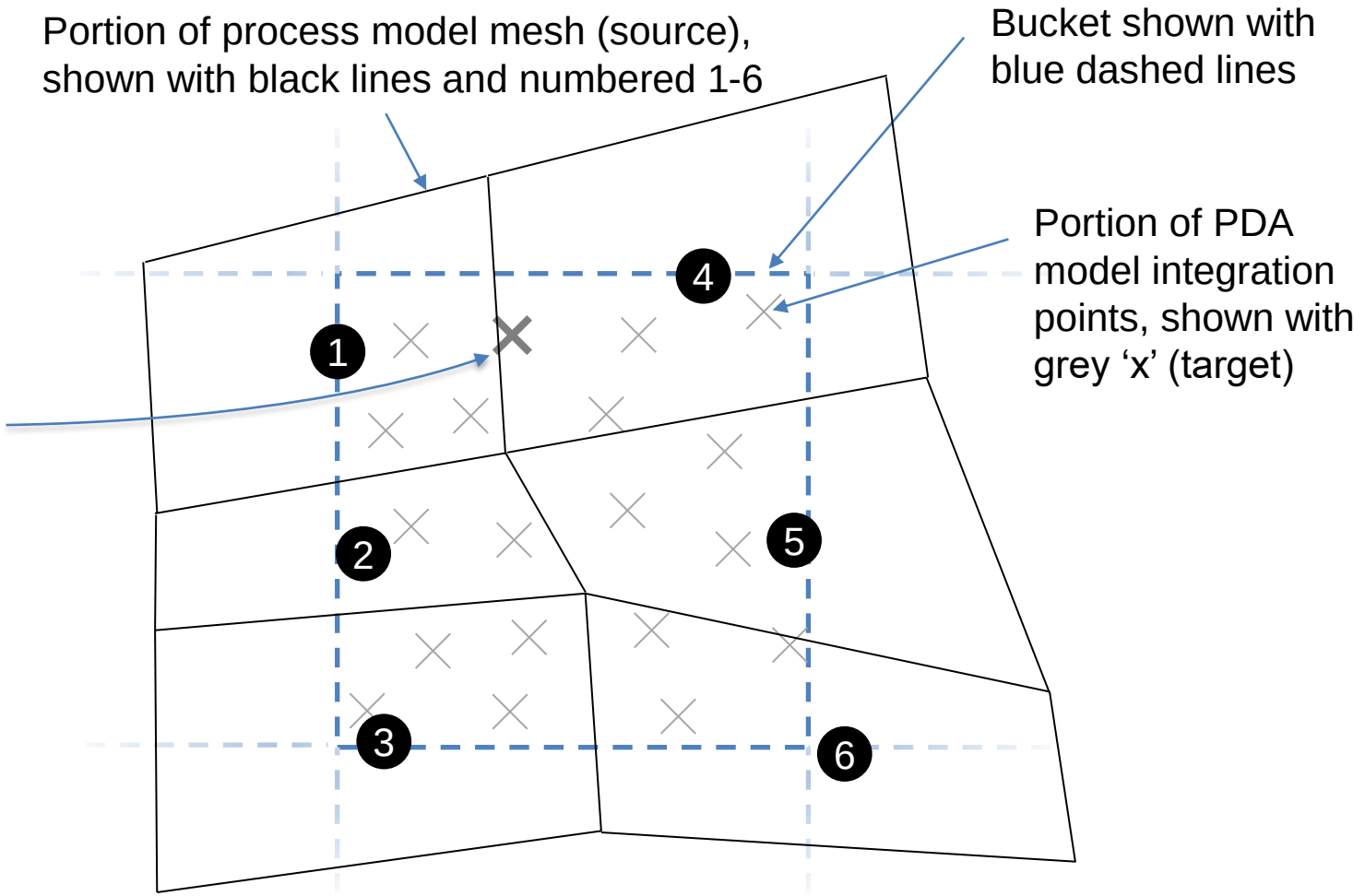
1. **Divide the domain into buckets so that search subdomain is small (i.e., bucket sort)**



Direct Mapping

Use the source mesh shape functions to interpolate source results at target mesh integration point locations

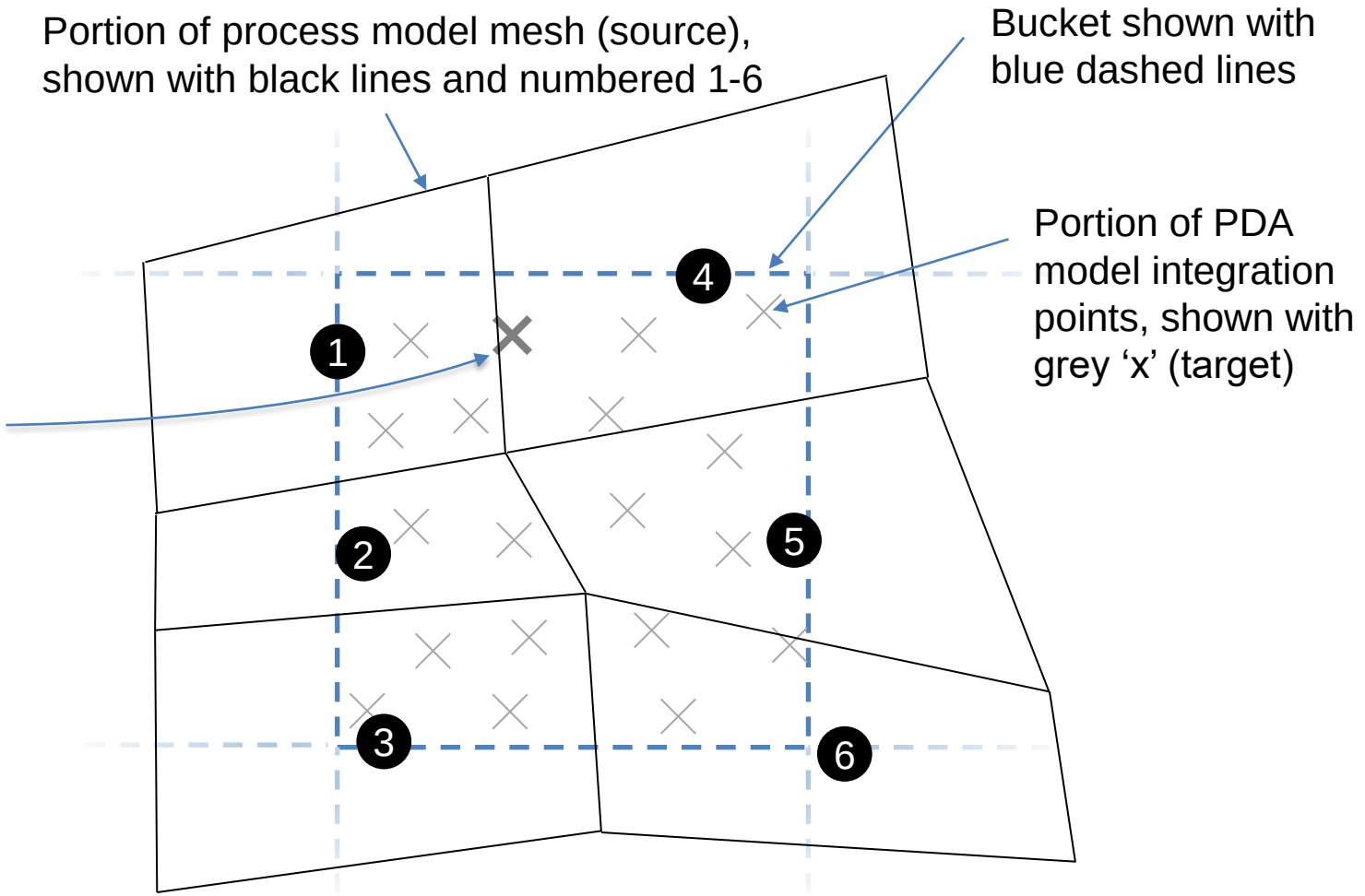
1. Divide the domain into buckets so that search subdomain is small (i.e., bucket sort)
2. **Identify which source element encloses each integration point in the target mesh (example):**
   - **Sort candidate source elements by distance from centroid to target integration point: 1, 4, 2, 5, 3, 6**
   - **The enclosing source element is the one with natural coordinates in [-1,1]: 4**



Direct Mapping

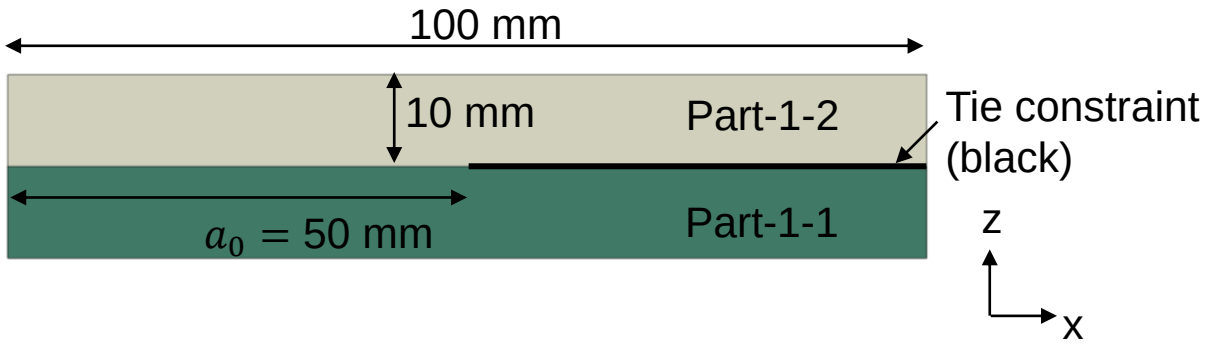
Use the source mesh shape functions to interpolate source results at target mesh integration point locations

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   - Sort candidate source elements by distance from centroid to target integration point: 1, 4, 2, 5, 3, 6
   - The enclosing source element is the one with natural coordinates in [-1,1]: 4
3. **Interpolate desired output values from enclosing source element at target integration point location**



Direct Mapping Example

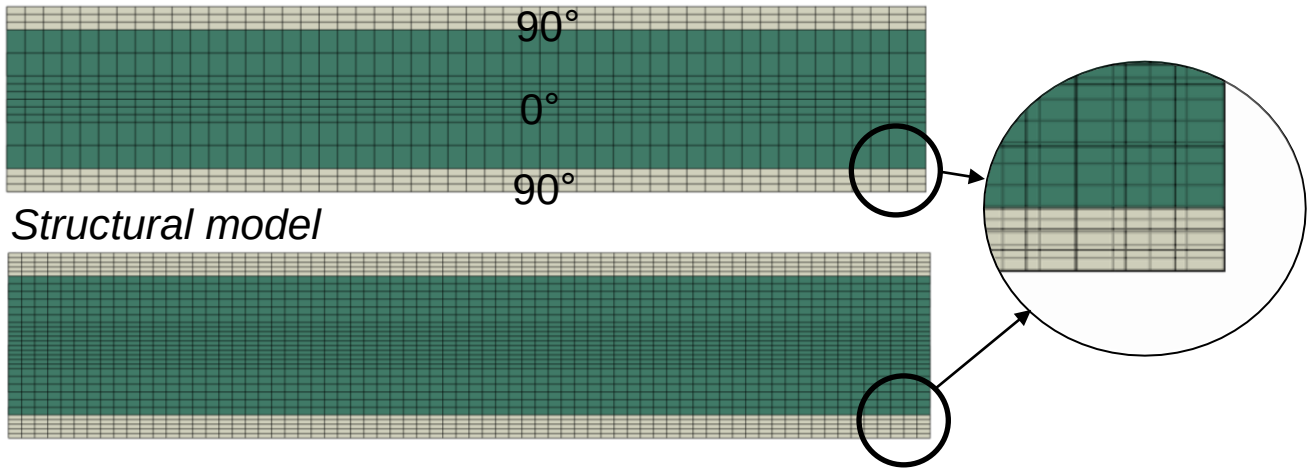
Geometry and part definitions



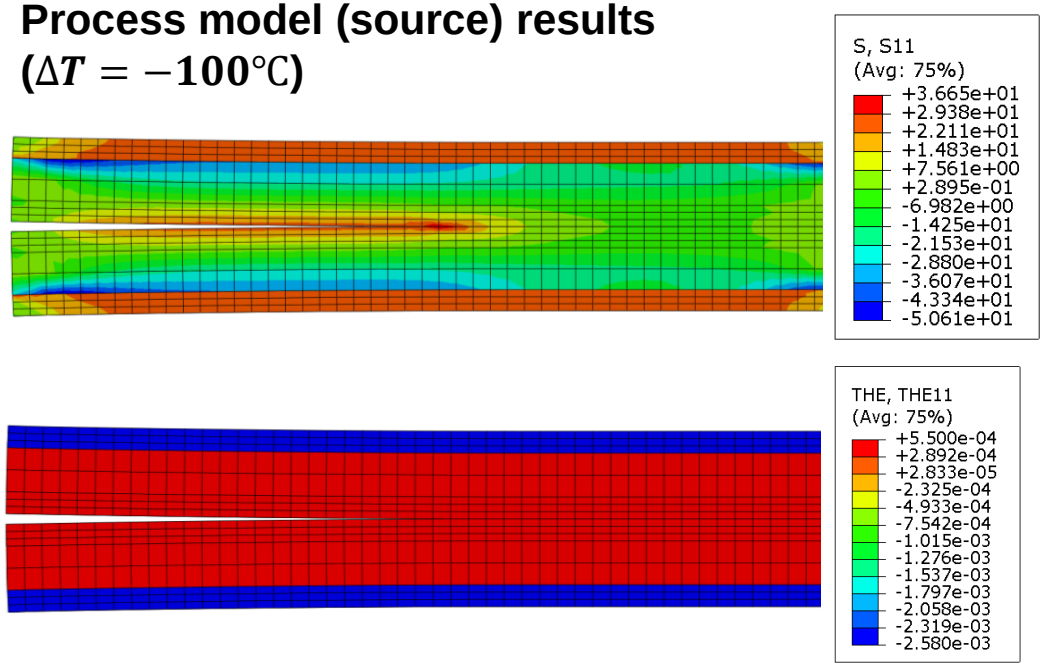
- Simplified example: double cantilever beam (DCB) with unsymmetric arms
- IM7/8552 material properties [Wanthal 2017]
- Cure modeled as a thermal cooldown $\alpha\Delta T$, ε_{eqnms} = 'THE' (thermal strain)

Material zones and meshes

Pseudo process model ($\alpha\Delta T$)



Process model (source) results ($\Delta T = -100$°C)

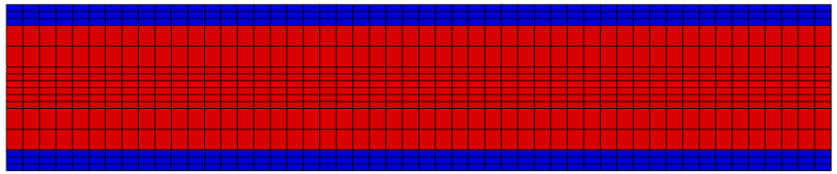


Direct Mapping Example Results

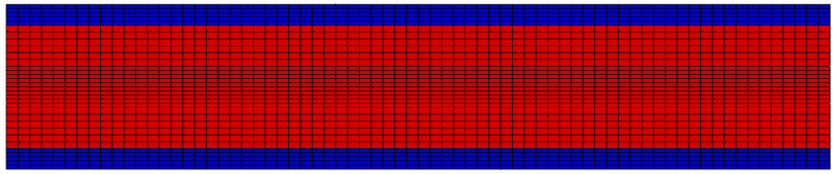
Pseudo process model

Structural model

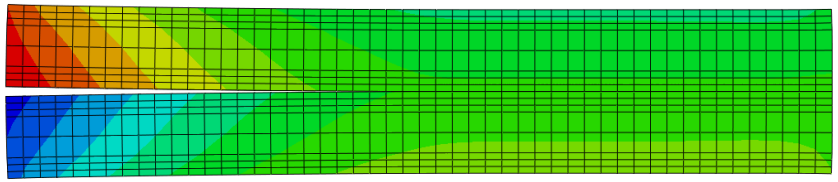
Predicted and mapped ε_{eqnms} (component 11)



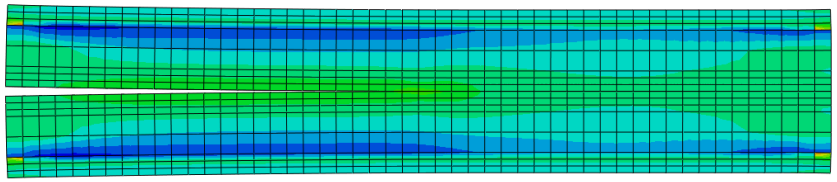
Direct mapping



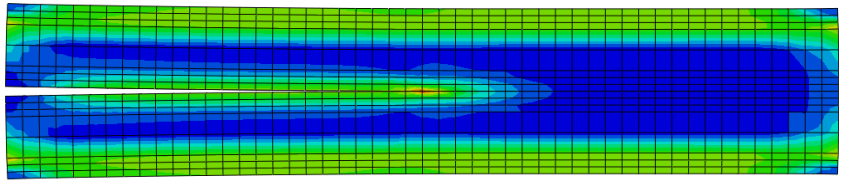
Deformation (y component)



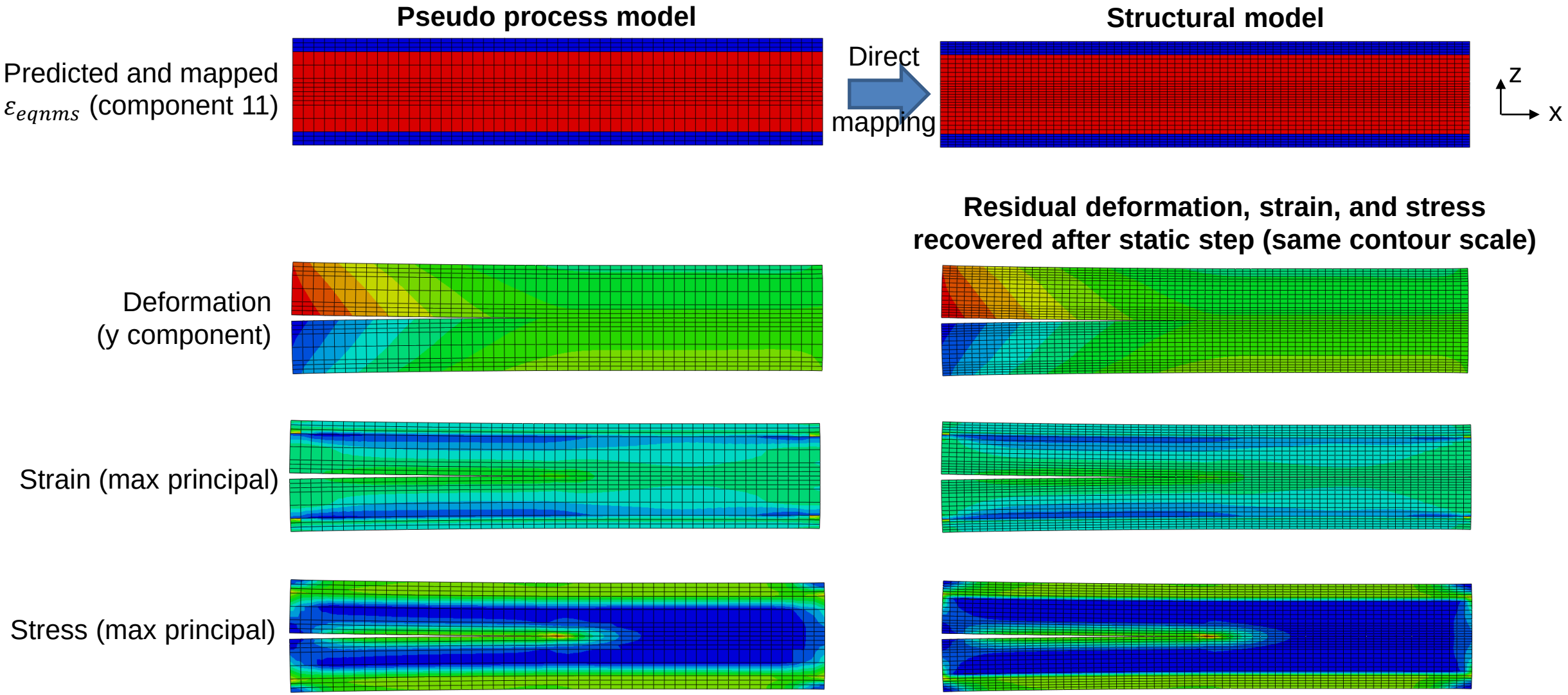
Strain (max principal)



Stress (max principal)



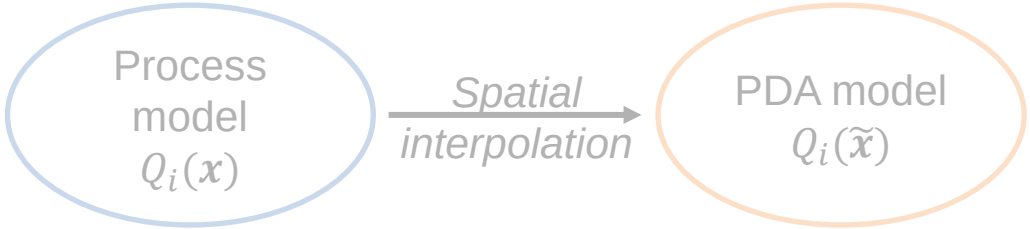
Direct Mapping Example Results



Direct mapping using COMPRO results is being pursued currently

Two Approaches for Mapping

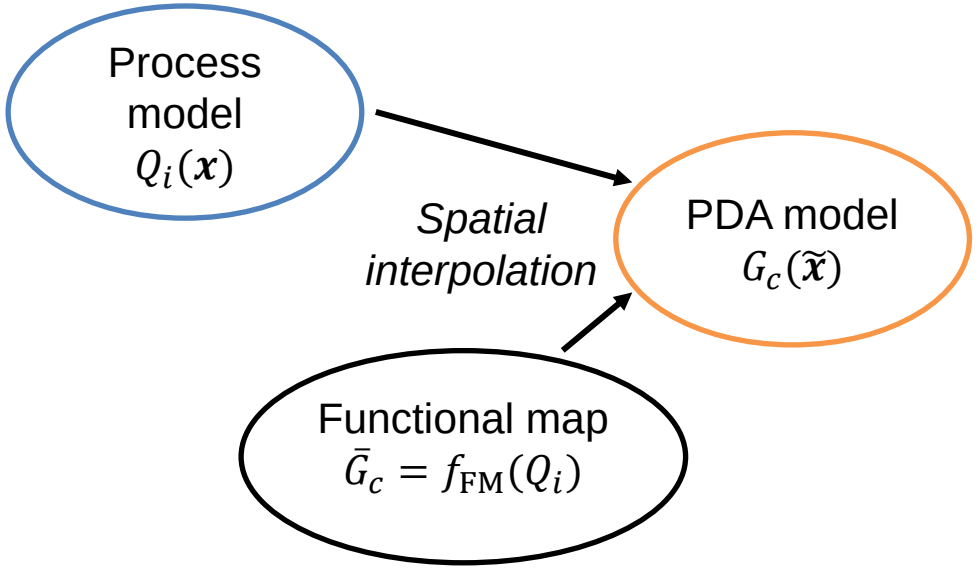
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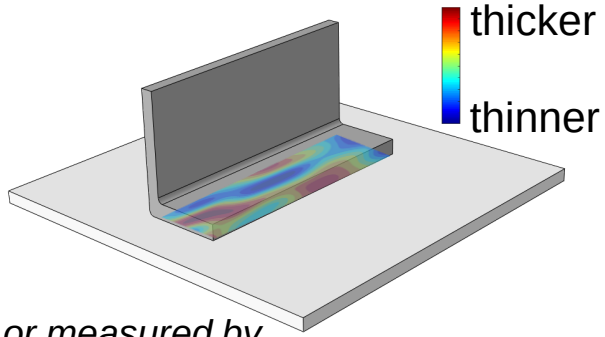
Functional mapping



- A function relationship is assumed between the MQOI and fracture toughness (f_{FM}), determined by test or simulation
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  - Degree of cure
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Functional Mapping

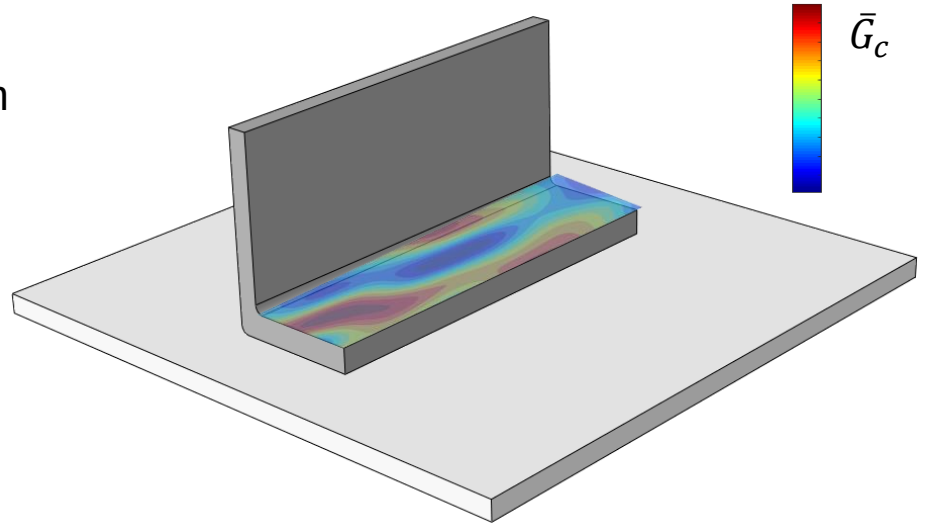
1) As-manufactured bondline field, e.g., bondline thickness, t



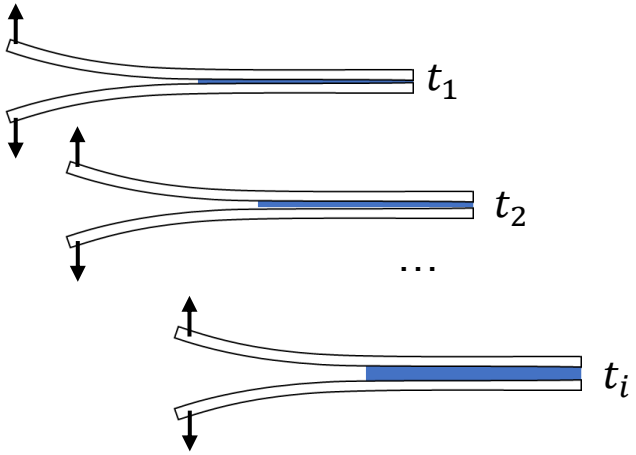
Predicted or measured by nondestructive evaluation (NDE)

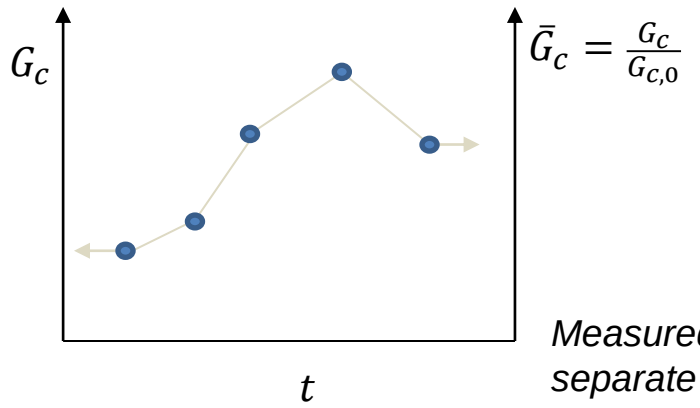
For each integration pt. with thickness t_j, interpolate $\bar{G}_c$ from functional map

3) Mapped fracture toughness



2) Data for functional map, e.g., $G_c = f_{\mathrm{FM}}(t)$

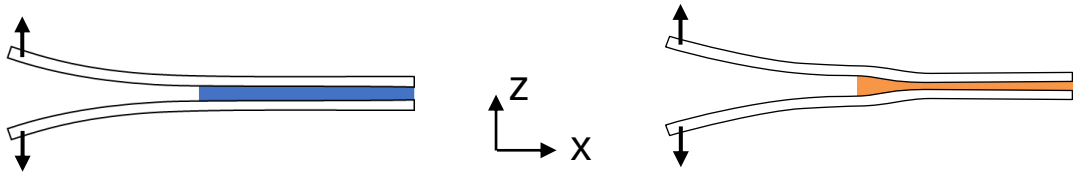




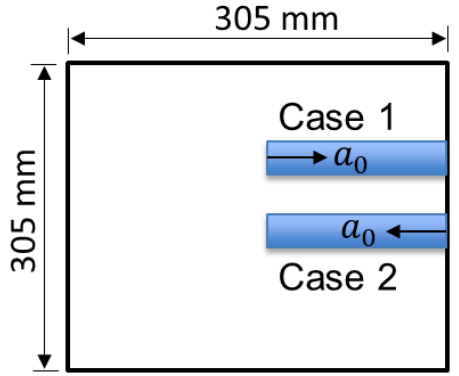
Measured in test or predicted by separate dedicated simulations

Functional Mapping: Summary of Three Examples

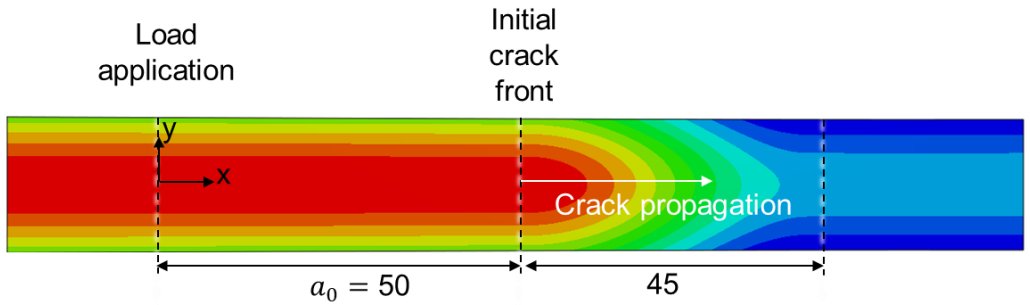
1. 1-Dimensional variation: simple verification



2. 1-Dimensional variation: specimen orientation

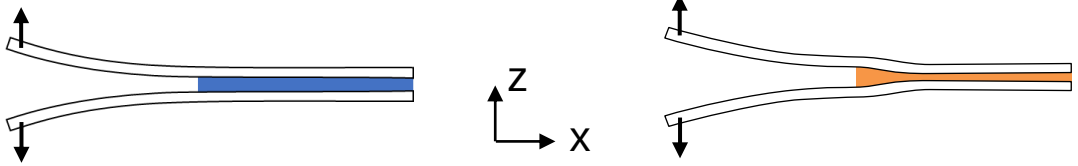


3. 2-Dimensional variation: change in crack front shape



Functional Mapping: Example 1

Constant bondline thickness

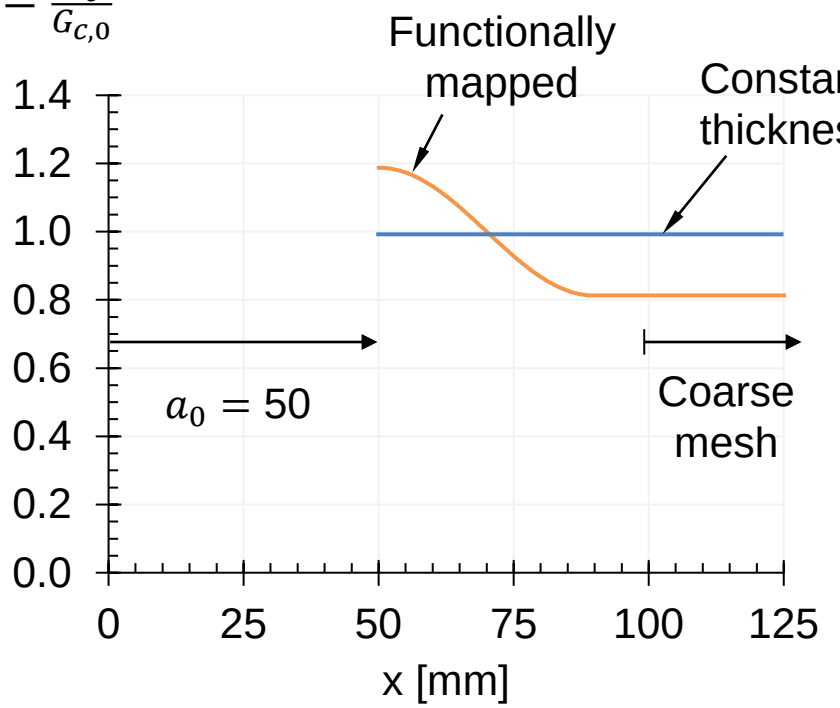


Variable bondline thickness (sinusoidal)

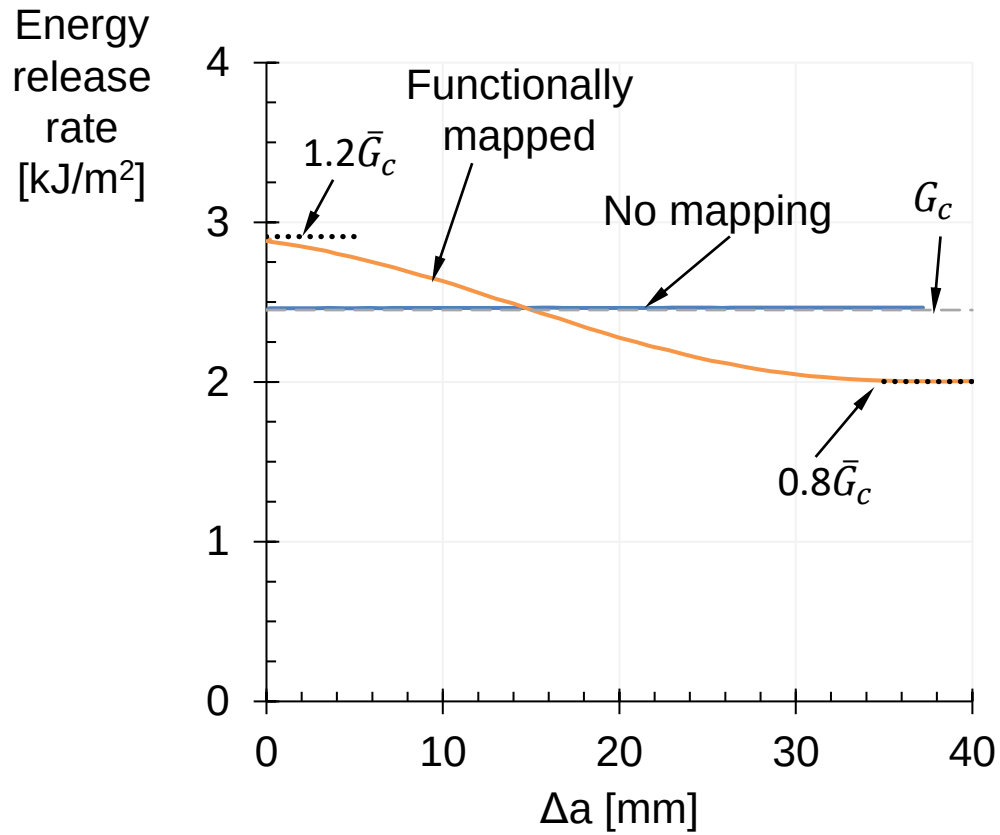
f_{FM} assumed to be linear

$G_{c,0}$ = 2.45 kJ/m^2

$\bar{G}_c = \frac{G_c}{G_{c,0}}$

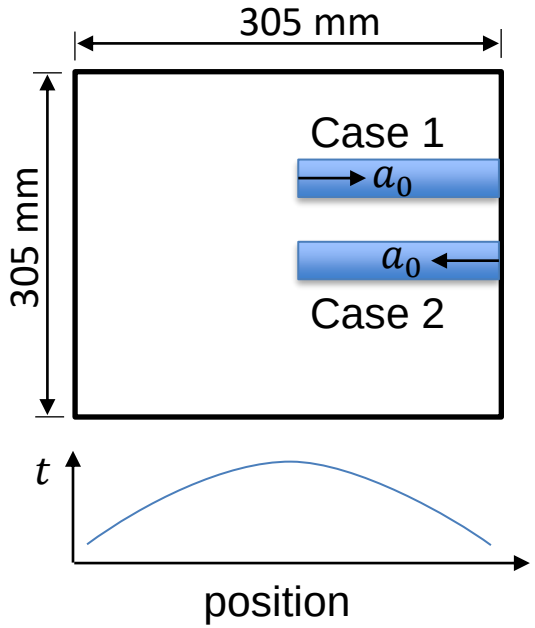


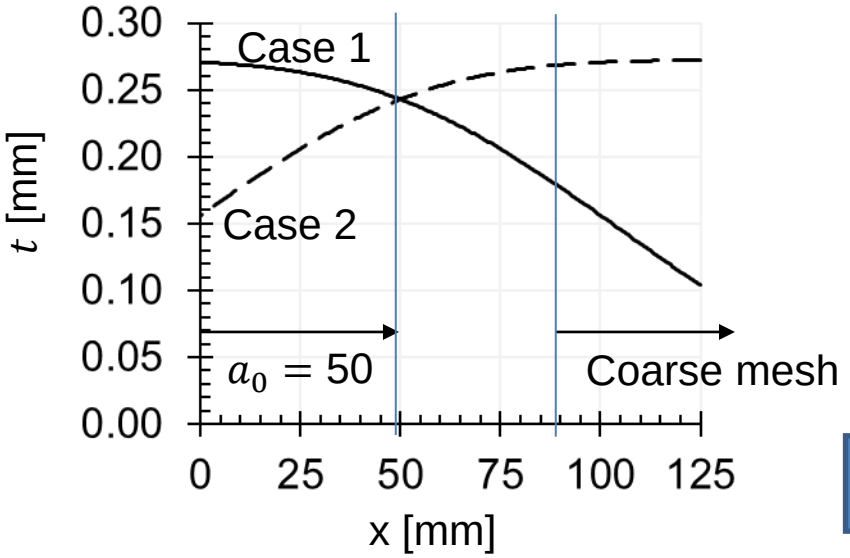
Predicted R-curve from numerical computation of the J-integral



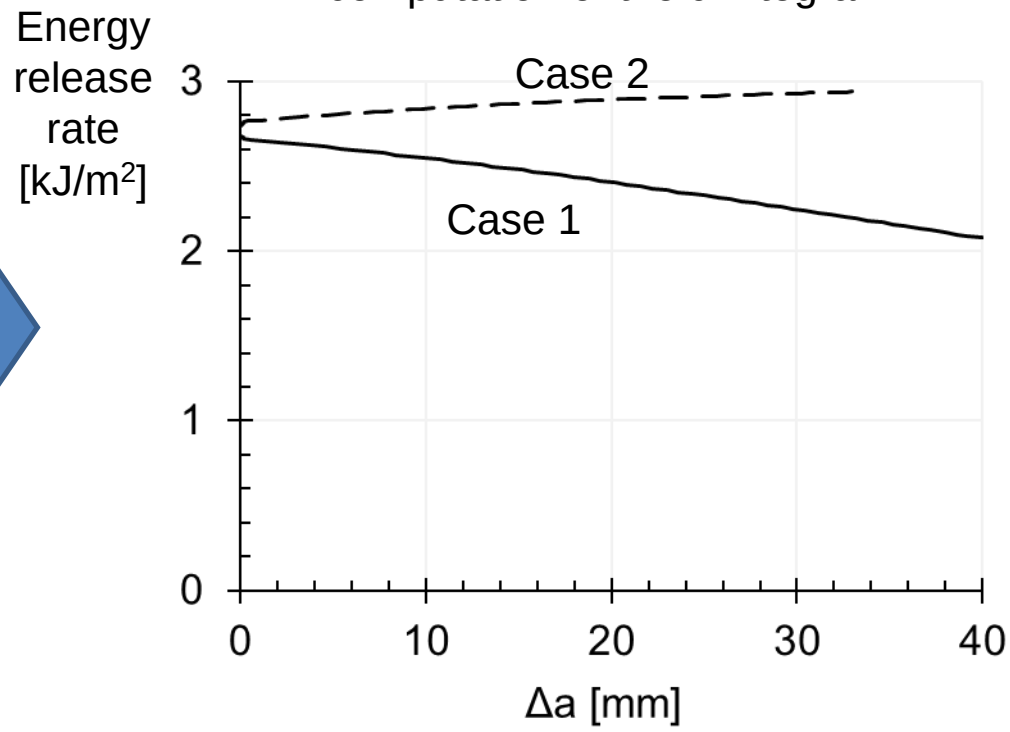
Functional Mapping: Example 2

Bonded flat panel thickness variation predicted by COMPRO process model

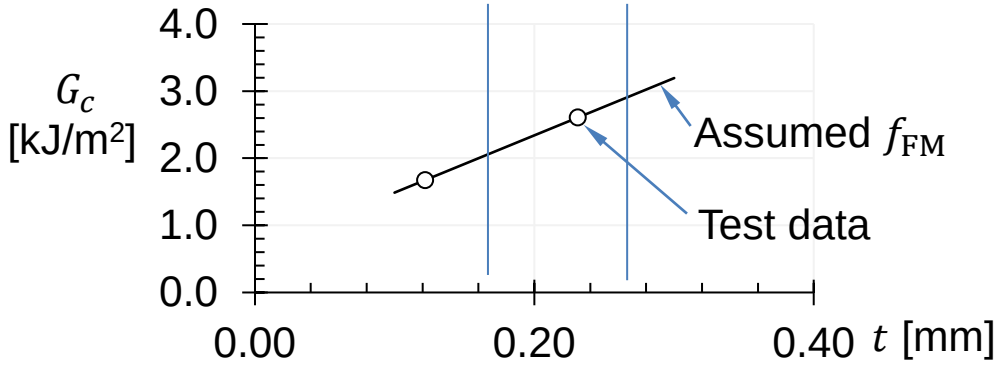




Predicted R-curve from numerical computation of the J-integral

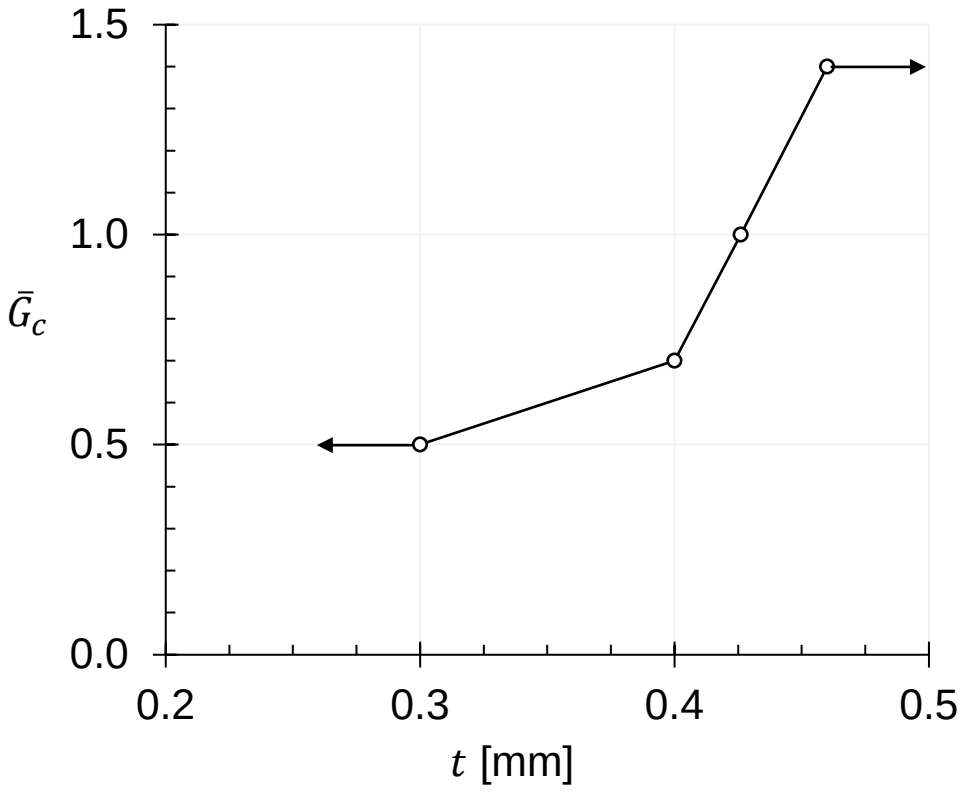


Linear f_{FM} based on test data

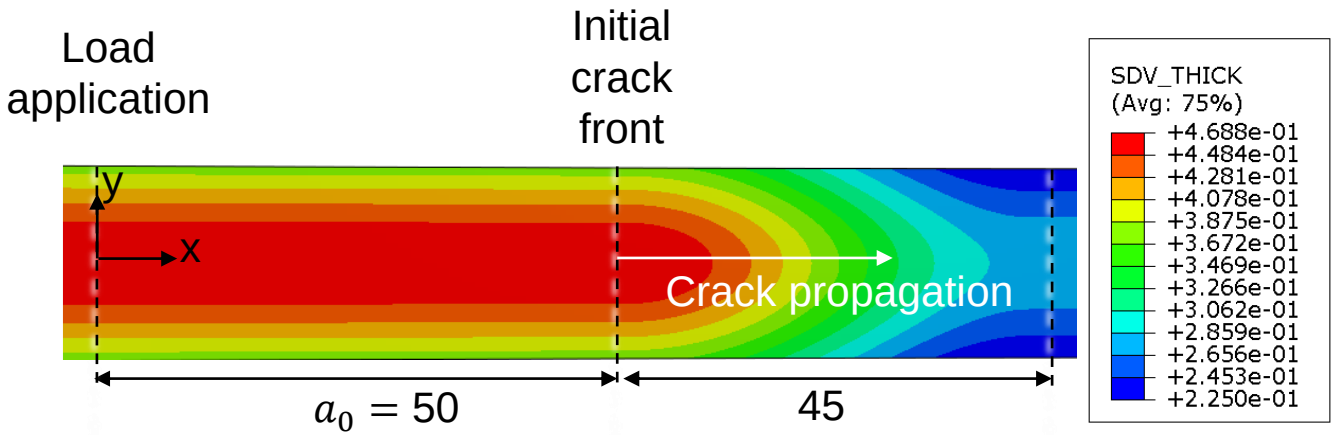


Functional Mapping: Example 3 (2-Dimensional Variation)

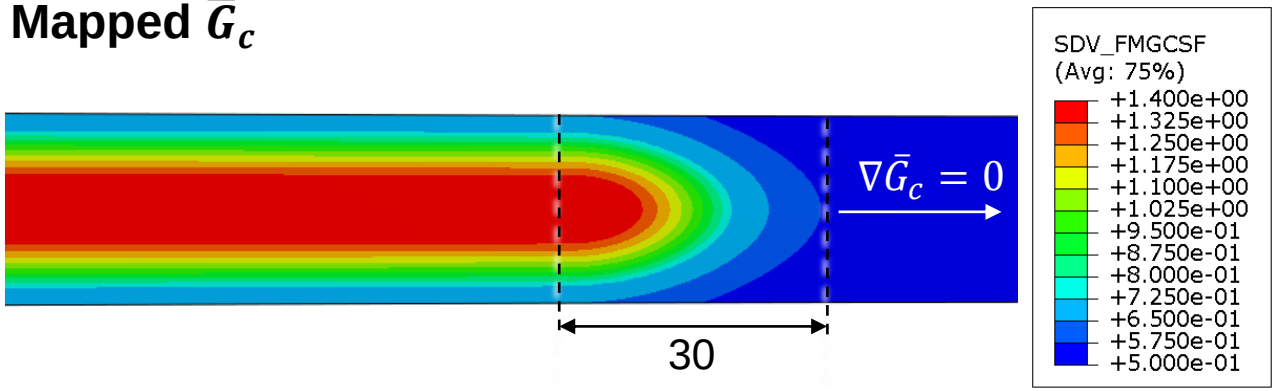
Assumed functional map, f_{FM}



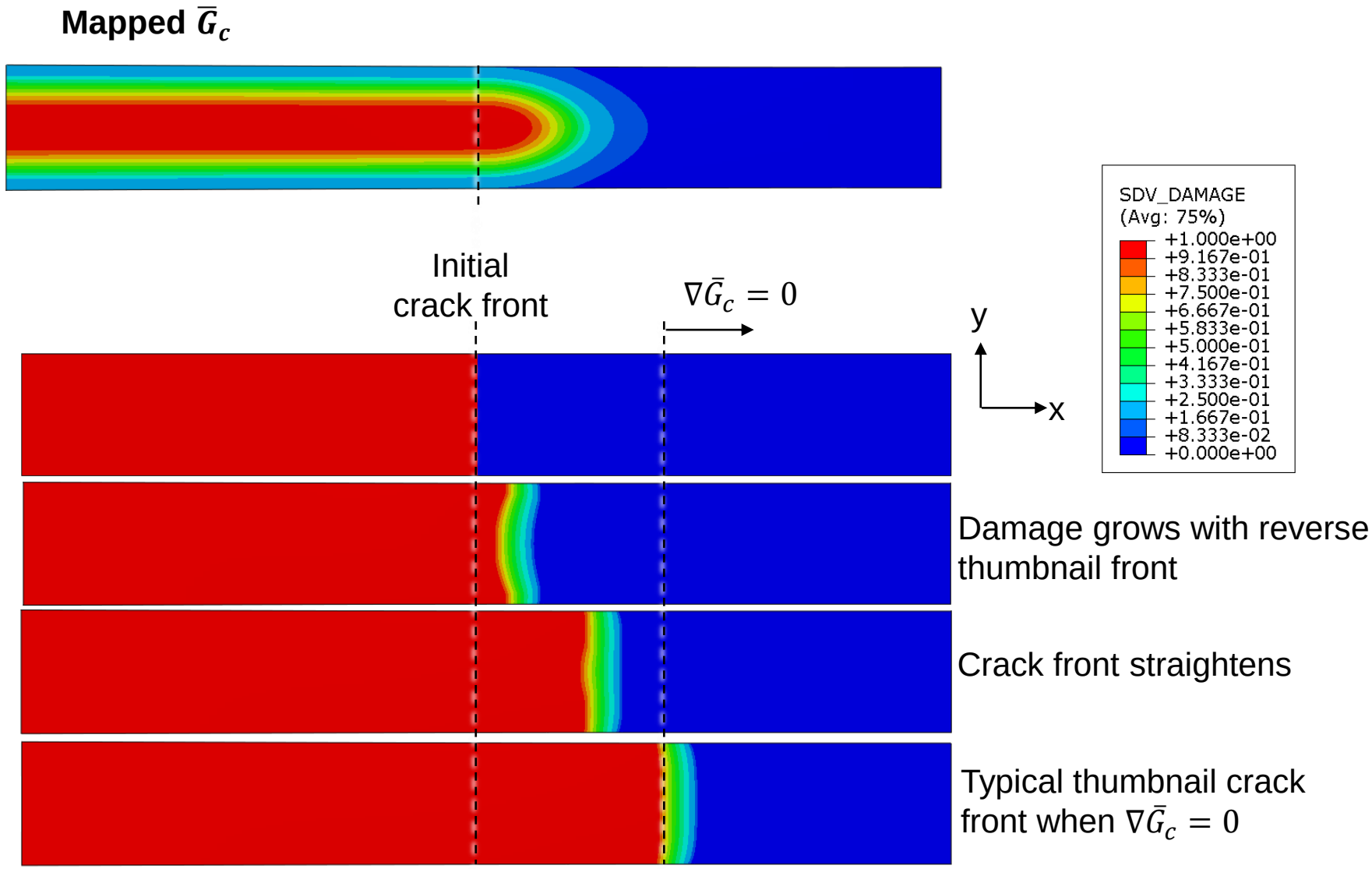
Synthetically generated bondline thickness, t [mm]



Mapped $\bar{G}_c$



Functional Mapping: Example 3 (2-Dimensional Variation)



Summary

- Developed a framework to include process results as initial conditions in PDA models for secondary adhesive bonding
  - Enables for process-to-performance assessments
- Direct mapping for residual stresses, strains, and deformations
  - Interpolate equivalent nonmechanical strain, ε_{eqnms}, following ICM2
  - Use an efficient bucket sort search algorithm for mapping between dissimilar meshes
- Functional mapping for bondline thickness, degree of cure, and porosity
  - General approach for mapping quantities that have a functional relationship with fracture toughness (f_{FM})
  - The functional map is established based on test data (or potentially simulations)
  - As-manufactured condition predicted by process modeling (or potentially measured by NDE)
- Current efforts are focusing on validation of the bondline thickness functional mapping and direct mapping using COMPRO simulation results

Acknowledgement

- This work was supported by the Transformational Tools & Technologies (TTT) Project
- Thanks to Tyler Hudson for fabricating the DCB specimens

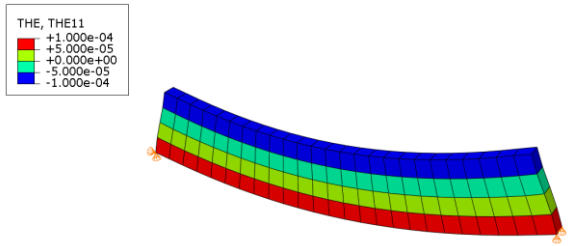
Questions

Backup

Direct Mapping: Example 1

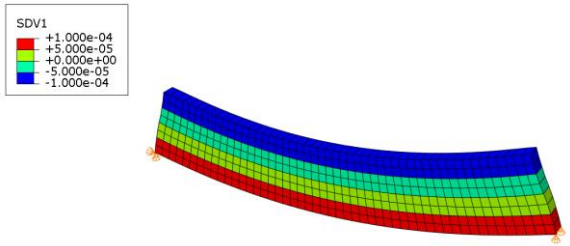
- Demonstrate mapping between dissimilar meshes

Pseudo process (source) model

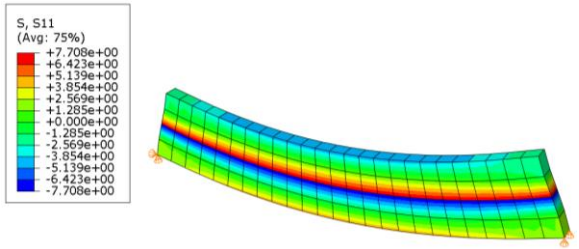


(a) Pseudo process model with different thermal strain (11 component) in each row of elements

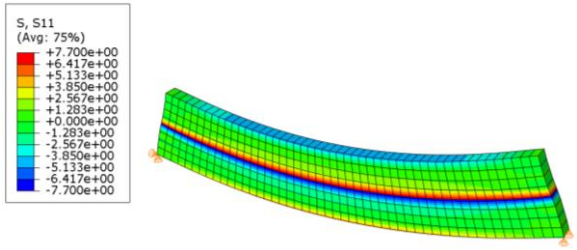
Structural (target) model



(b) $\varepsilon_{eqnms,1}$ mapped onto a refined mesh

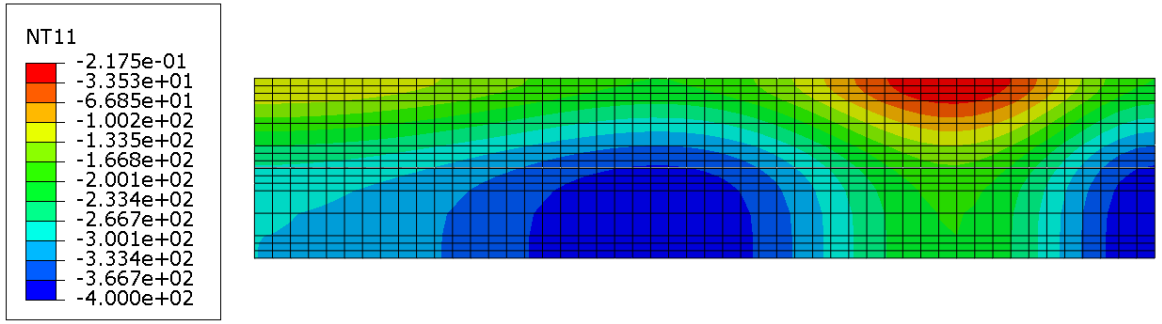


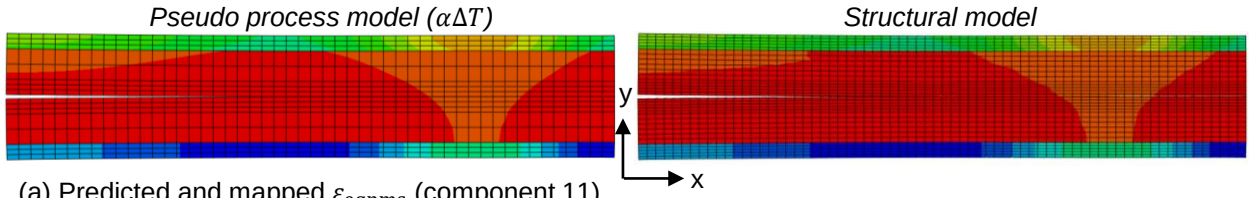
(c) Residual stress σ_{11} predicted by the pseudo process model



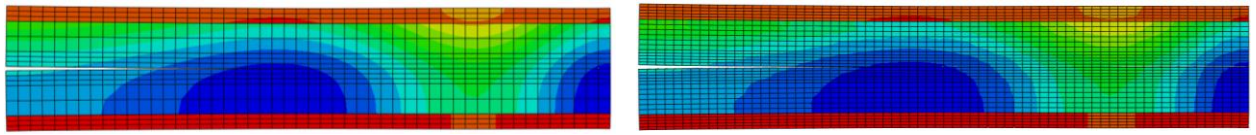
(d) Residual stress σ_{11} recovered after equilibrium step

Direct Mapping Example

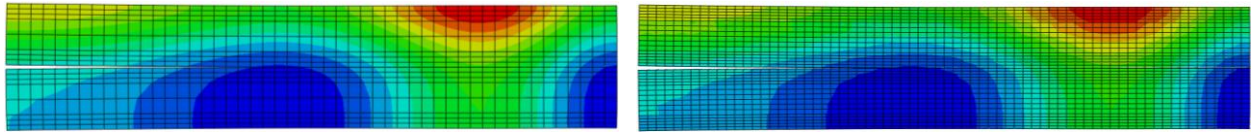




(a) Predicted and mapped $\varepsilon_{\mathrm{eqnms}}$ (component 11)



(b) Predicted and mapped $\varepsilon_{\mathrm{eqnms}}$ (component 22)



(c) Predicted and mapped $\varepsilon_{\mathrm{eqnms}}$ (component 33)