SAND2021-9047C

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Uncertainty Quantification of Delamination Failure within Composite Structures using a Submodel Based Multi-Fidelity Approach

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16th US National Congress on Computational Mechanics

July 25-29, 2021

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Overview

- Motivation
- Background
  - Residual stress modeling
  - Considerations in incorporating additional detail
- Multi-Fidelity Approaches Considered
  - 3 Approaches considered
  - Comparison using a traditional sampling UQ
- Conclusions

Motivation

- Large composite structures are computationally expensive
  - Multiple materials – glass or carbon reinforced polymers (GFRP or CFRP)
  - Various material orientations
  - Homogenization and/or shell elements reduce cost
- Flaws occur in composite structures
  - Will the flaw begin to grow under loading conditions?
  - Account for uncertainty when specifying inspection requirements.
- Modeling delamination failure add complexity and cost
  - Increased detail needed
  - Cohesive Zone (CZ) elements

Background – Modeling Residual Stresses

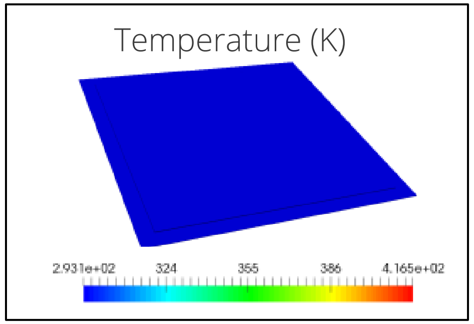
Simplified thermal strain based approach
- Lower experimental and computational cost
- Augmented with the stress-free temperature
  - Indicates when thermal strains should develop
  - Accounts for polymer shrinkage

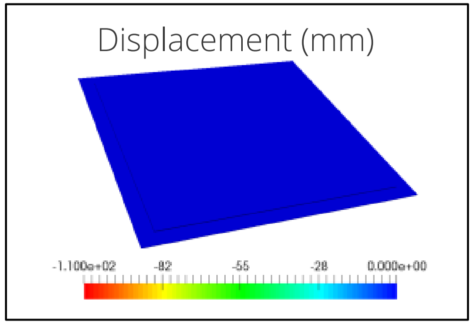
Approximated composite curing cycle in two consecutive simulations:

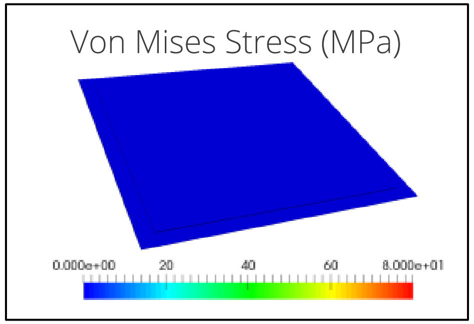
1st Simulation
- Composite is uncured, compliant, isotropic
- Isothermal heating from ambient to stress-free temperature
- Update reference configuration

2nd Simulation
- Composite material is “activated” with room temperature, orthotropic material properties
- Isothermal cooling from stress-free temperature to ambient
- Differential thermal strains develop and residual stresses are formed

Simulation Results

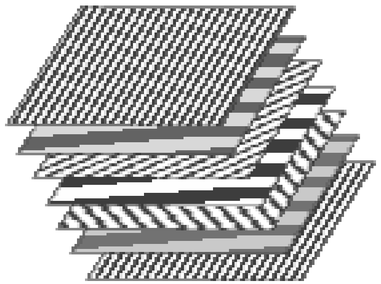






Modeling with Homogenized Composites

Composite Layup

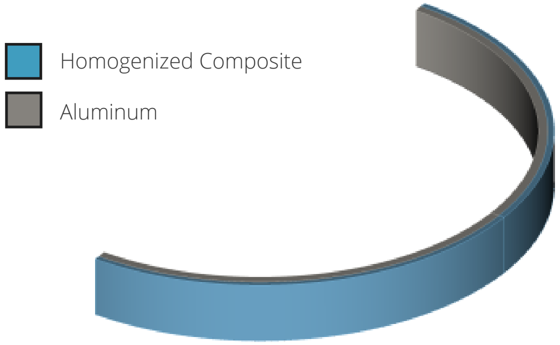


- Any number of plies
- Multiple materials
- Different orientations

Homogenize Layup

- Single material & orientation

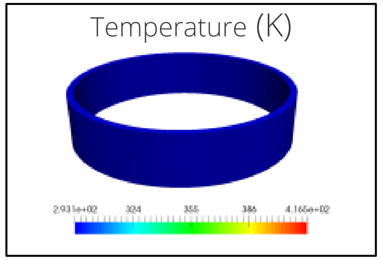
Build Model

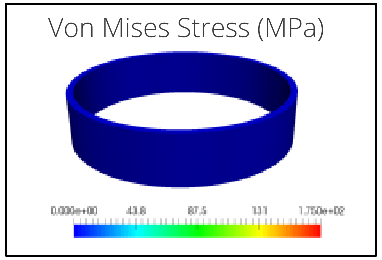


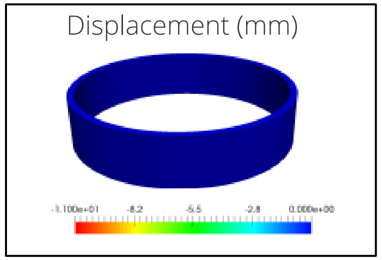
- Single composite layer to reduce model size

Uncertainties

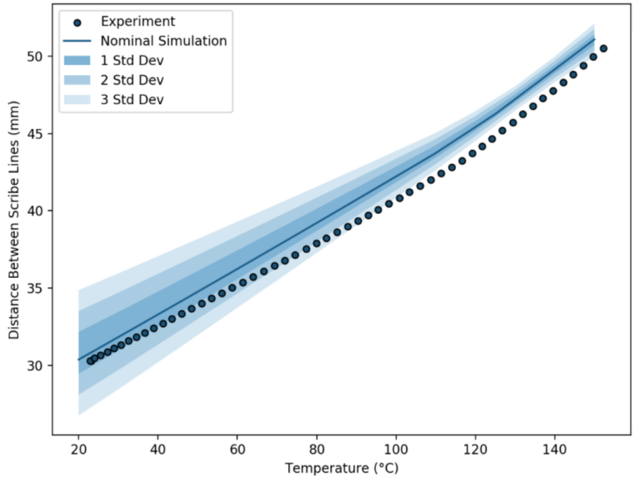
Run Simulations

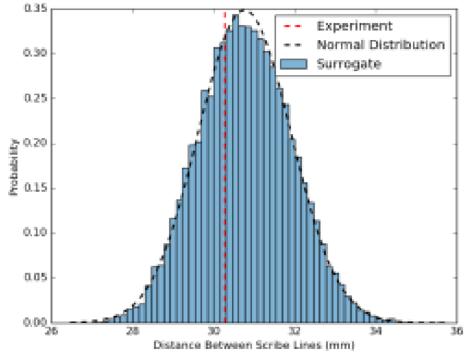






Sensitivity Studies and UQ

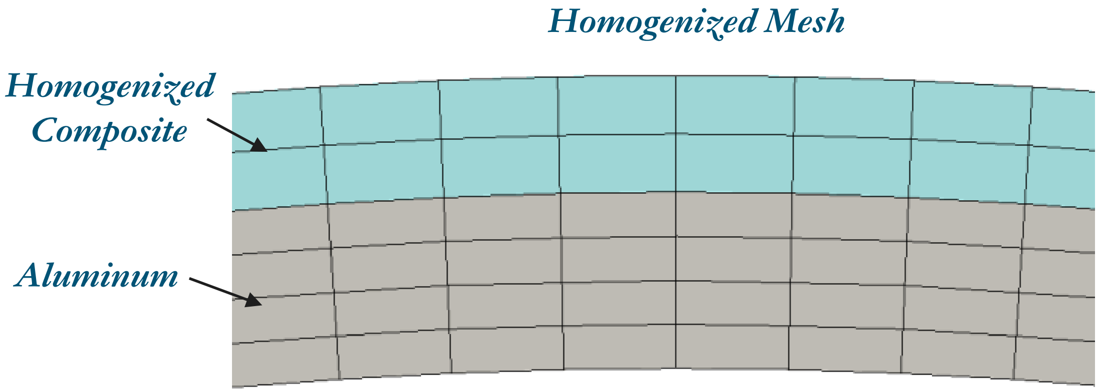


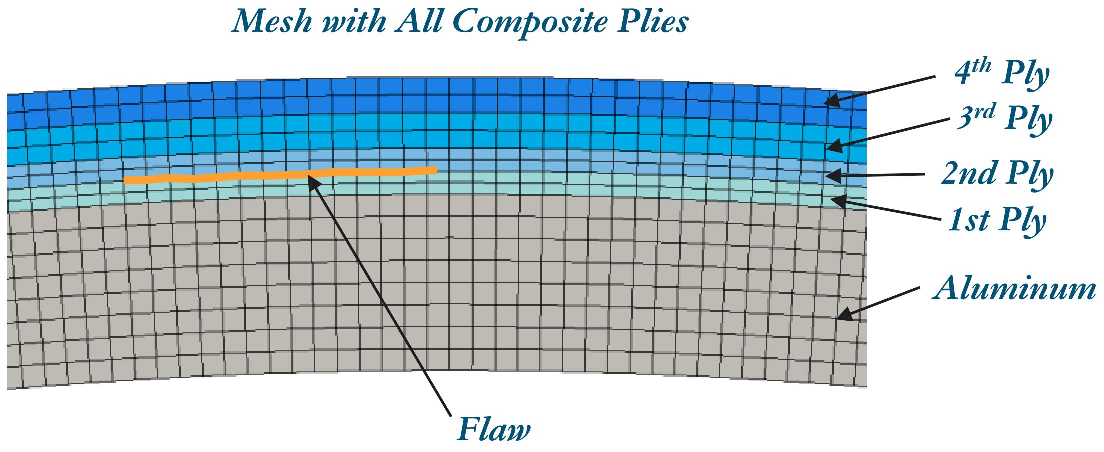


23°C
$\mu = 30.77$ *mm*
$\sigma = 1.15$ *mm*

Modeling More Detail

- Include all composite plies and cohesive zone elements
  - Each ply must be meshed
  - Cohesive zone elements require a very fine mesh





- Submodeling can make this more efficient
  - Can UQ submodels be driven by a single global model?
  - Will a multi-fidelity approach improve accuracy and efficiency?

Possible Multi-Fidelity Workflows Considered

1 – Mesh Refinement Levels

Submodel
Mesh = 0.24mm
→
Submodel
Mesh = 0.12mm
→
Submodel
Mesh = 0.06mm

Easiest to implement

2 – Homogenized Model Updating

Homogenized Model
Nominal Parameters
→ Submodel

→

Homogenized Model
Updated Parameters
→ Submodel

Modifying material parameters will cause conflicts with the submodel boundaries. The 'high fidelity' would run an updated global model to combat this.

3 – Model Size

Small Submodel
→
Large Submodel
→
Full Detail Model

Includes the full detail model to account for any loss in accuracy of the submodels. This will be the most expensive and difficult depending on the size of the full detail model.

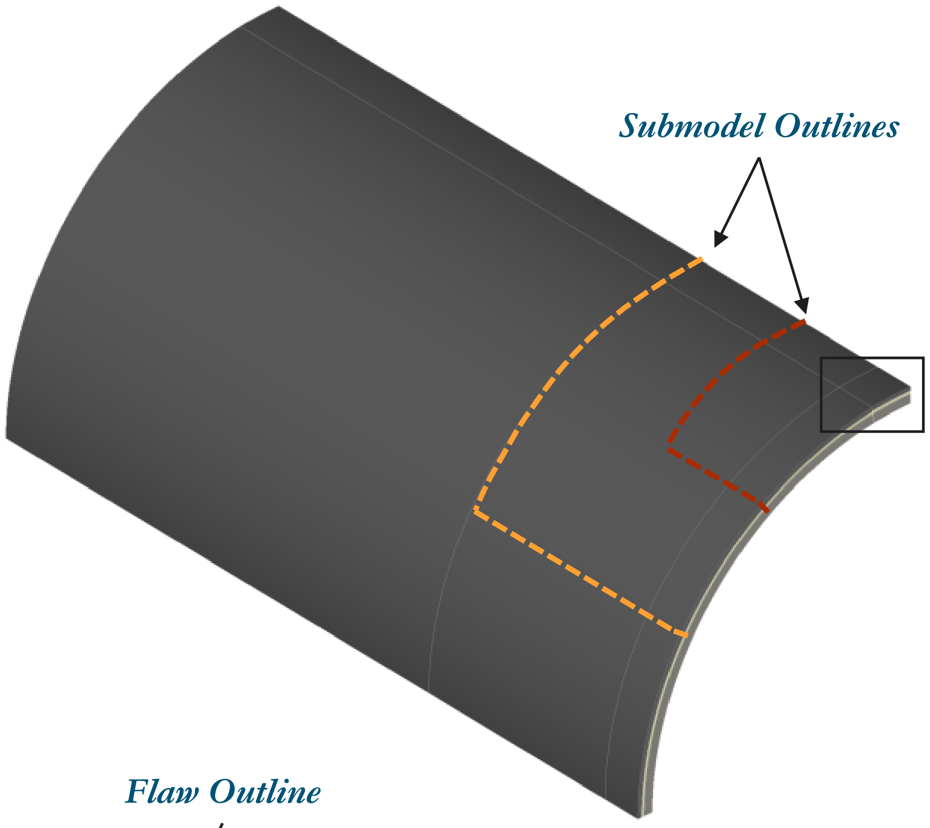
Low -------------------- Fidelity -------------------- High

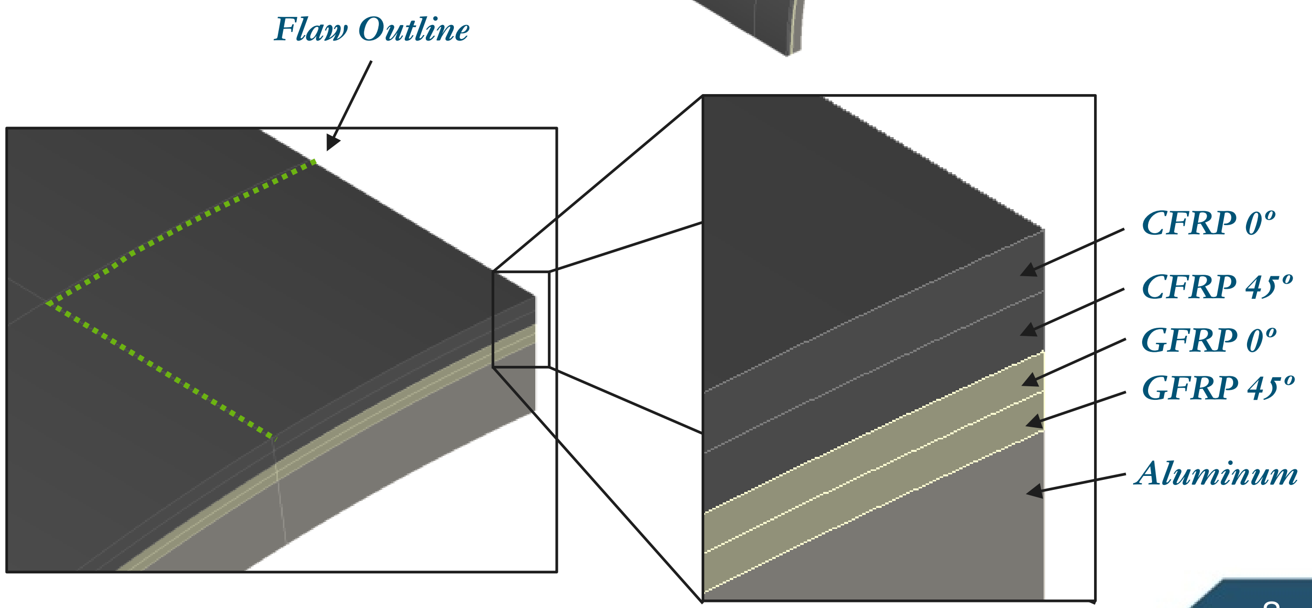
Test Problem

- Multi-material cylinder
  - [Aluminum, GFRP 45º, GFRP 0º, CFRP 45º, CFRP 0º]
  - 108mm inner diameter, 305mm long, and 3mm total thickness
  - A 16mm square flaw included at material interfaces
- Determine when the flaw begins to propagate
  - Temperature is reduced isothermally (increasing residual stress)
  - Solution is terminated once CZ elements fail
- 4 models considered
  - Homogenized
  - Full detail model
  - Large and small submodels
    - Driven by a homogenized model

Mesh Sizes

Elements Through Thickness	Homogenized	Full Detail	Large Submodel	Small Submodel
1	7K	509K	112K	26K
2	54K	3.8M	848K	199K
3	181K	12.7M	2.8M	659K
4	429K	29.8M	6.6M	1.5M

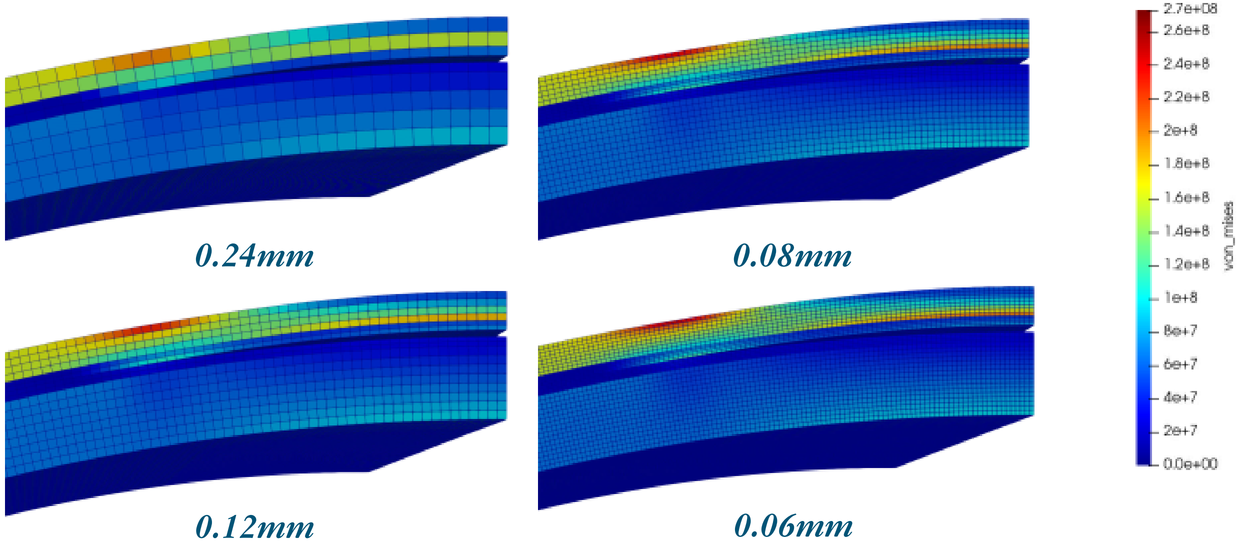




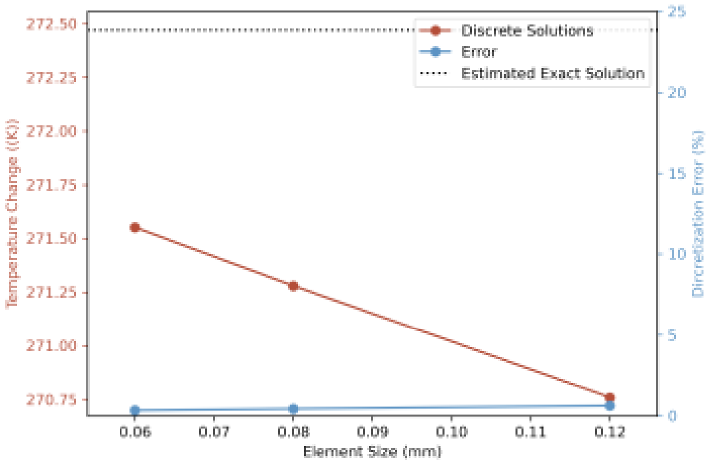
Mesh Refinement Levels

- 4 levels of refinement considered
  - Large submodel
  - Flaw positioned at GFRP-GFRP interface
- Richardson's Extrapolation
  - Low discretization error
  - CZ's may not be convergent though

Stress Field at 273.15K



Richardson's Extrapolation Results



Model Cost and Results

Element Size (mm)	Total Elements	CPUs	Run Time	Failure Temp (K)
0.24	112K	36	00:05:56	269.45
0.12	848K	216	00:37:31	270.76
0.08	2.8M	576	00:49:40	271.28
0.06	6.6M	1152	01:55:58	271.55

Small improvement in error for significant computational cost

Updating Homogenized Model Properties

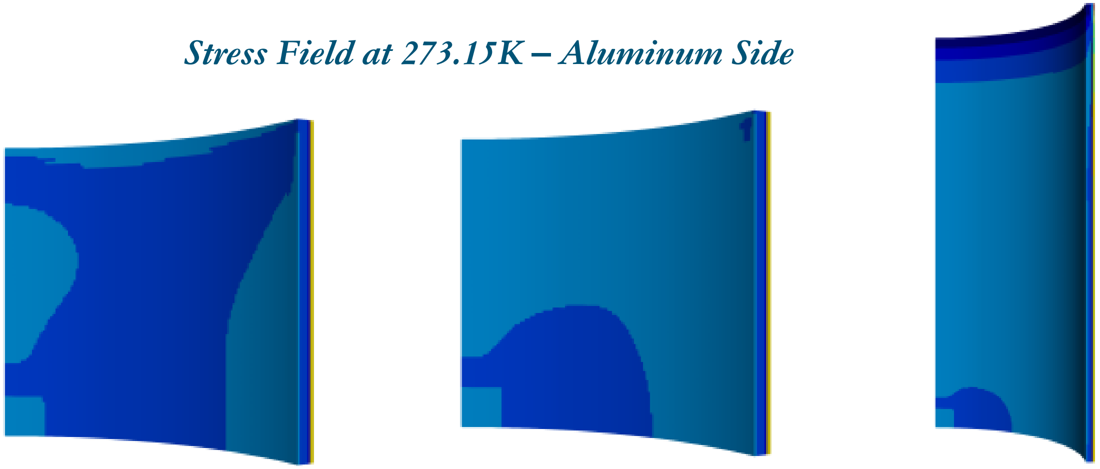
- Nominal Submodel
  - Uses pre-existing nominal homogenized results
  - ~6 min runtime on 36 cores (1 simulation)
- Updated Submodel
  - Homogenize composite properties → homogenized model → submodel
  - ~20 min runtime on 36 cores (11 simulations)
- Compared with a small UQ study
  - LHS study with known sensitive parameters
  - Differences noticeable in stress field, but no difference in average failure temperatures
  - Cylinder may be too stable of geometry
  - Failure temperature may be driven by more local effects

Model Results

Defect Location	Workflow	Average Failure Temp (K)	Difference (K)
Aluminum - GFRP	Nominal	246.19	0.01
	Updated	246.20	
GFRP-GFRP	Nominal	269.55	0.03
	Updated	269.52	
GFRP-CFRP	Nominal	287.21	0.62
	Updated	287.83	
CFRP-CFRP	Nominal	256.25	0.05
	Updated	256.30	

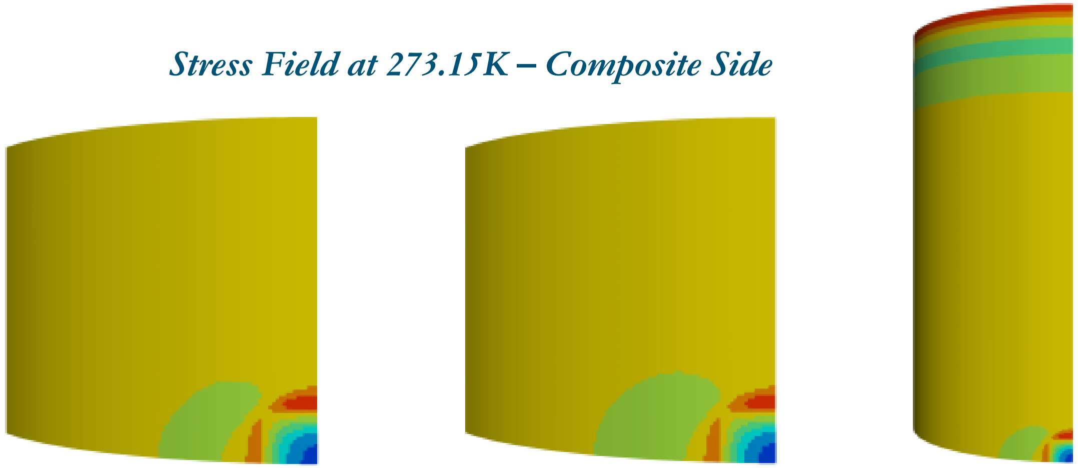
No improvement for additional computational cost

Stress Field at 273.15K – Aluminum Side



Nominal ***Updated*** ***Full***

Stress Field at 273.15K – Composite Side



Nominal ***Updated*** ***Full***

Model Size

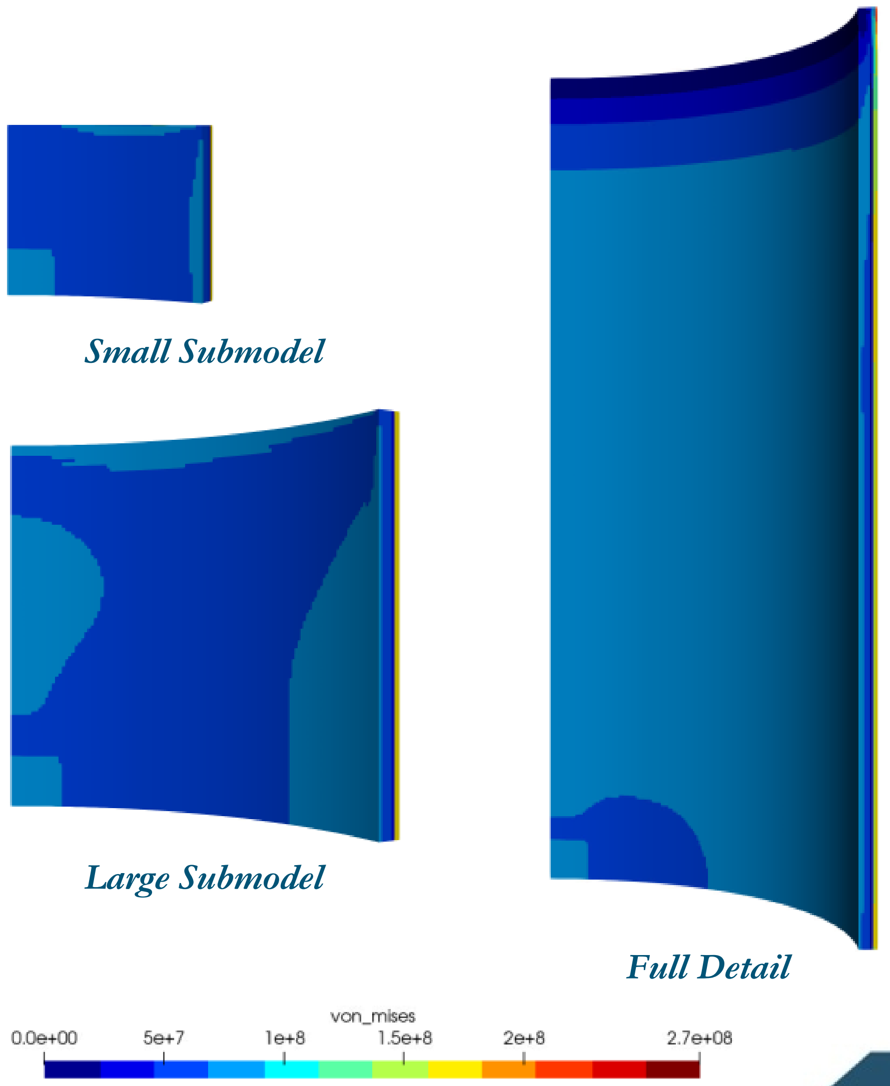
- Compared 3 model sizes with the same small UQ study
  - More significant boundary effects in small submodel
  - The full detail model shows significant differences
    - Interfaces with greater stiffness and CTE mismatch have greater differences
  - Submodels appears to follow same trends

Model Results

Defect Location	Model	Average Failure Temp (K)	Difference to Full Detail (K)
Aluminum - GFRP	Small Submodel	245.73	-12.33
	Large Submodel	246.19	-11.87
	Full Detail	258.06	-
GFRP-GFRP	Small Submodel	267.80	-2.18
	Large Submodel	269.52	-0.46
	Full Detail	269.98	-
GFRP-CFRP	Small Submodel	285.36	22.21
	Large Submodel	287.21	24.06
	Full Detail	263.15	-
CFRP-CFRP	Small Submodel	-	-
	Large Submodel	256.25	4.56
	Full Detail	251.69	-

Submodels may not be capturing the same behavior as the full detail model, but capture the same trends

Stress Field at 273.15K – Aluminum Side



Conclusions

- Submodels can significantly reduce the cost
  - CPU time reduced ~100x
  - Be mindful of boundary size
- Compared 3 approaches that could be used for multi-fidelity
  - Mesh refinement showed minimal change
  - Updating the homogenized global model show no difference
    - Its possible that local behavior dominates the flaw behavior
  - Model Size
    - Full detail models show different behavior than submodels at multi-material interfaces
    - Submodels follow same trends as the full detail model
- Future Work
  - Use model size as basis for a multi-fidelity UQ study of flaw failure temperatures
  - Validation of flaw failure due to residual stress

Questions?