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Independent mesh method and RX-FEM modeling of 3d interlock woven composites with open hole

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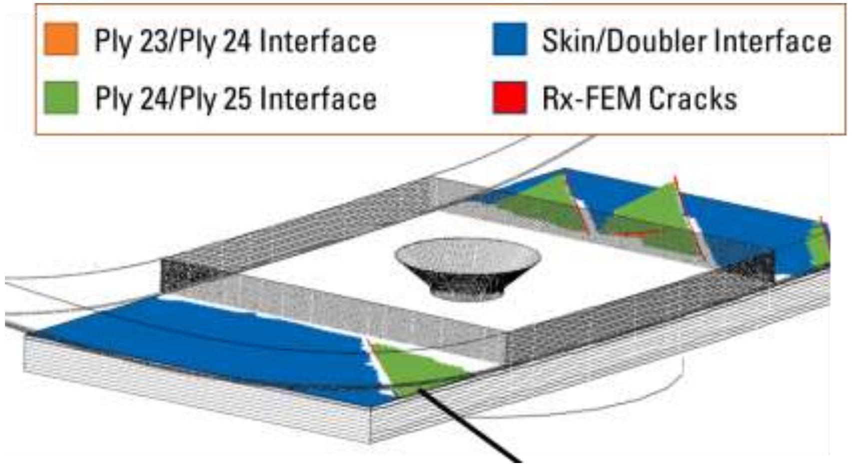
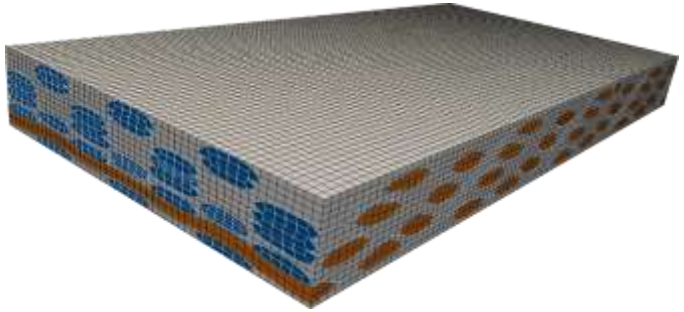
Analysis Methods

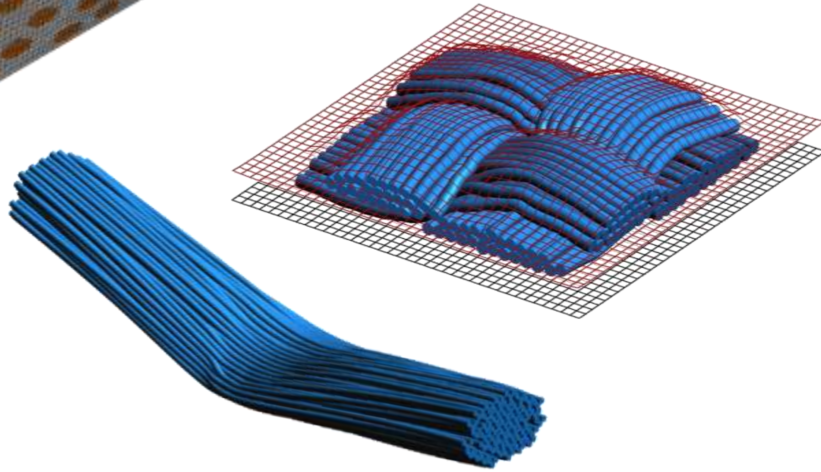
Hoos et al, ASC 2019



- **BSAM:**
  - 3D FE damage modeling code developed for unidirectional & textile composites
  - Discrete intra-ply matrix cracks (Rx-FEM Cracks)
  - Discrete inter-ply delamination (CZM)
  - Progressive fiber fracture (CDM)
  - Catastrophic fiber fracture (CFV)

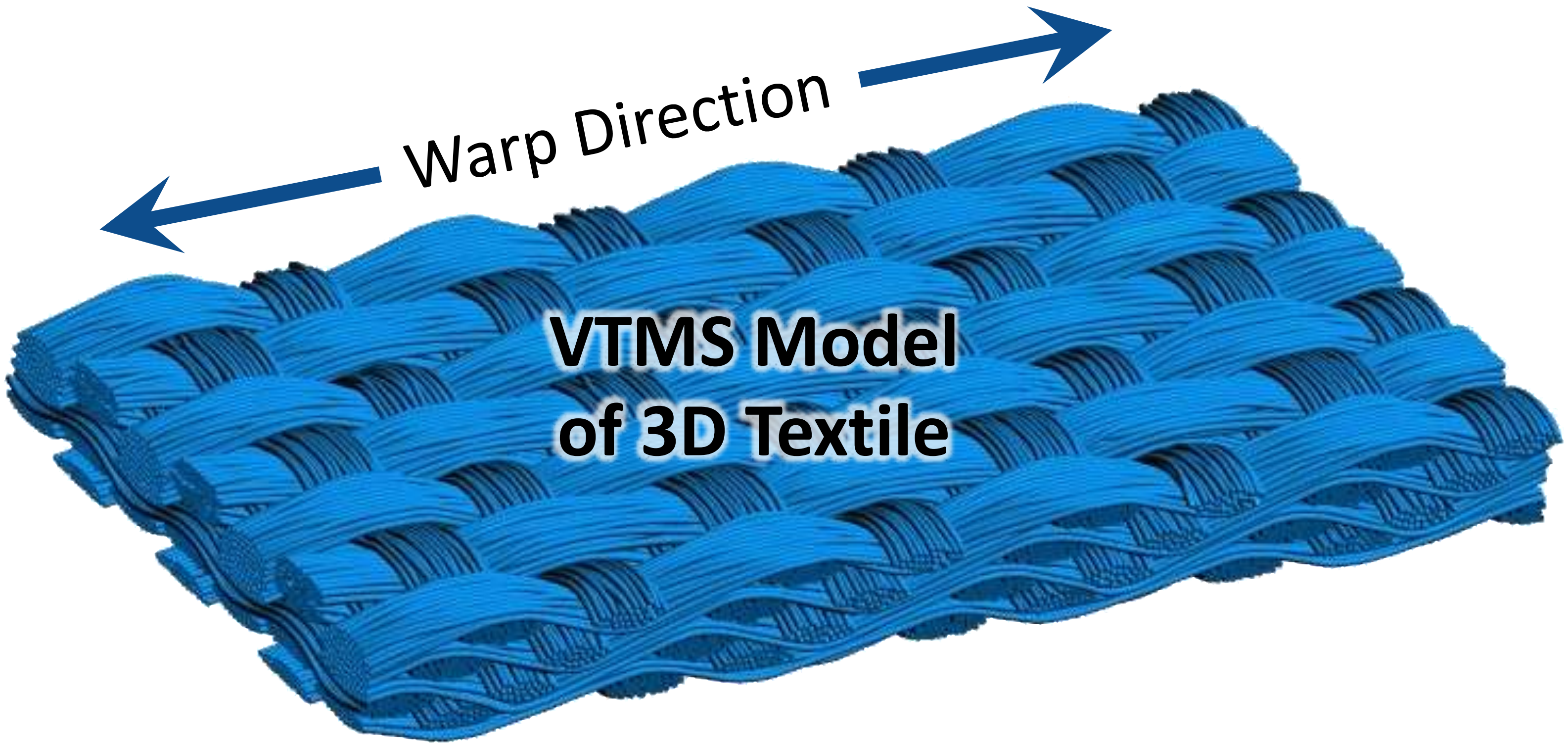


- **Independent Mesh Method (IMM):**
  - FE implementation for complicated textile geometry stress and failure analysis
  - Avoids difficult meshing situations



- **Virtual Textile Morphology Suite(VTMS):**
  - Mechanistic simulation of textile processing
  - Linkage to IMM and BSAM

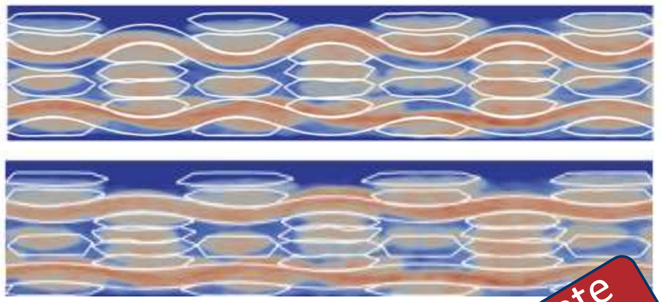
Determining Weave Architecture



Variation of Weaving Tension
(Warp-to-Fill)

1:1

1:6



	E_{11}	E_{22T}
1:1 (% Error)	-10.3	21.5
1:6 (% Error)	0.52	-1.42

accurate moduli

Determining Tow Properties

Initial Assumptions

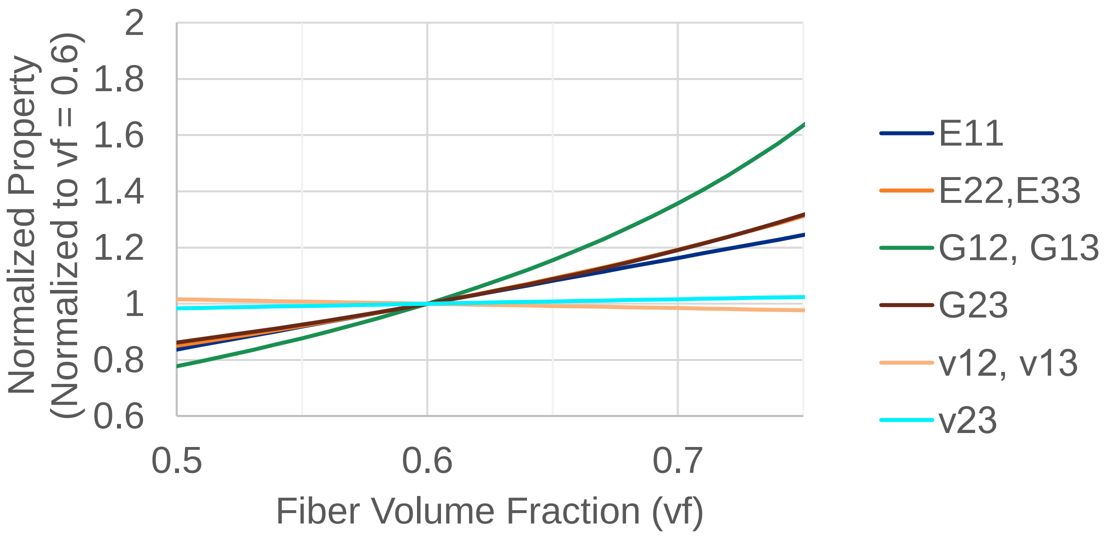
- Tow properties are tape properties with orientation that follows tow geometry
- Warp tows and fill tows have different FVF, but all tows in the same direction have same FVF
- FVF in the tow does not change with changing cross-sectional area

All tow elastic and strength properties scaled.

Fracture properties are not scaled.

Using Chamis's Equations + Experiment

- Chamis provides straightforward method for scaling strength for tape based on FVF and constituents
- However, Chamis's equations are ideal and experiment data differs
- **Concept**: use Chamis's equations with results normalized at experiment FVF to scale experiment values

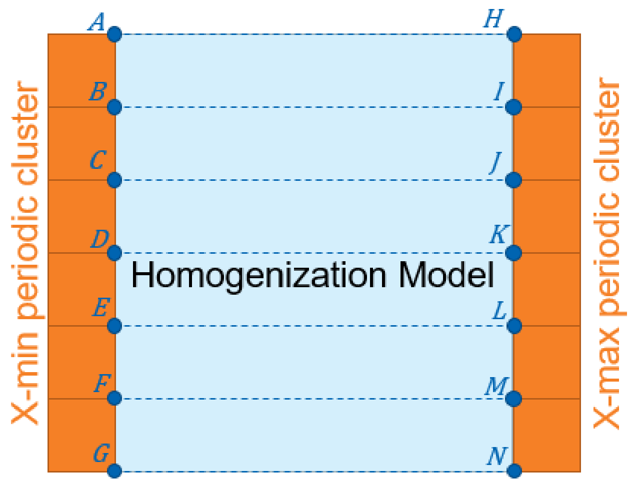


Chamis, "Simplified composite micromechanics equations for hygral, thermal and mechanical properties", 1983. NASA-TM-83320.

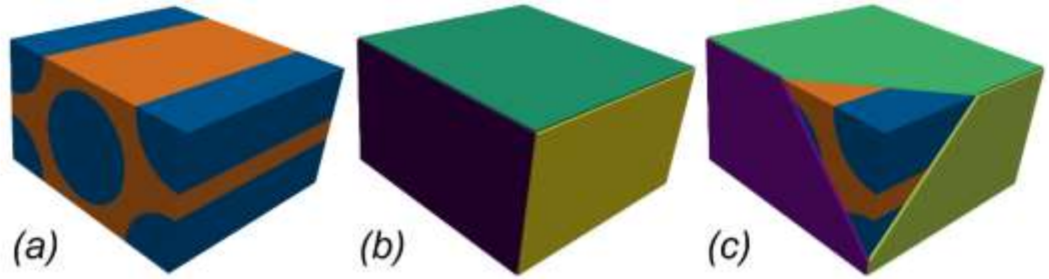
Elastic Homogenization

Periodic Cluster Method (PCM)

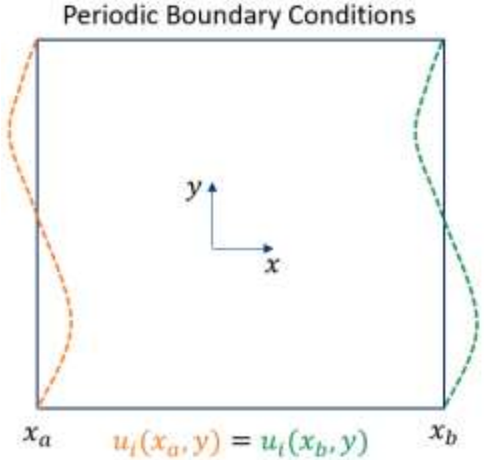
1. Add clusters to all 6 sides of model and tie displacement on opposing faces together
2. Connect added clusters to model using penalty connection
3. Apply displacement shift to one side of model to introduce strain
4. Repeat for six different loading cases and then homogenize results

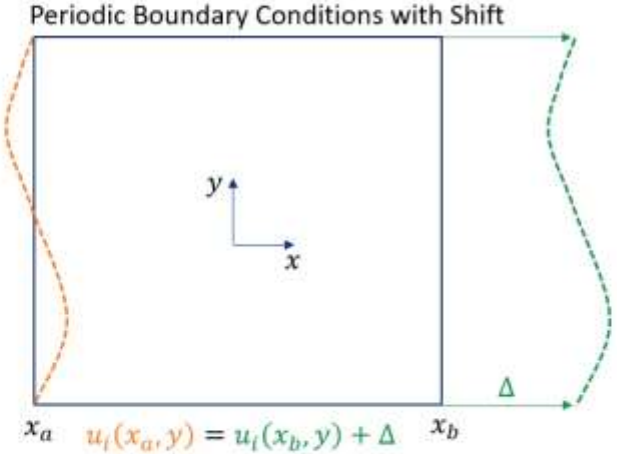


$$u_{Ai} = u_{Hi}$$
$$u_{Bi} = u_{Ii}$$
$$u_{Ci} = u_{Ji}$$
$$u_{Di} = u_{Ki}$$
$$\dots$$
$$u_{Gi} = u_{Ni}$$



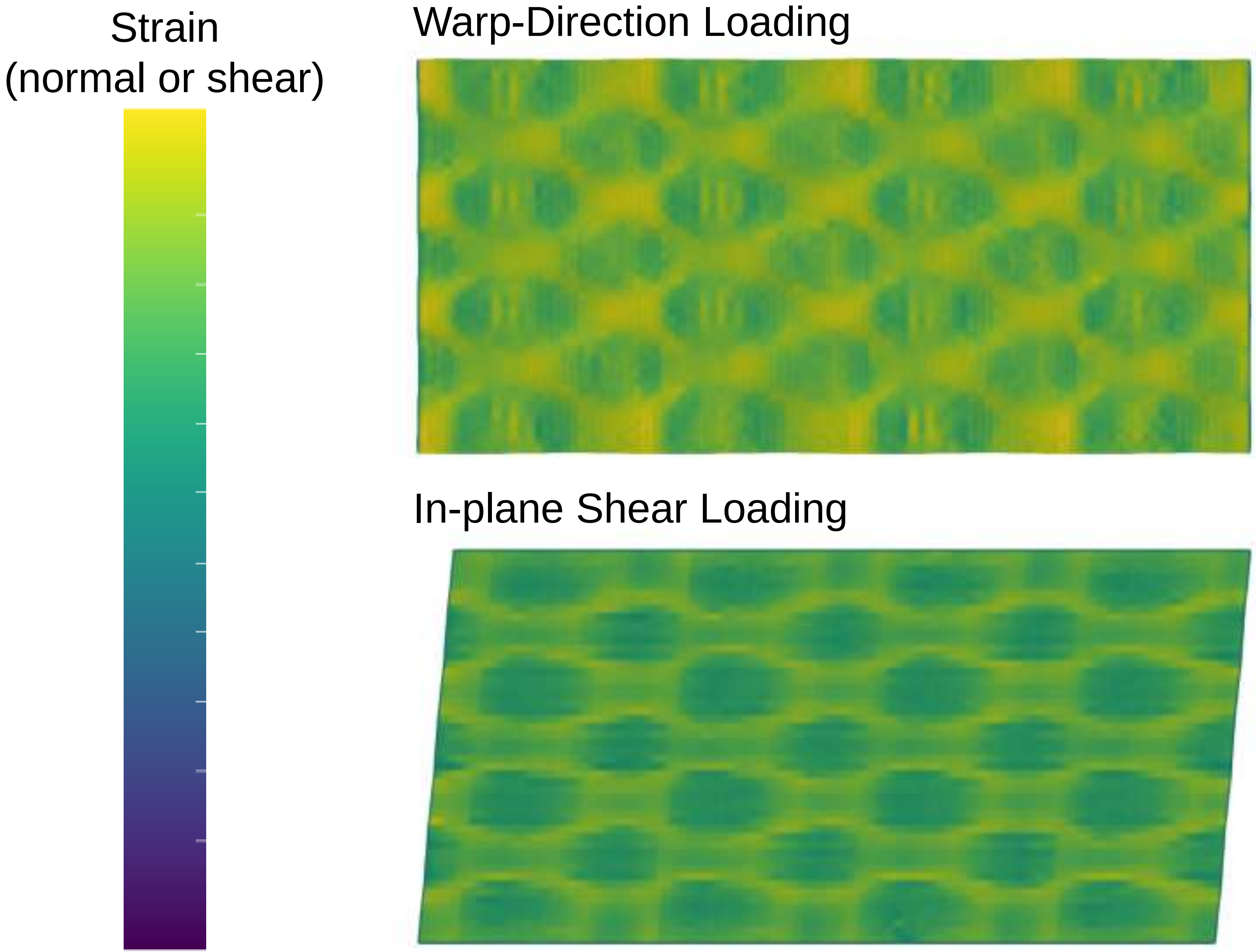
Note: the above (a-c) are a conceptual drawing, not the textile architecture considered herein





Validation: Results

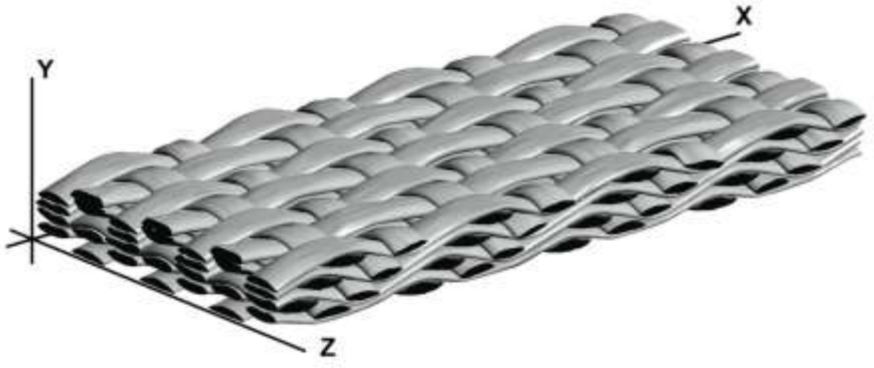
Property	Error from Experiment
E_{11}	0.5%
E_{22}	1.8%
v_{12}	-44.3%
G_{12}	-9.7%



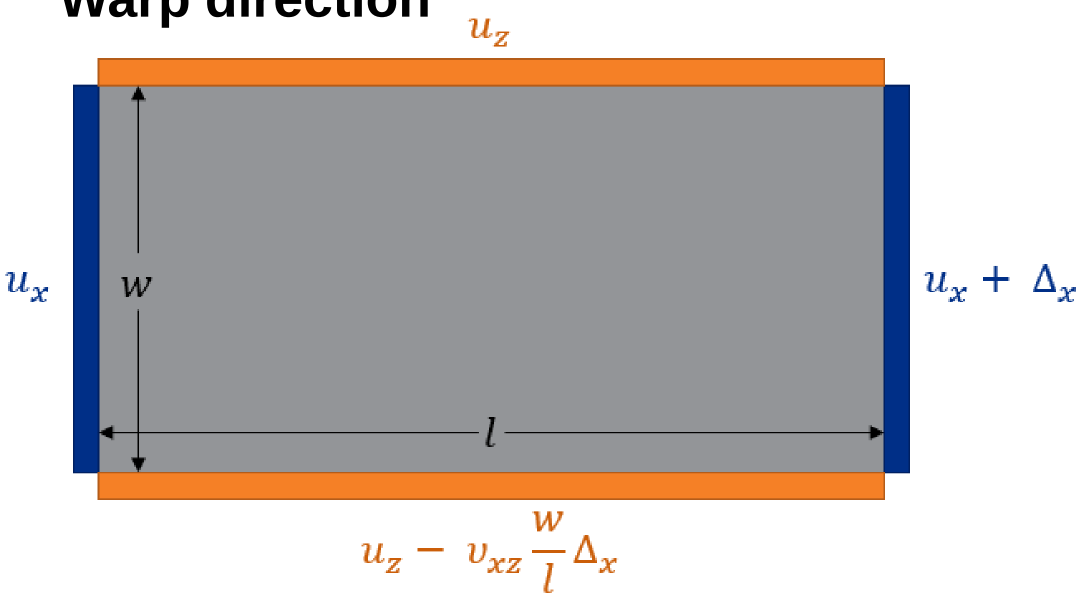
Unnotched Strength Prediction

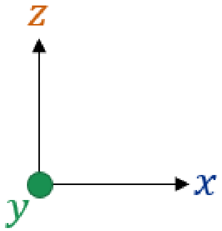
Unnotched Strength Prediction

- Use PCM, removing periodicity in 1 or 2 directions, depending…
- Fill and Warp test coupon width: 25 mm
- Warp direction:
  - 11 mm wide → periodicity in x and z directions
  - Width much smaller than test specimen
- Fill direction:
  - 22 mm wide → periodicity in z direction only
  - Width close to test specimen
- Through-thickness: no periodicity

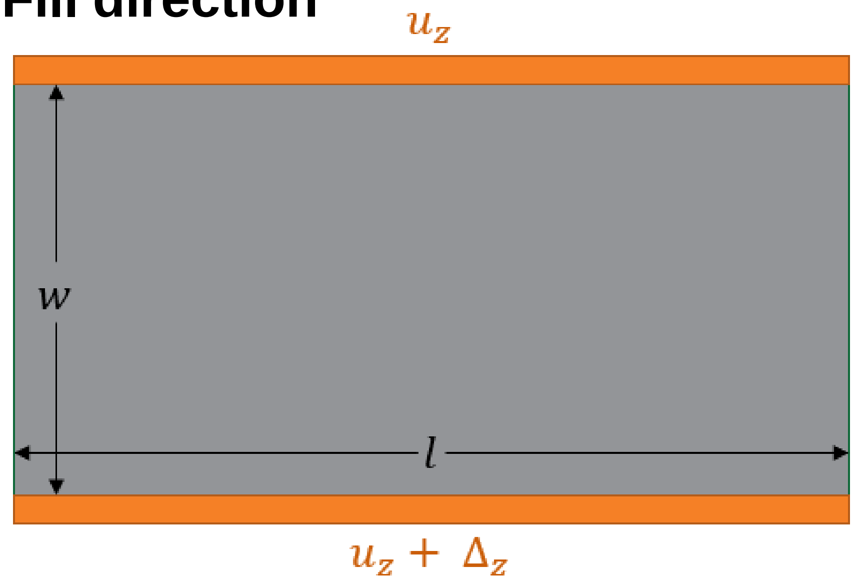


Warp direction

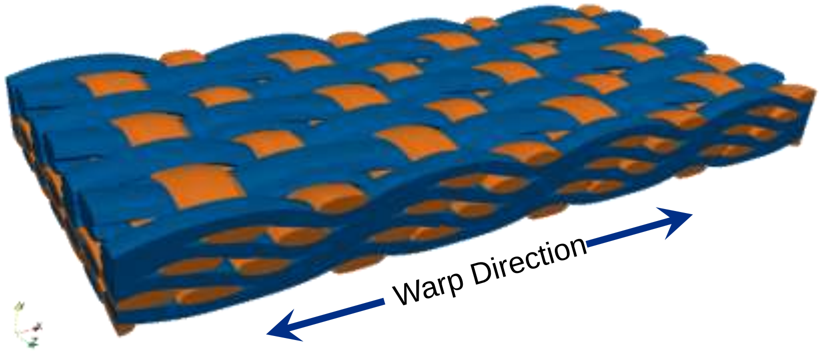


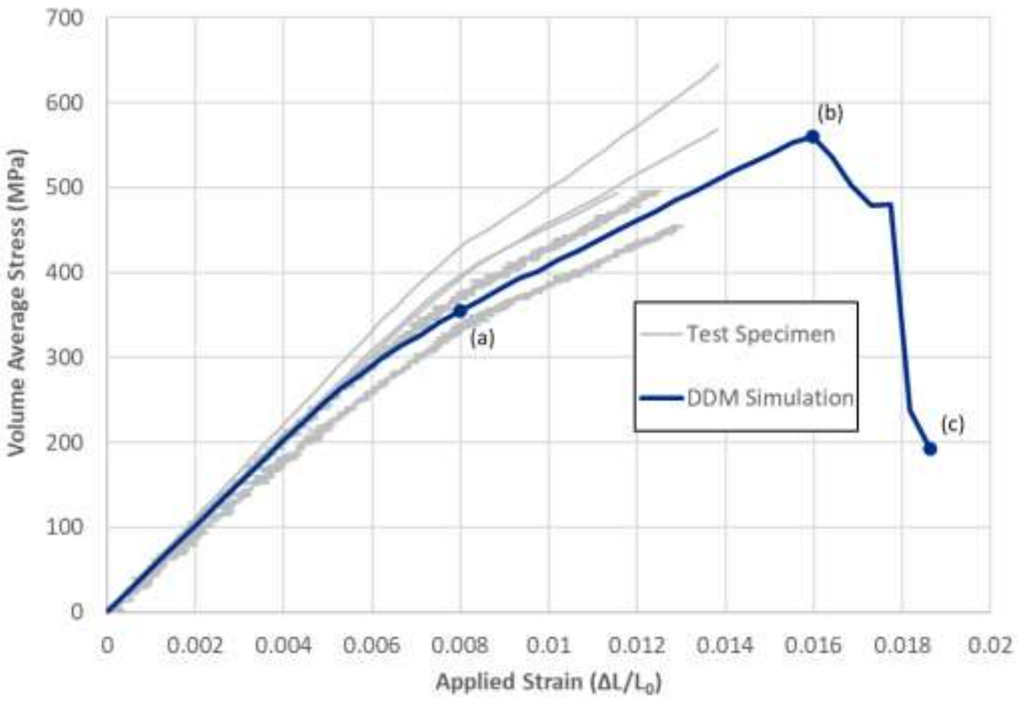


Fill direction

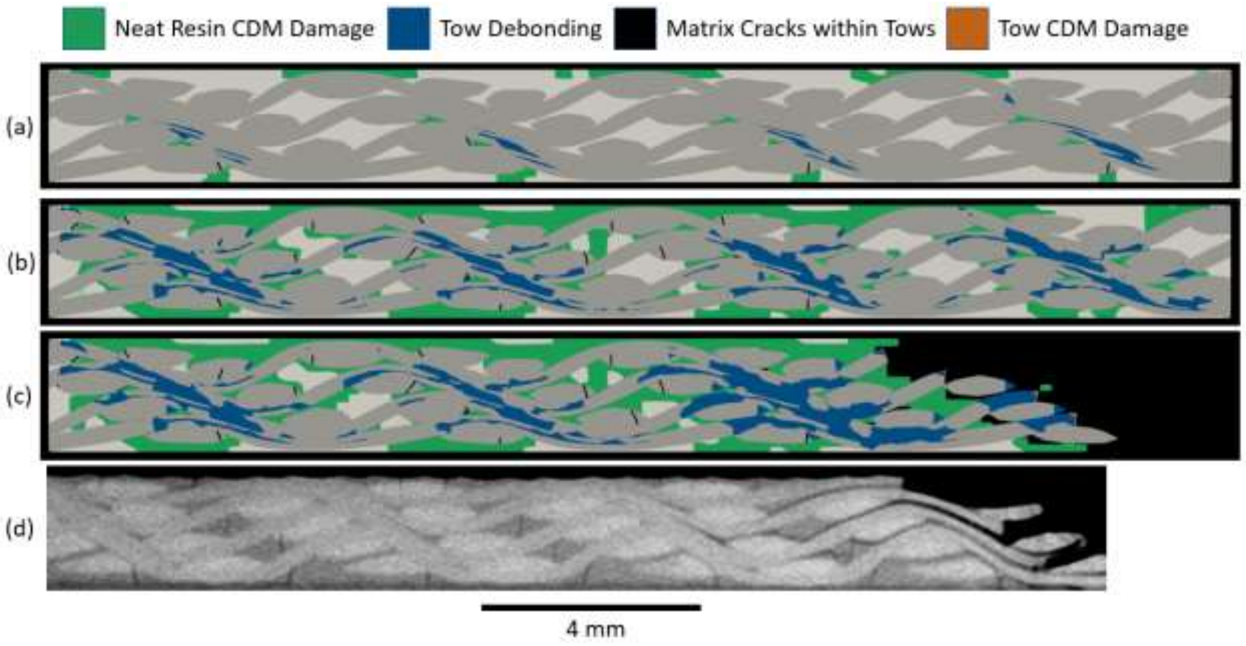


Unnotched Warp Direction Tension

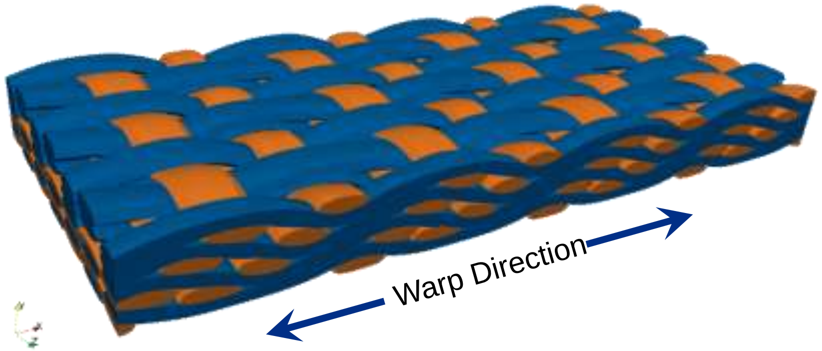


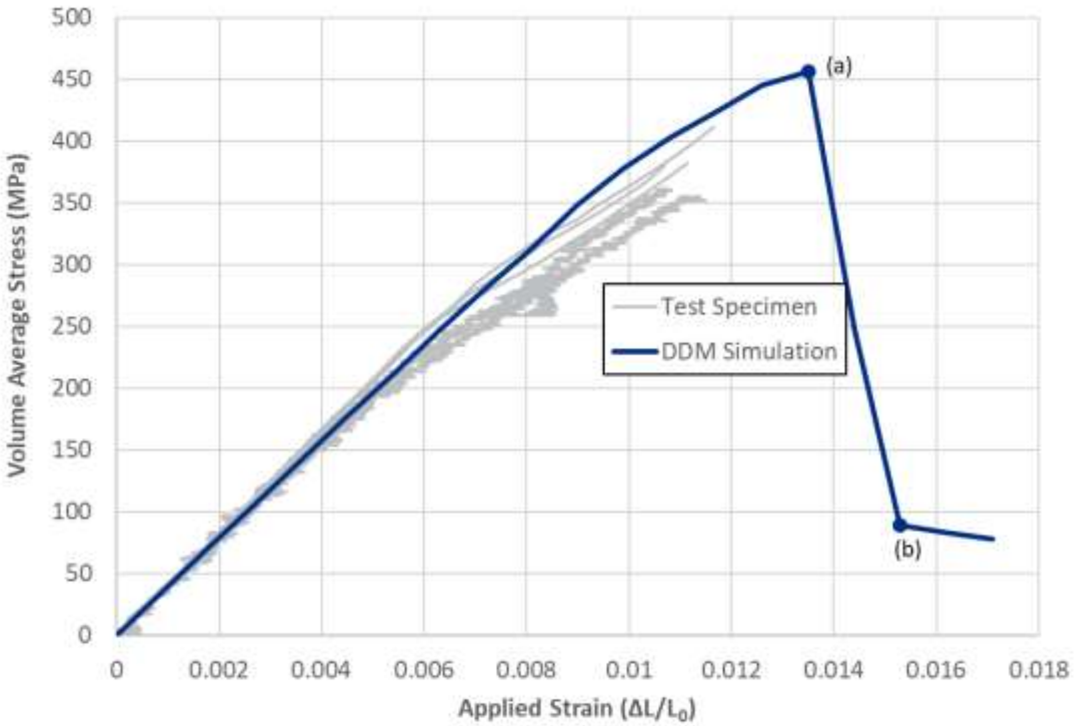


Warp Loading Simulated vs X-ray CT Damage

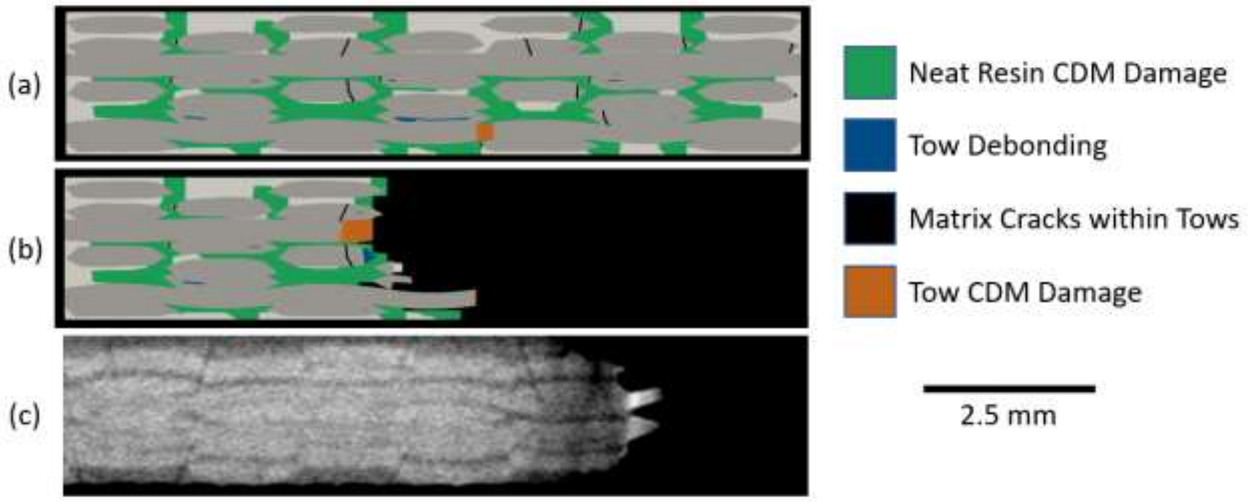


Unnotched Fill Direction Tension



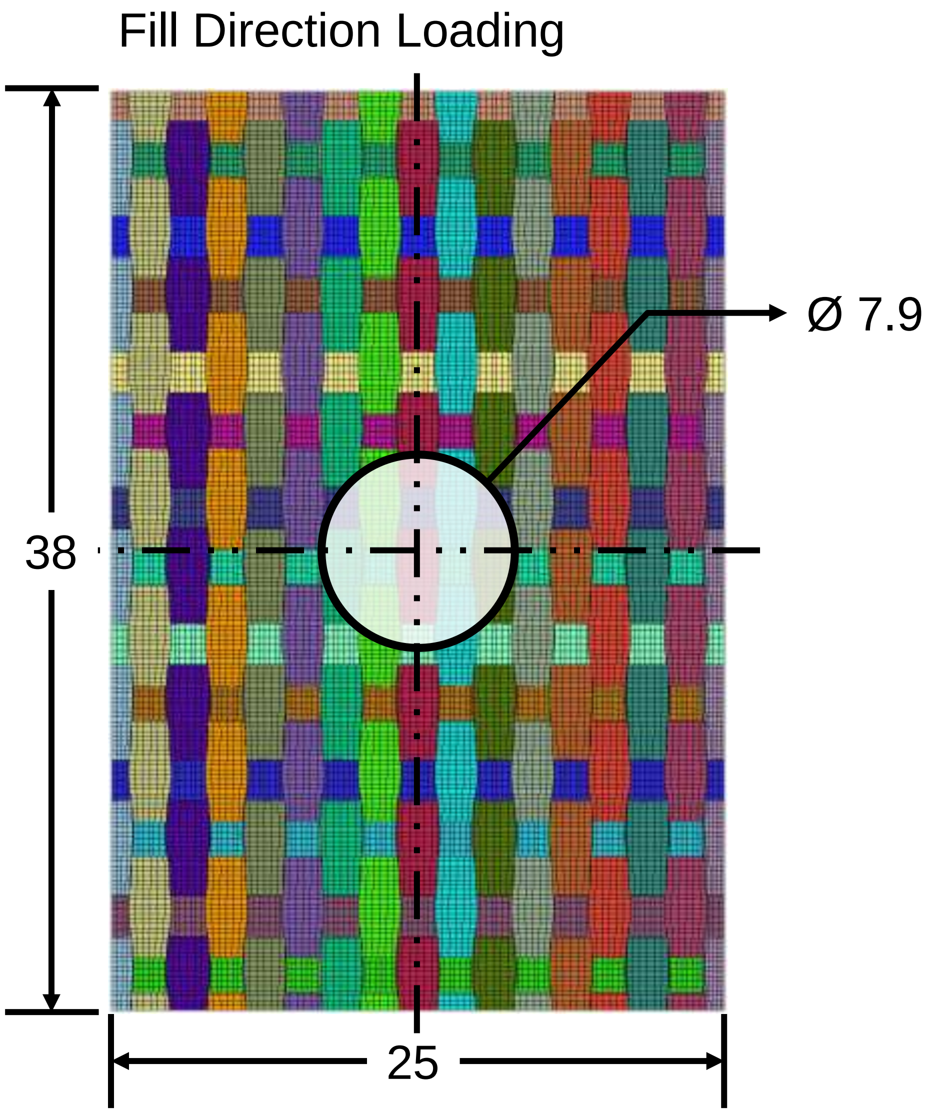


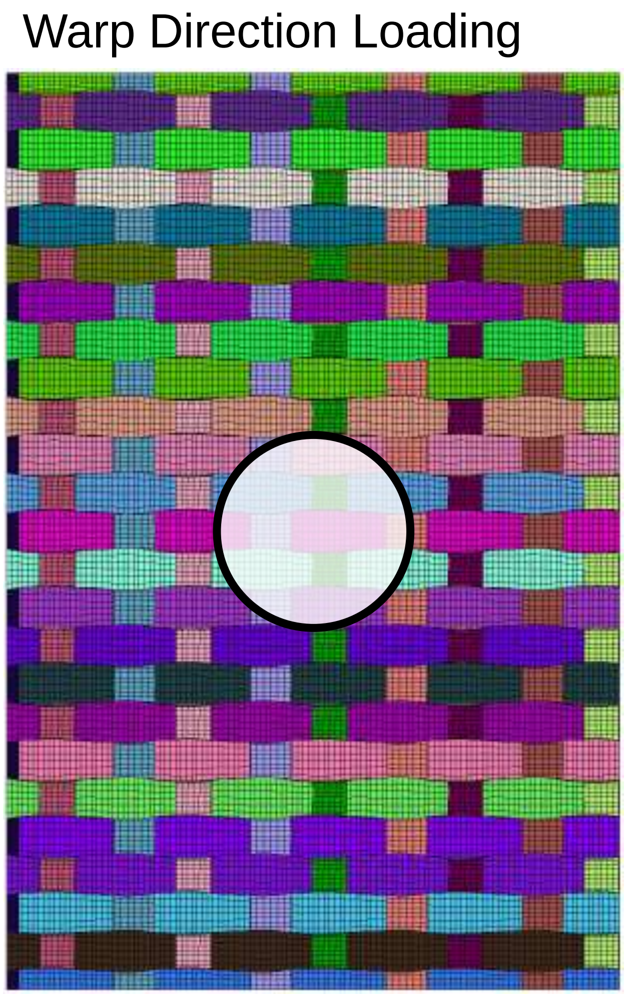
Fill Loading Simulated vs X-ray CT Damage



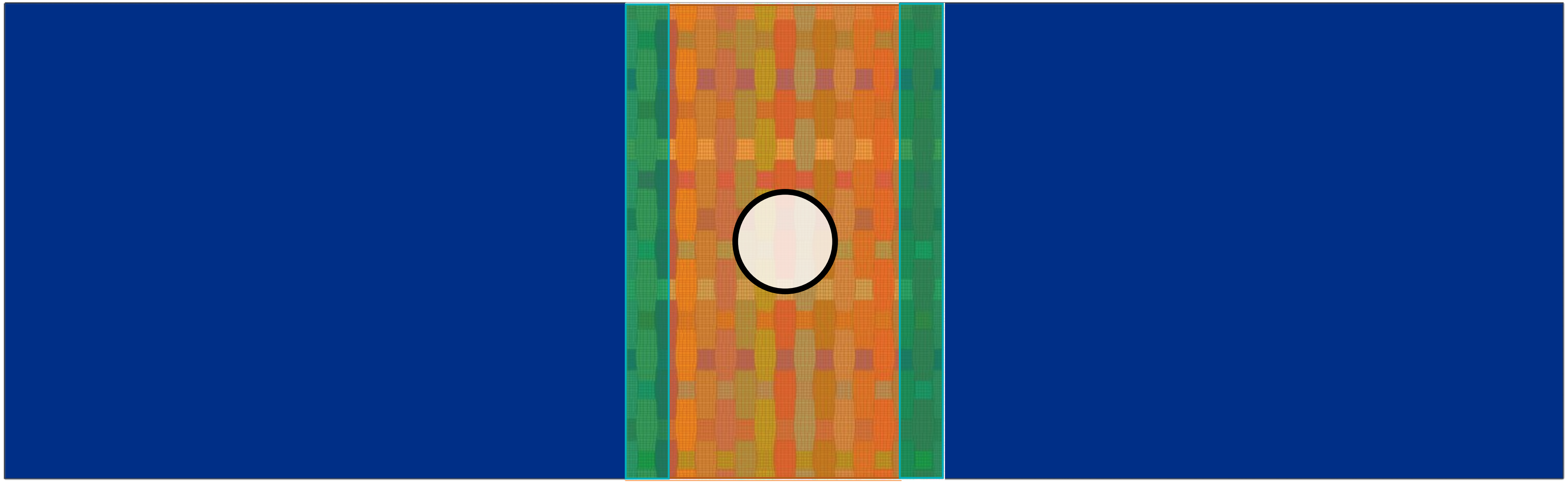
Open Hole Tension Prediction

RML2 OHT Tow Models





RML2 OHT Property Assignment and Damage



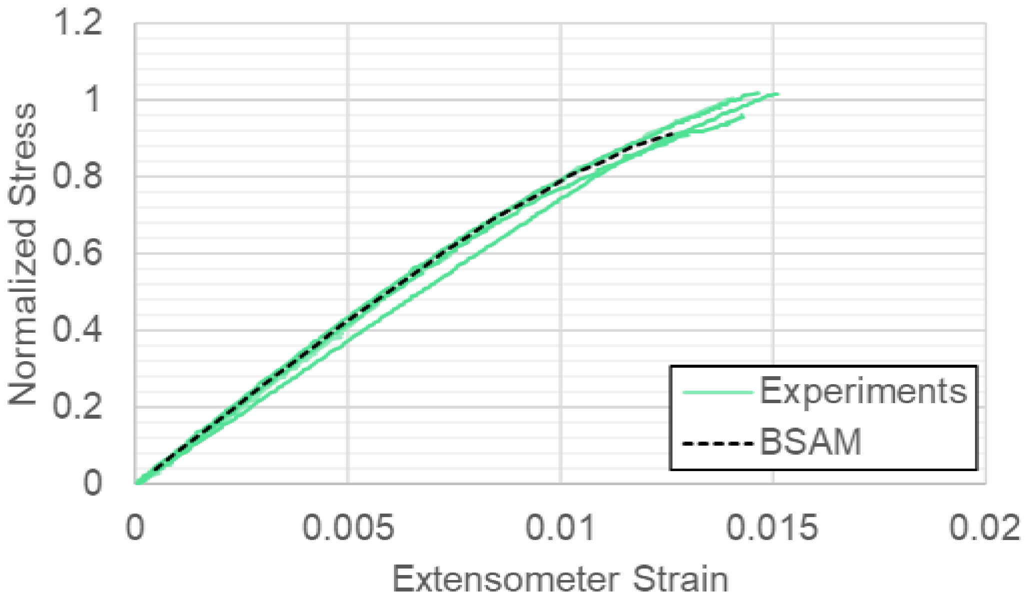
Macro-level modeling; homogenized properties; No damage

Meso-level modeling; matrix and tows modeled separately; No damage

Meso-level modeling; matrix and tows modeled separately; Damage enabled

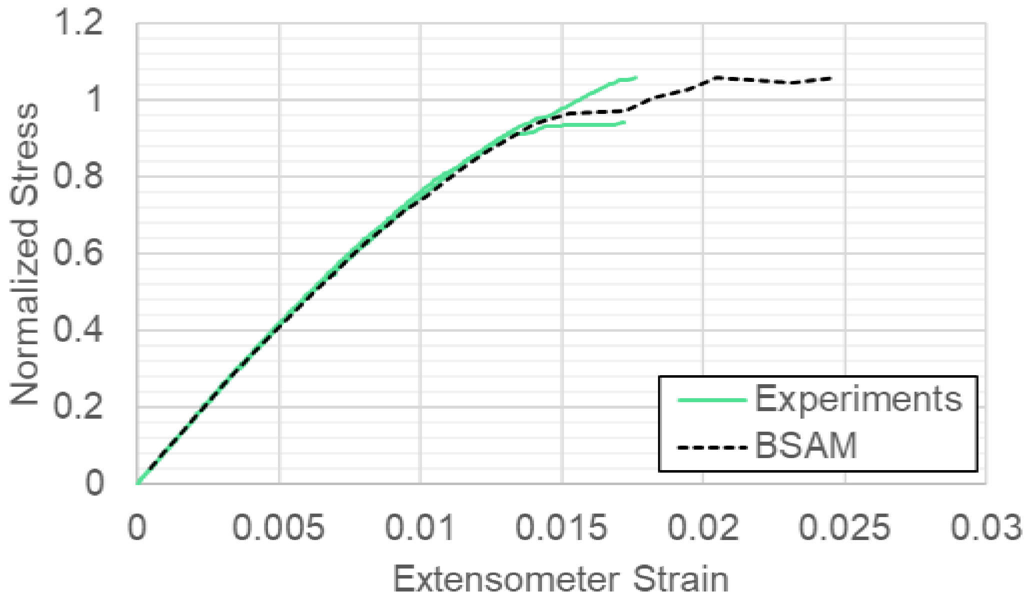
OHT Stress-Strain Results

Fill-Direction Loading



n = 4	Error from Experient
Modulus (1000-3000 µe)	2.9%
Strength	-8.9%

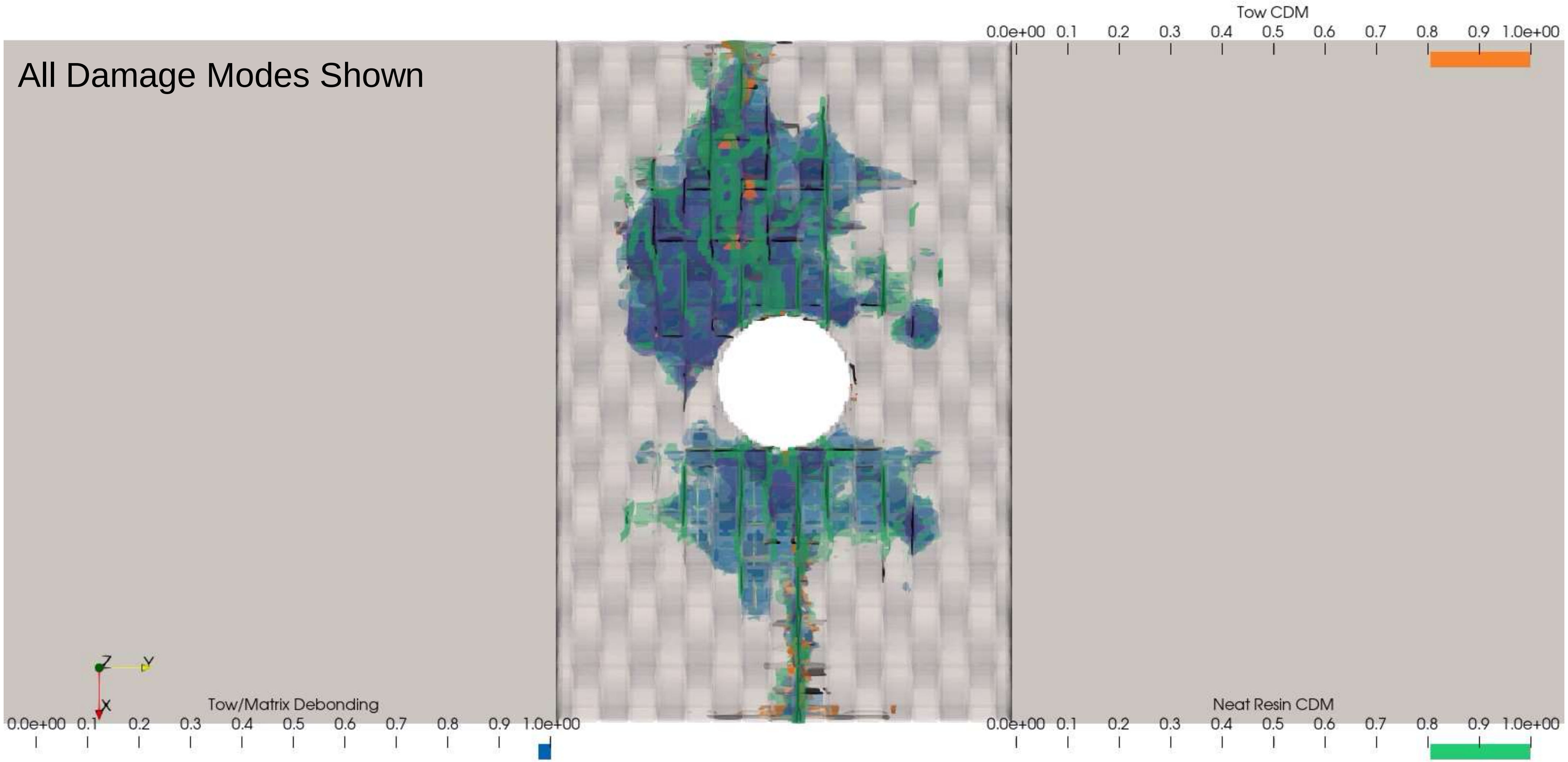
Warp-Direction Loading



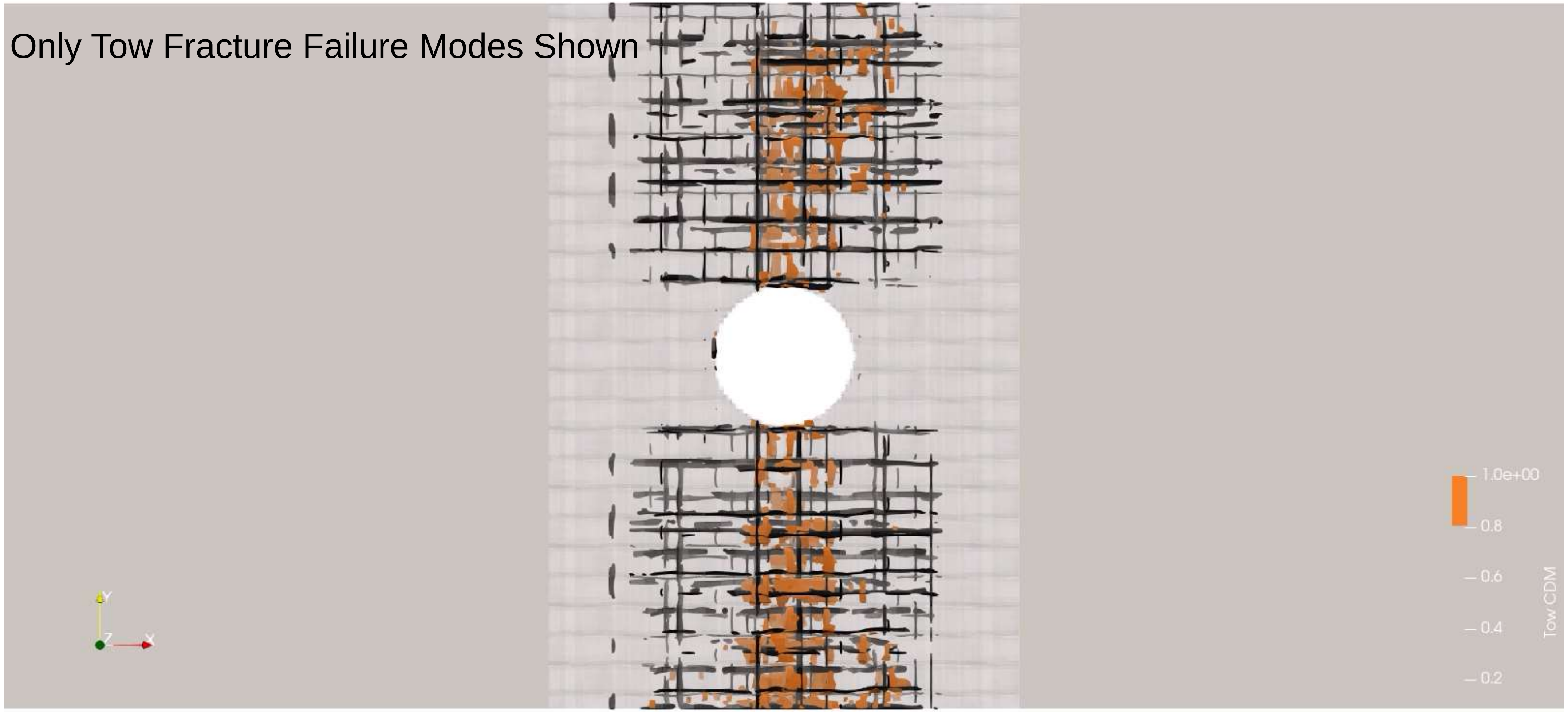
n = 2	Error from Experient
Modulus (1000-3000 µe)	-4.4%
Strength	5.9%

Note: these predictions were blind with no knowledge of experimental results

Fill Direction Damage Progression



Warp Direction Damage Progression



Conclusions & Future Work

Conclusions

- Processing to Performance simulation procedures yielded good results
  - Morphology developed successfully with VTMS
  - Homogenized properties were calculated using PCM.
- Unnotched tension predictions
  - Warp ~ 6%
  - Fill ~ 22%
- Open Hole Tension
  - Warp ~5% blind prediction vs experiment
  - Fill ~9% blind prediction vs experiment

Future Work

- Open Hole Compression using OHT models
- Processing-induced flaws
- Bonded joining

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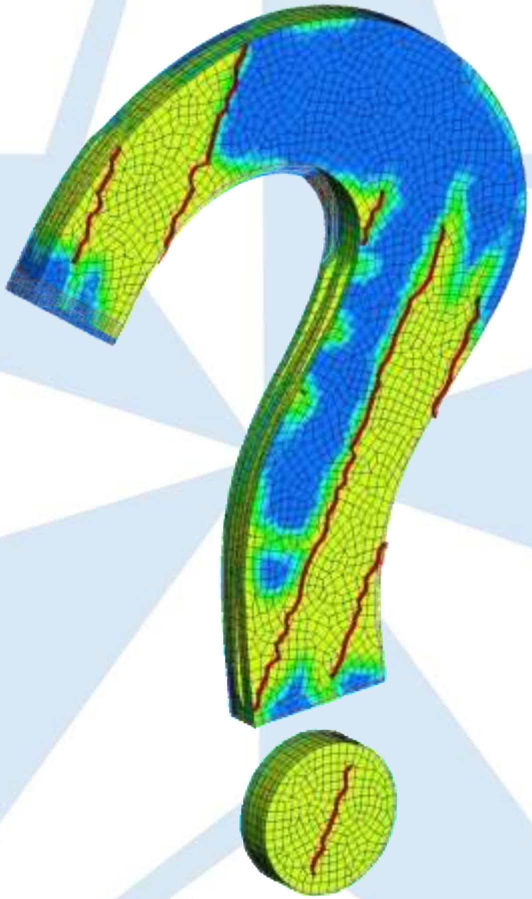
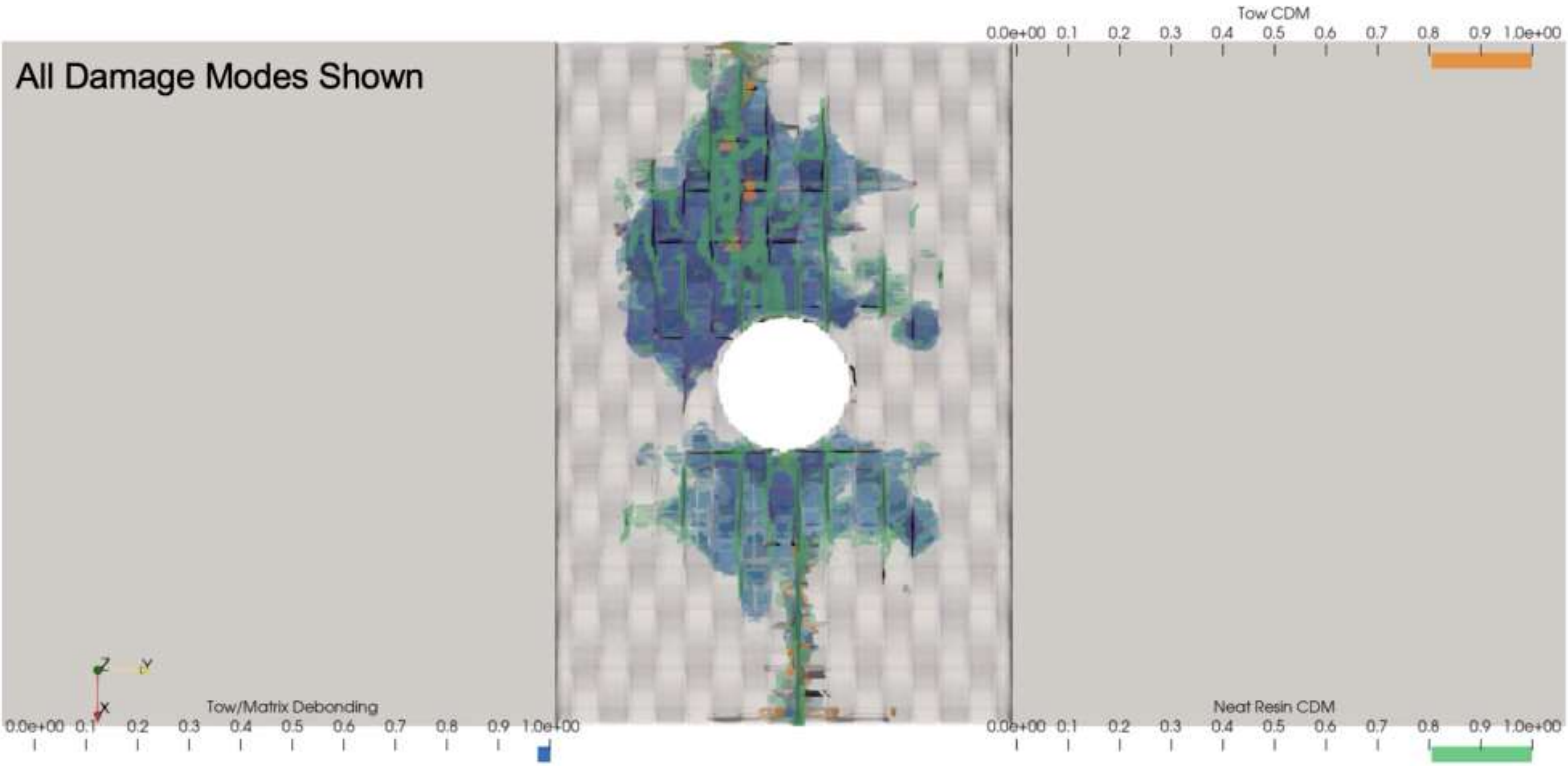
Questions?



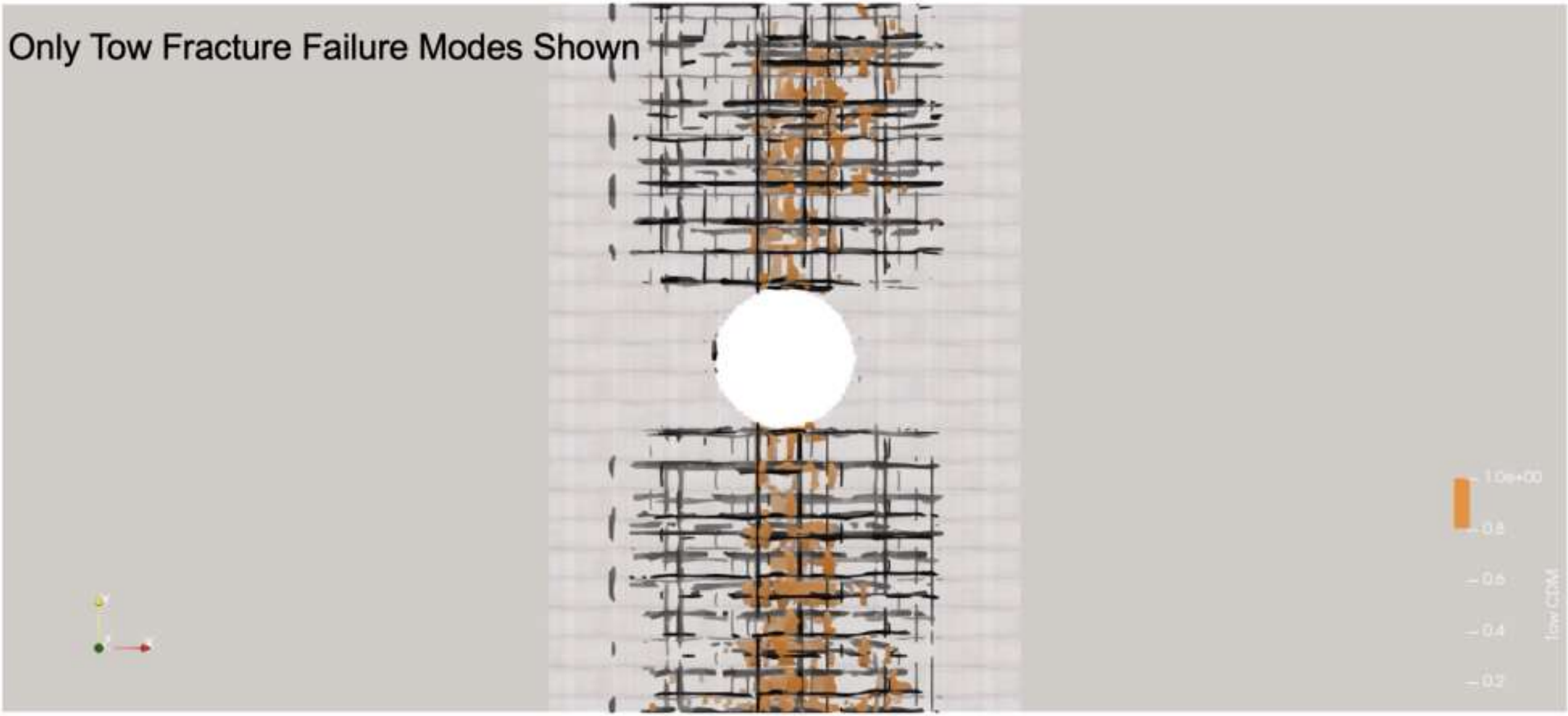
This work was supported by Southwest Research Institute of San Antonio, TX, subcontract to the University of Texas at Arlington under AFRL contract FA8650-19-C-5213.

Additional Charts

Fill Direction Damage Progression

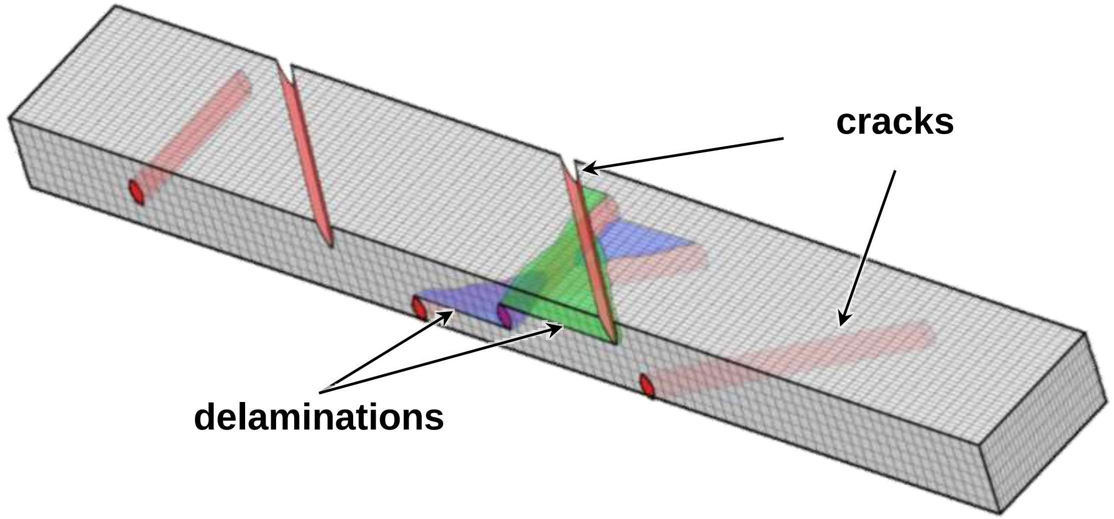


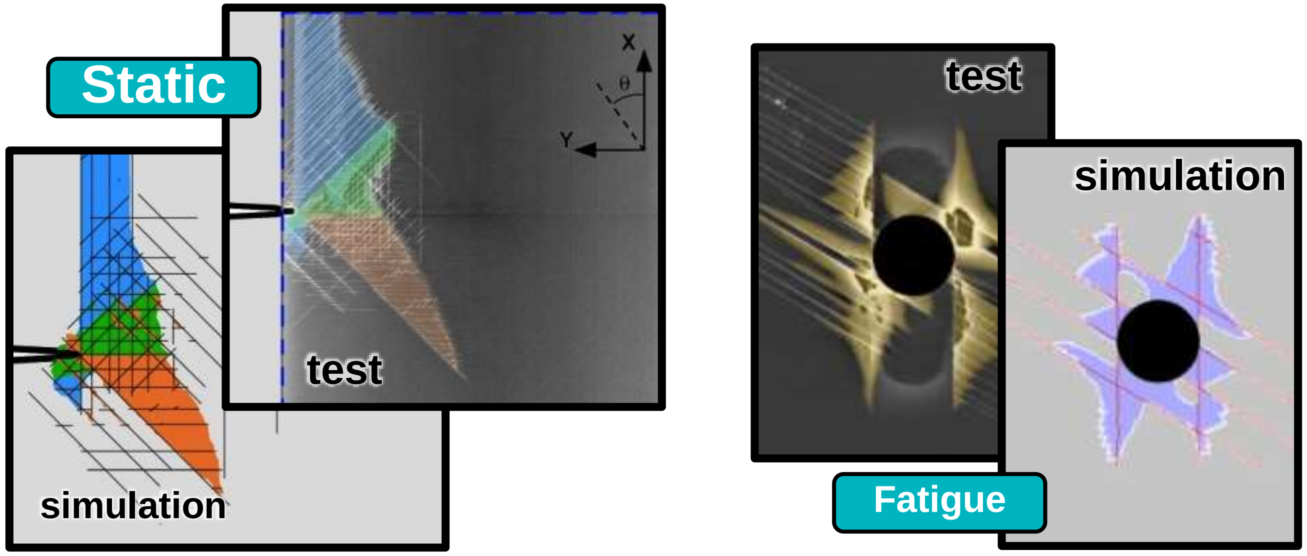
Warp Direction Damage Progression



Discrete Damage Approach (in BSAM)

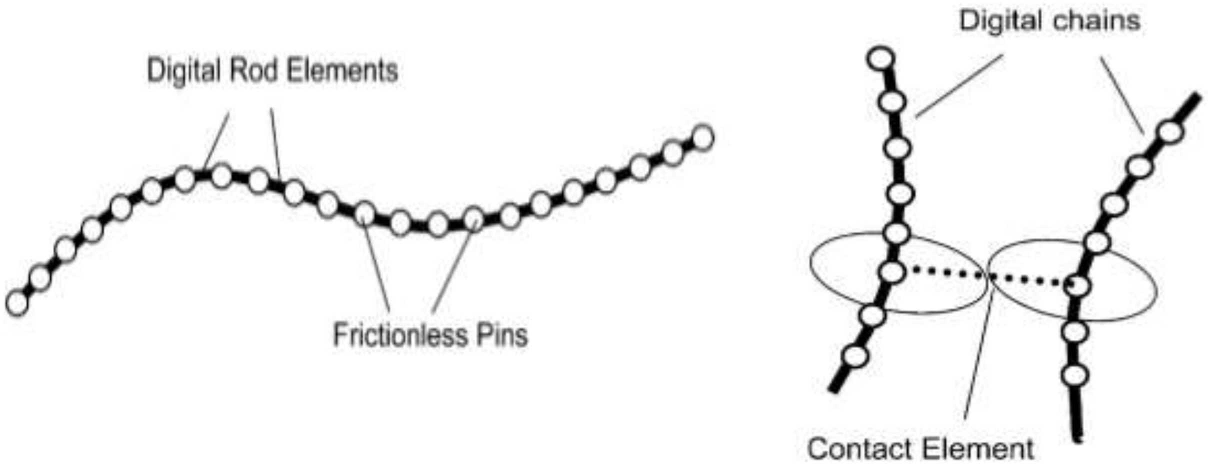
- **Rx-FEM**
  - AFRL-unique methodology
  - Captures matrix crack discontinuity
  - Preserves integration schema
    - Cracks & delams behave well numerically!
- **Initiation (Matrix Damage)**
  - LaRC-04 for matrix cracks ***{NASA}***
  - Hashin-Rotem + Miner Rule for fatigue
    - Matrix cracks & delamination ***{AFRL}***
- **Propagation (Matrix Damage)** ***{AFRL}***
  - Cohesive Zone Method for static & fatigue
  - CZM altered according to Miner Rule
- **Initiation/Propagation (Fiber Damage)**
  - Critical Failure Volume (stochastic) ***{AFRL}***
  - Continuum Damage Mechanics ***{mod. NASA}***
  - Damage Mechanics ***{ONERA France}***
- **Moisture, Oxidation, Swelling, etc.**
  - Mixture Theory for Oxidation {***RXCC - Rick Hall***}
  - Moisture {**UTA & Stevens Institute**}

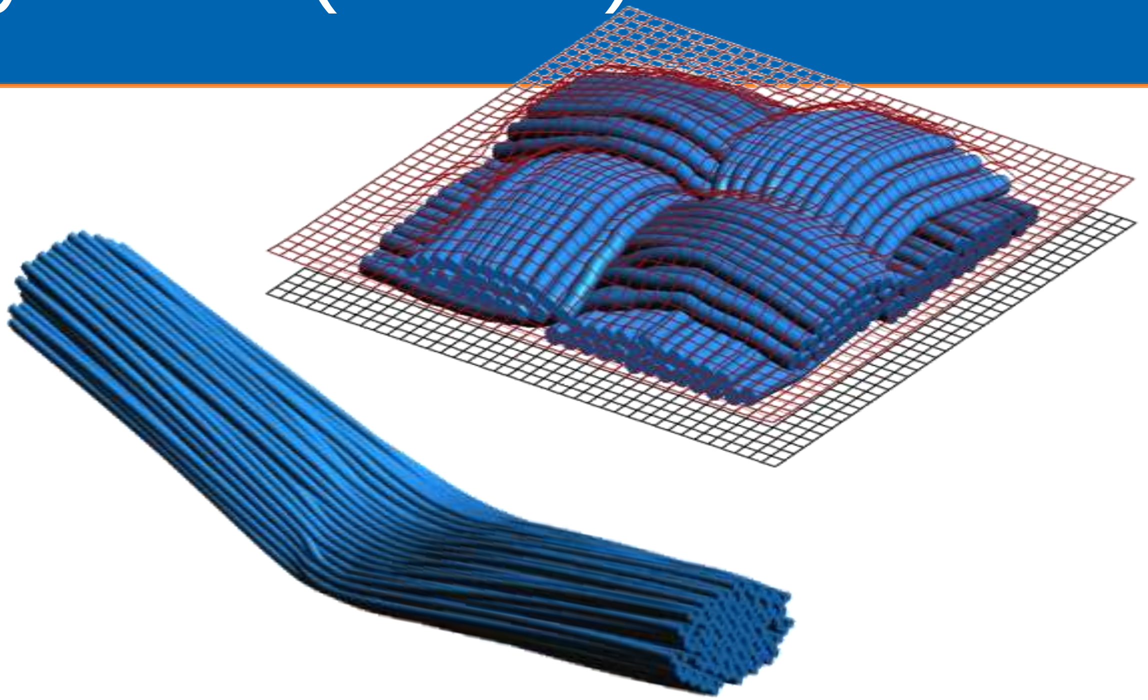




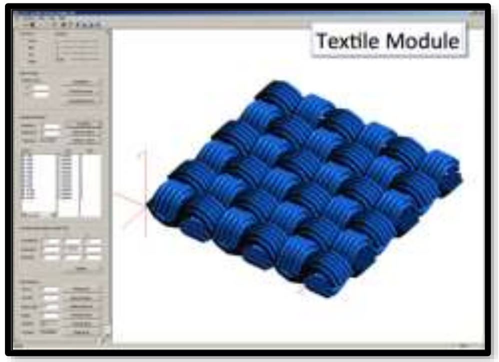
Virtual Textile Morphology Suite (VTMS)

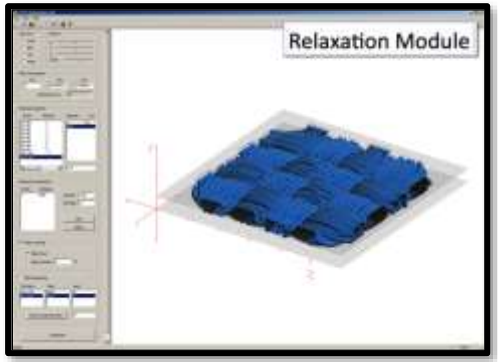
Multi-Chain Digital Element Method

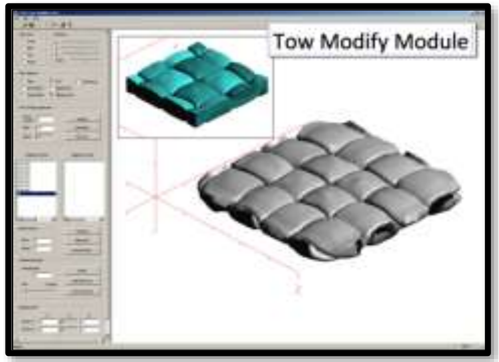


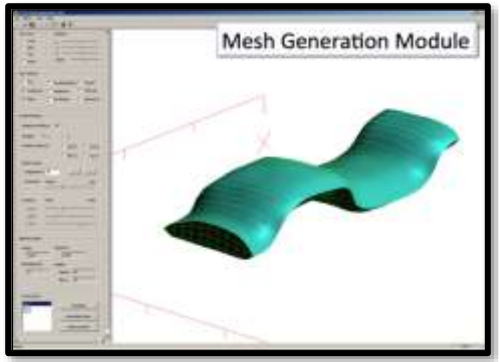


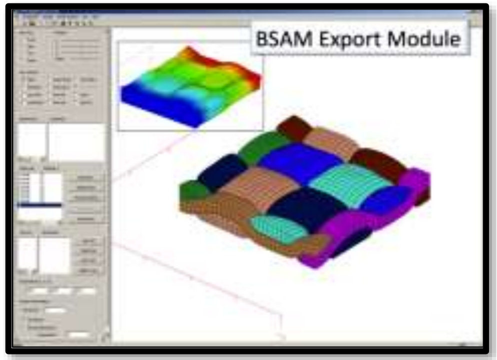
5-module software suite





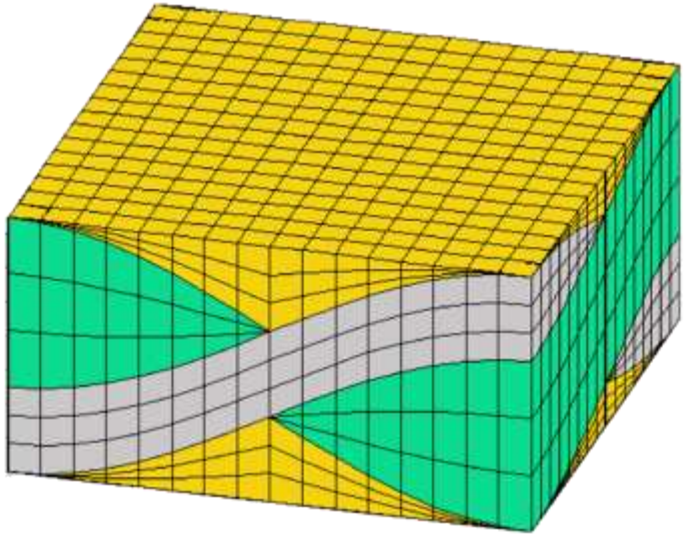






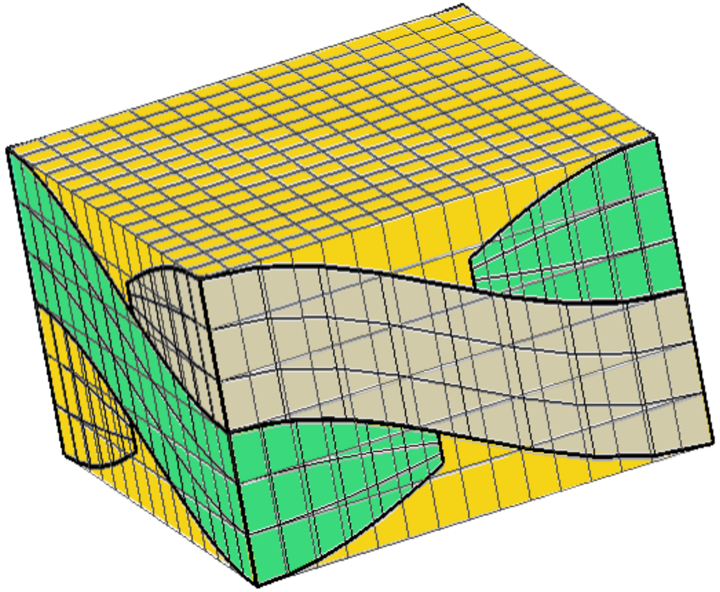
Independent Mesh Method (IMM)

Standard FEA Approach



- Generally depends on <u>perfect</u> definition of geometry and nodal connectivity between regions
- Even if meshable, it can still produce elements with unacceptable aspect ratios

IMM



- Does <u>not</u> depend on perfect definition of geometry
- Region connectivity accomplished through penalty method.
- Region meshing becomes tractable

Method for Resin Integration around Tow Boundaries