Probabilistic Sensitivity Studies of Composite Damage Models

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Outline

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III. Open-Hole Tension Study Objectives and Model Development
IV. Probabilistic Analysis Approach
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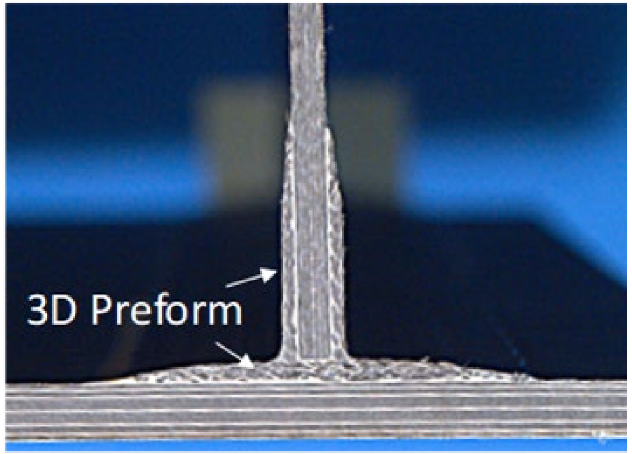
    2. Response Surface Modeling
V. Probabilistic Analysis Results and Discussion
VI. Summary and Conclusions

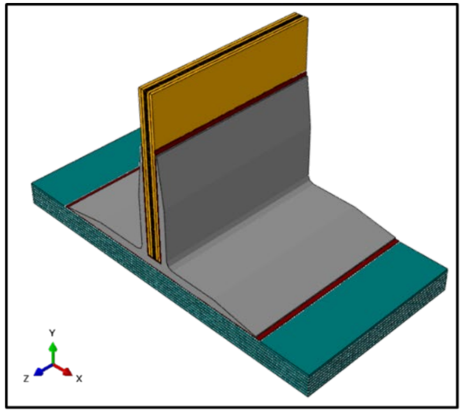
Background and Motivation

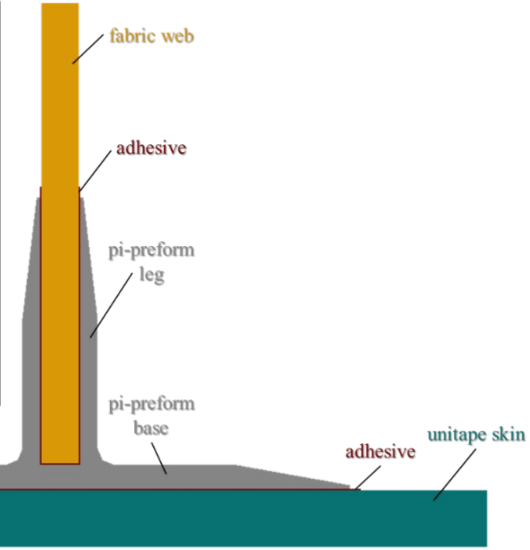
- **Bonded composite primary structures for advanced aircraft systems**
  - **Advantages:** (1) reduced weight, (2) reduced part count, and (3) improved performance
  - **Challenges:** (1) limited software tools for design and analysis, (2) impact of uncertainties and manufacturing defects not well understood[2], and (3) fasteners used because bond is not trusted



Pi-joint Demonstration Article[1]

- **OPPERA Program**: **O**MC (Organic Matrix Composite) **P**rocess-to-**P**erformance **E**valuation, **R**esearch, and **A**nalysis
  - **Program objective:** Develop validated process-to-performance (P2P) methods to predict static response and fatigue life of bonded composite structures → reduce cost and schedule impacts during certification
  - **Demonstration article:** bonded composite pi-preform joint
  - **Study objective:** develop engineering tool for assessing structural response of bonded composite pi-joints under uncertainty





- **Research question:** Identify opportunities to mature probabilistic approaches in the P2P framework

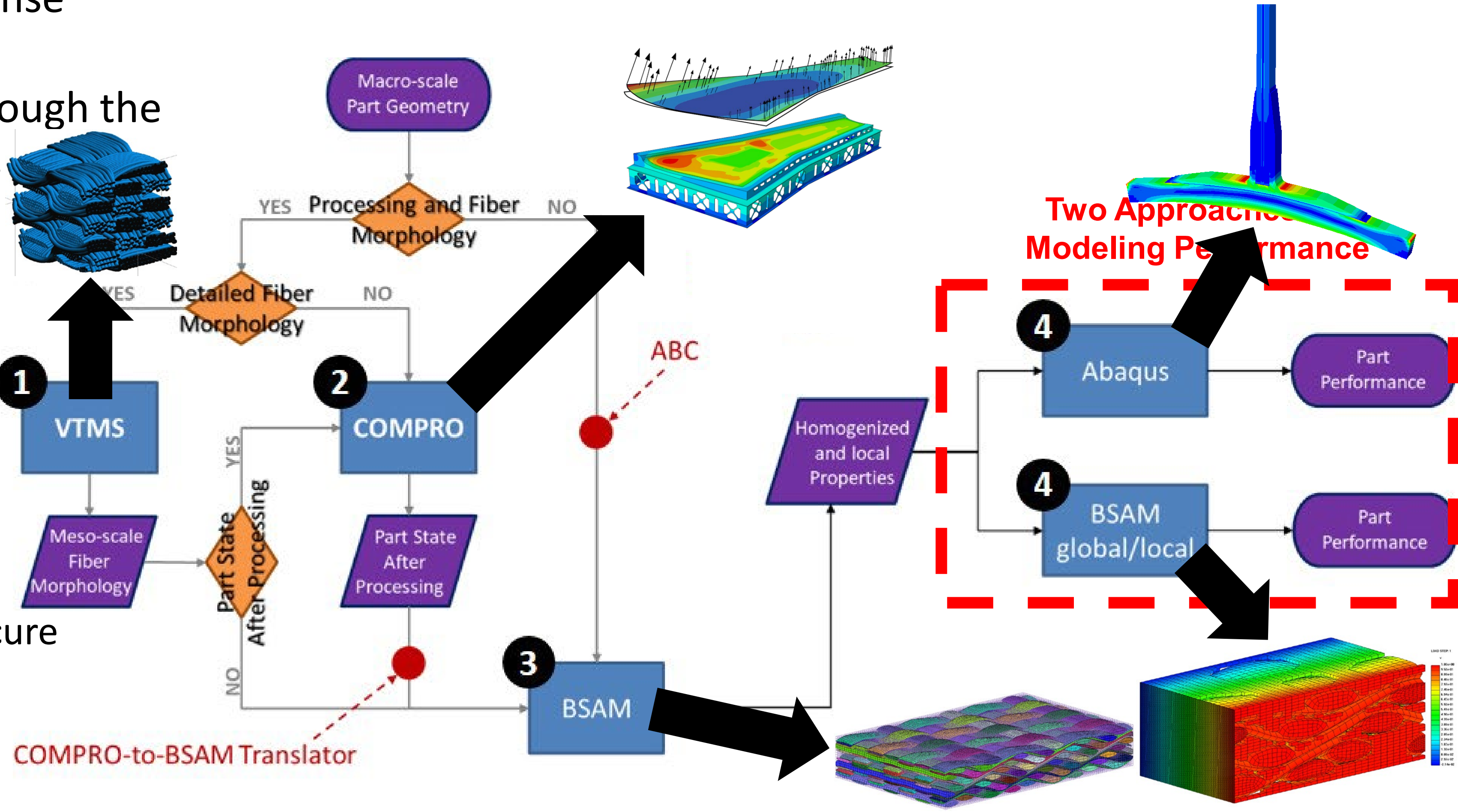
[1] Flansburg et al., AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 2009.
[2] Omairey et al., SN Applied Sciences, 2021.

Overview of OPPERA P2P Framework

- **Multiscale framework for process-to-performance (P2P) modeling** → mesoscale fiber architecture to macroscale component response

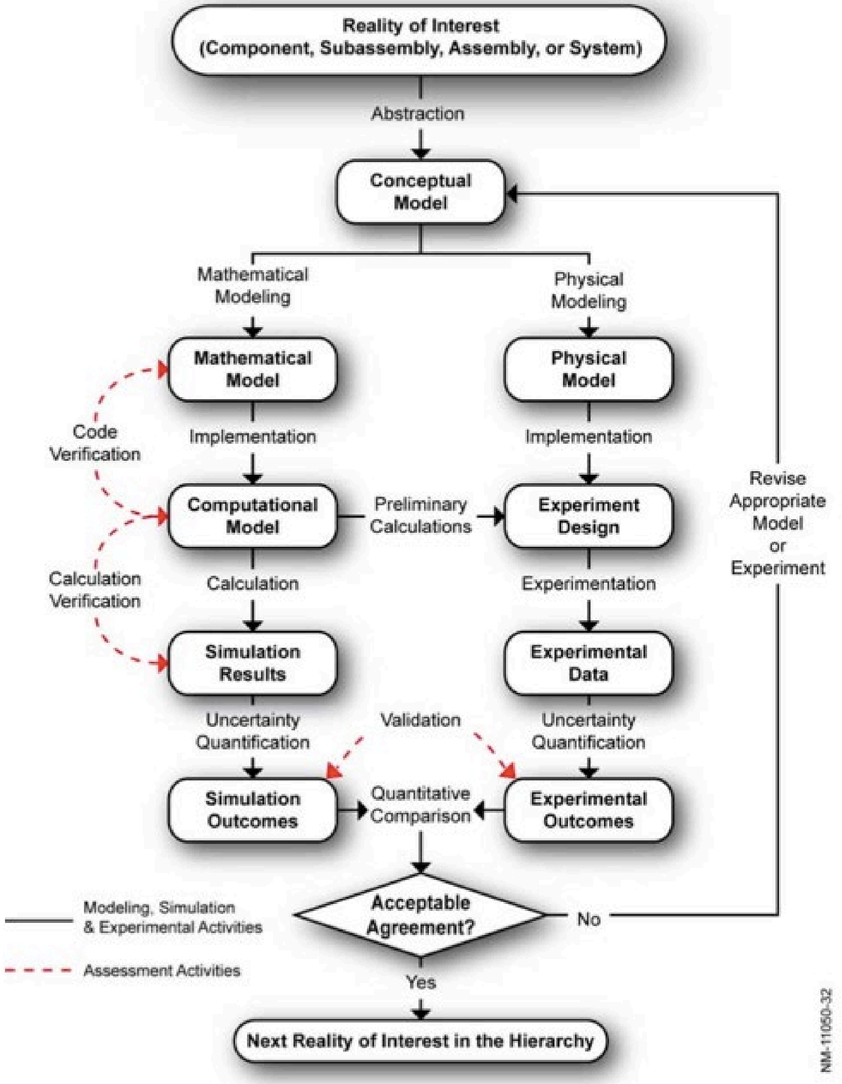
- **Flexible** → multiple paths through the framework to capture various phenomena and allow for flexibility in solution fidelity

- **Predictive Capability**
  1. Fiber bed compaction and relaxation
  2. Material properties, residual stresses, and porosity evolution during cure
  3. Damage evolution at mesoscale and macroscale
  4. Final part capability



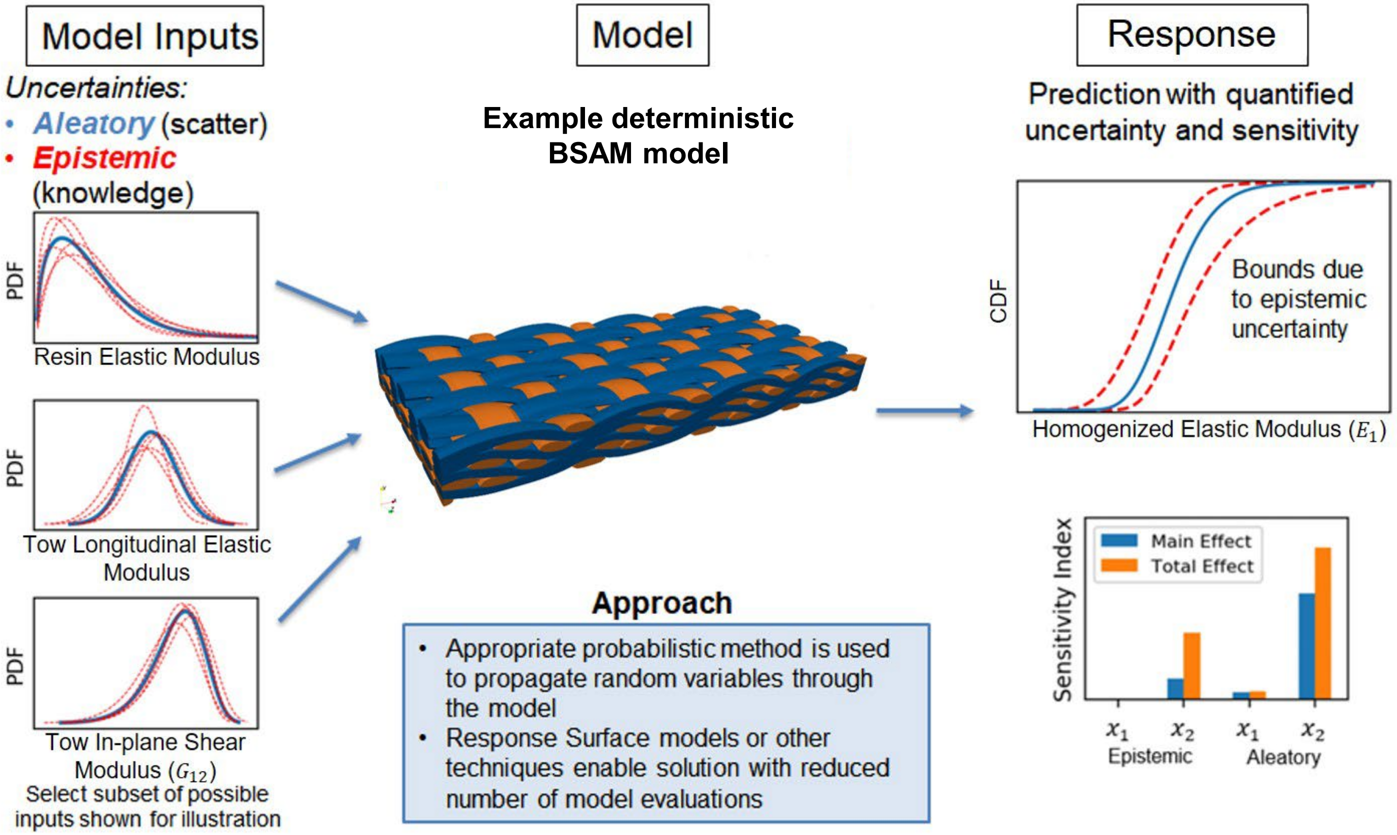
Verification and Validation (V&V)

- Systematic approach for identifying important phenomena, approximations, and uncertainties
- Guides resource allocation for gathering experimental data to reduce uncertainty (e.g. sensitivity analysis)
- Formal documentation of assumptions, limitations, and justification of results with supporting data
- Some key elements of V&V approach:
  - Phenomena importance and ranking table (PIRT): used to understand key phenomena and capabilities for modeling the phenomena
  - Tool maturity level (TML): formal assessment of the predictive capability of the model



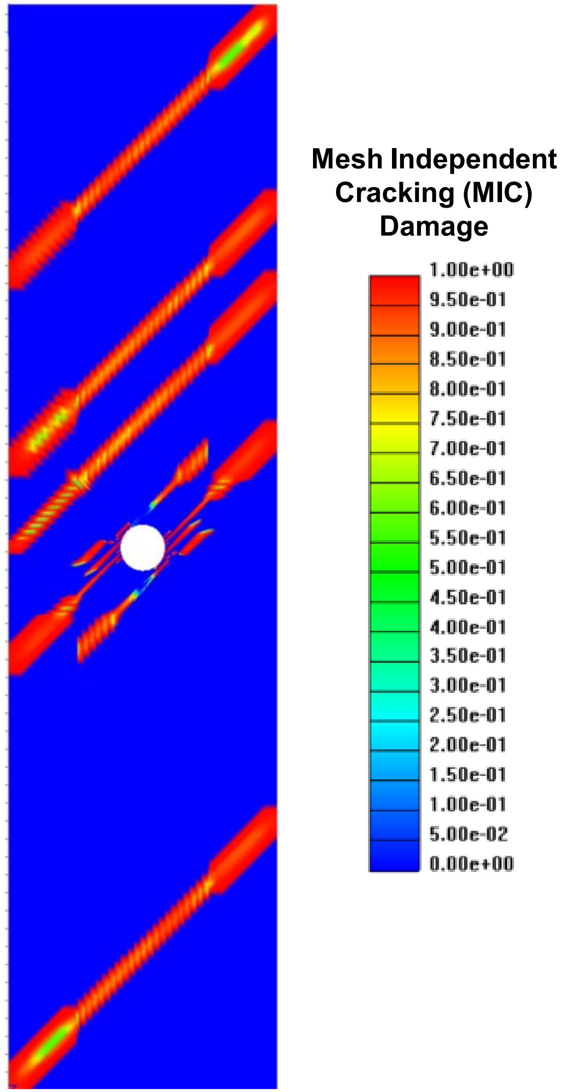
UQ and Sensitivity Analysis

- NESSUS® 10.0 probabilistic analysis software
  - Model inputs can be defined as random variables and described by a probability density function
  - Probabilistic methods are used to propagate uncertainties through models and compute variance-based sensitivities
  - Estimate the contribution from aleatory (inherent variations) and epistemic (knowledge-based) uncertainty
- Sensitivities are dependent on…
  - Strength of the correlation between the input parameter and the response
  - Range of variation for the random variable in the analysis
- Supports identifying steps that could be taken to reduce uncertainty in model predictions and mature models/framework



Open-Hole Tension Study Objectives

- Investigate the relationship between uncertainty in mechanical and fracture properties and variability in the maximum load for different layup configurations
- Identify potential opportunities for reducing uncertainty in the model prediction
- Guide resource allocation for further data collection
- Mature probabilistic modeling in the P2P framework

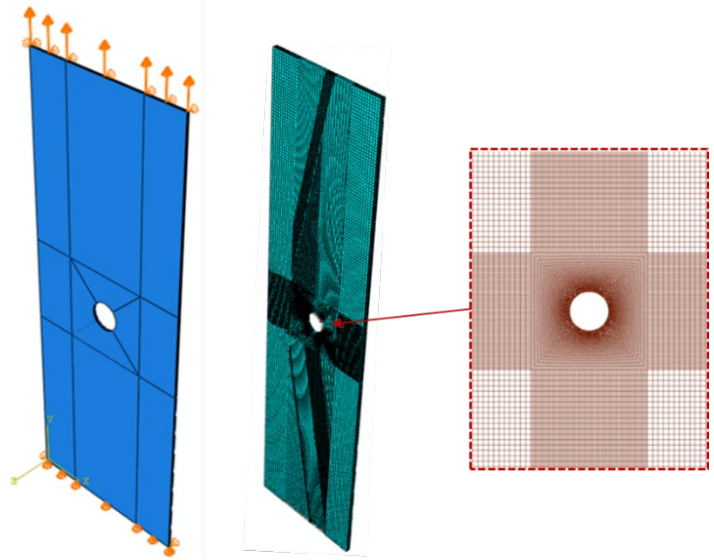


Parametric Open-Hole Tension Model

- **Geometry:**
  - ASTM D5766 → L = 6”, W = 1.5”, and ⌀ = 0.25”
  - Minimum element size near the hole = 1.81 mils (0.046 mm)
  - 8-ply quasi-isotropic layups (7.2 mils thick/ply)
    1. $[45/0/-45/90]_S$
    2. $[0/45/90/-45]_S$
    3. $[90/-45/0/45]_S$

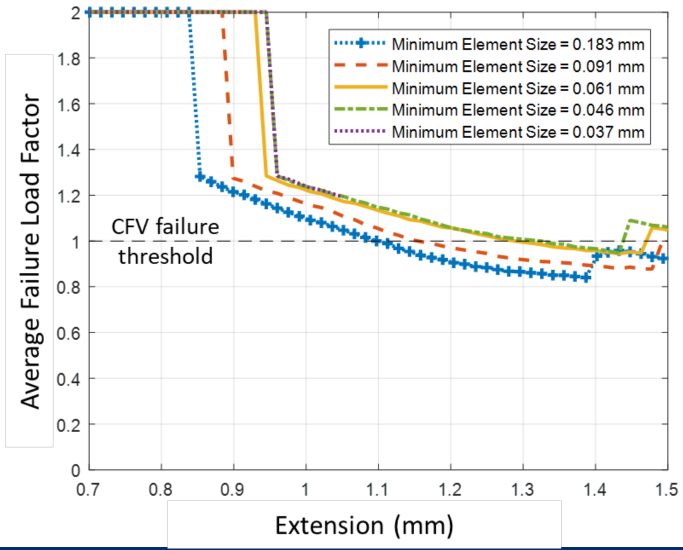
LaRC04 initiated MIC failure

CFV fiber failure



- **Material:**
  - 8552-1/IM7 unitape ply-level orthotropic properties (homogenized each ply → not explicitly modeling fiber architecture)
  - BSAM material 105 to capture nonlinear shear stress-strain

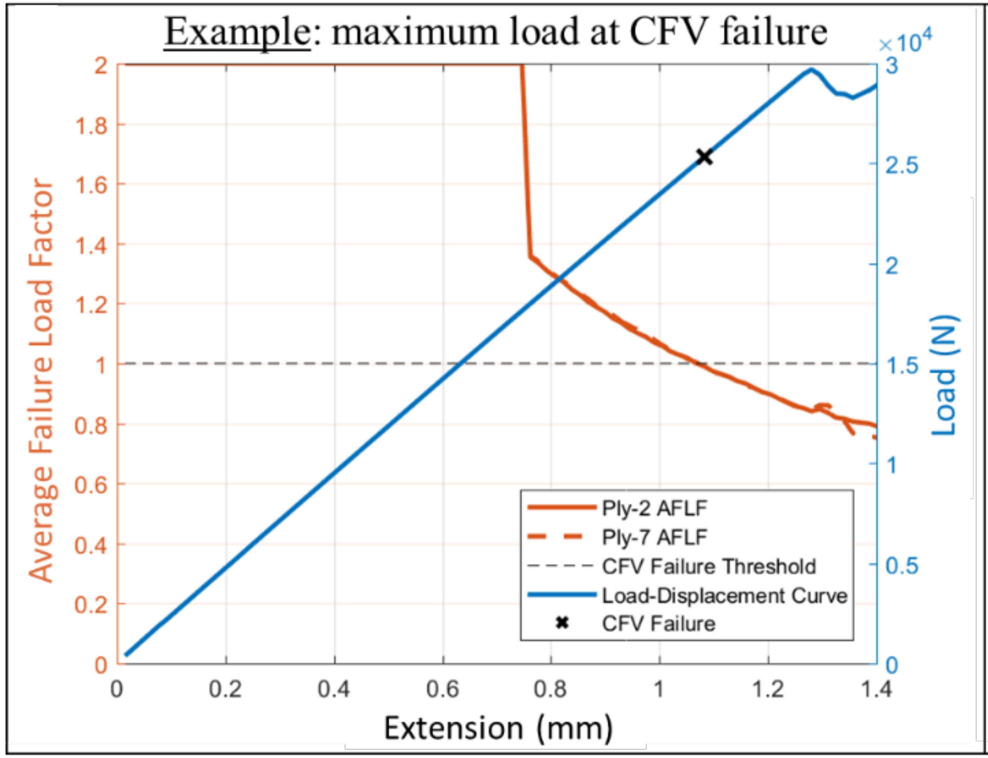
- **Damage Modeling:**
  - BSAM crack type 101 for matrix cracking
  - Matrix crack initiation according to LaRC04 criterion
  - Interface between plies modeled by Turon-Camanho cohesive zone
  - Critical failure volume (CFV) for fiber failure

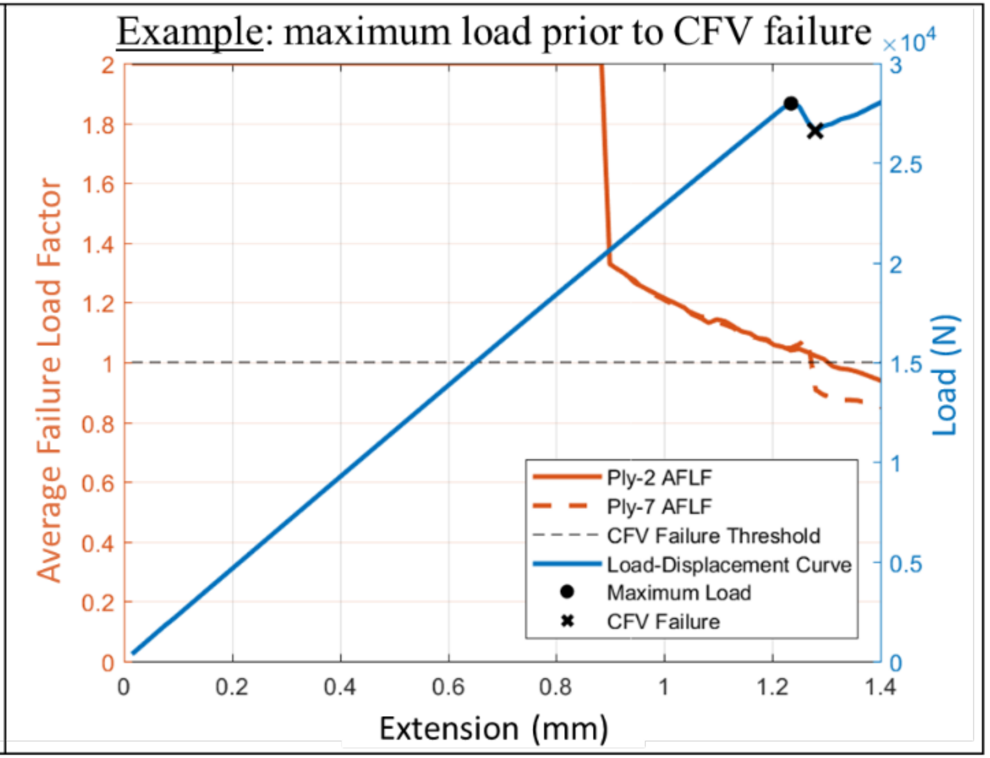


Open-Hole Tension Maximum Load

- Maximum load = the maximum load at (or prior to) CFV failure

- CFV failure is predicted when the average failure load factor (AFLF) goes below 1 for any 0° ply → scaling factor based on current strength vs. applied load





Summary of Open-Hole Tension PIRT

OHT BSAM Model Variable	Nominal Value	Units	Sensitivity Study Distribution	Distribution Parameters	Relative Importance of Variation	Confidence
MATERIAL SYSTEM: 8552/IM7 UNIDIRECTIONAL TAPE						
Material Orthotropic Constitutive Model						
Elastic modulus longitudinal tension (E_{11})	162	GPa	Normal	μ = 162, σ = 3.59	Medium	High
Elastic modulus transverse tension (E_{22})	8.95	GPa	Normal	μ = 8.95, σ = 0.293	Medium	High
Poisson's ratio in-plane (ν_{12})	0.316		Normal	μ = 0.3156, σ = 0.0167	Medium	High
Shear stress-strain curve in-plane (τ_{12})	83.4	MPa	Normal (delta vector scaling)	μ = 83.4, σ = 1.33	High	High
Strength Properties						
Normal strength longitudinal tension (S_{11})	2559	MPa	Normal	μ = 2559, σ = 102	High	High
Normal strength transverse tension (S_{22})	64.0	MPa	Normal	μ = 64.0, σ = 5.91	Medium	Low
Shear strength in-plane offset ($S\tau_{12,offset}$)	0.8		Uniform	a = 0.65, b = 0.95	Medium	Low

OHT BSAM Model Variable	Nominal Value	Units	Sensitivity Study Distribution	Distribution Parameters	Relative Importance of Variation	Confidence
MATERIAL SYSTEM: 8552/IM7 UNIDIRECTIONAL TAPE						
Cohesive Zone Properties (Bi-linear)						
Mode I interlaminar energy release rate (G_n)	0.331	mm·N/mm^2	Normal	μ = 0.331, σ = 0.0170	Medium	Medium
Mode II interlaminar energy release rate (G_s)	0.677	mm·N/mm^2	Normal	μ = 0.677, σ = 0.0122	High	Medium
Mode II intralaminar energy release rate ($G_{s,intra}$)	1.28	mm·N/mm^2	Normal (CV = 5.14%)	μ = 1.28, σ = 0.0657	High	Low
Mixed mode exponent, Mode I and Mode II interlaminar (η)	2.2		Shifted Lognormal (-1)	μ = 1.104, σ = 0.3815 (λ = 0.0425, ζ = 0.3359)	High	Medium
Critical Failure Volume (CFV)						
Weibull modulus, shape parameter (α)	41.0		Lognormal	μ = 41.3342, σ = 5.5622 (λ = 3.7127, ζ = 0.1340)	High	Medium

Random Variables

- Ranked variables based on team's experience with quasi-isotropic OHT coupon testing
  - Relative importance of uncertainty and variation in the parameter
  - Confidence in the models and data
- 12 random variables in the probabilistic studies:

Elastic Properties
- Longitudinal Modulus, tension (E_{11})
- Transverse Modulus, tension (E_{22})
- In-plane Poisson's Ratio (ν_{12})

Strength Properties
- Longitudinal Strength, tension (S_{11})
- Transverse Strength, tension (S_{22})
- In-plane shear strength offset ($S_{\tau_{12,offset}}$)
- In-plane shear stress-strain curve (τ_{12})

Fracture/Failure Properties
- Mode I interlaminar energy release rate (G_n)
- Mode II interlaminar energy release rate (G_s)
- Mode II intralaminar energy release rate ($G_{s,intra}$)
- Mixed mode exponent, Mode I and Mode II interlaminar (η)
- CFV Weibull Scaling Modulus (α)

Data Source
- NCAMP Database
- University of Utah Data

Epistemic and Aleatory UQ

Delta Vector Scaling

Bayesian Model Calibration

Response Surface Modeling Approach

Generate Training Data (≥ 26 samples)

UQ, Baye
and maxi
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variables
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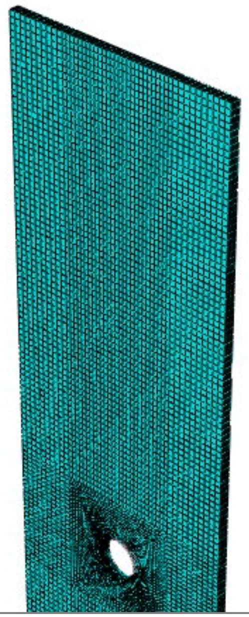
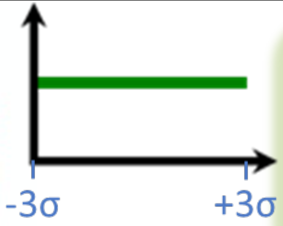
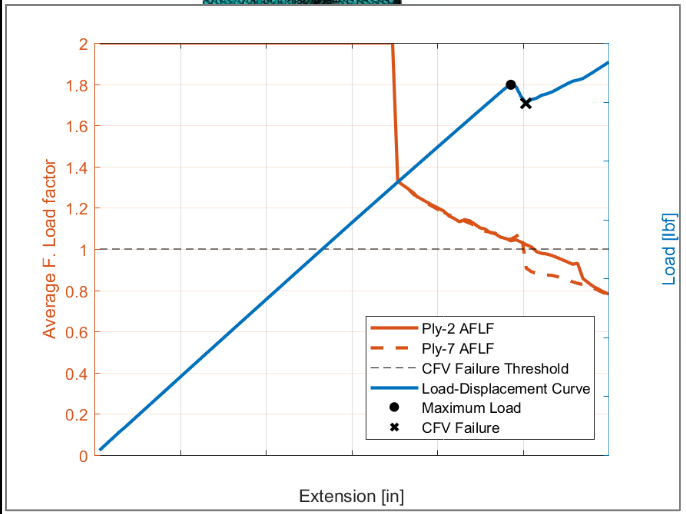




Elastic, Strength, and Fracture Properties

Parametric OHT Model

Maximum Load



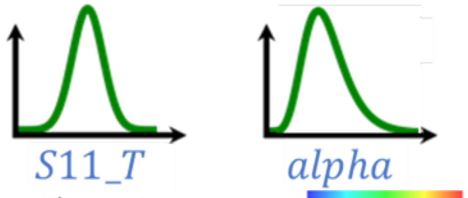
NESSUS Response Surface Toolkit

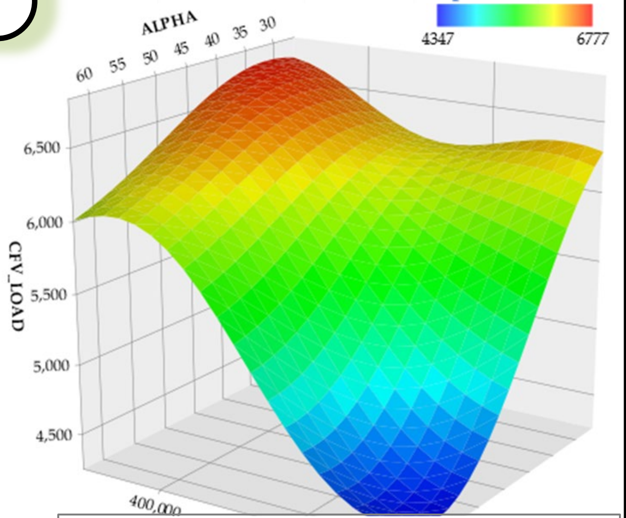
Sensitivity Study using RSM (10,000 samples)

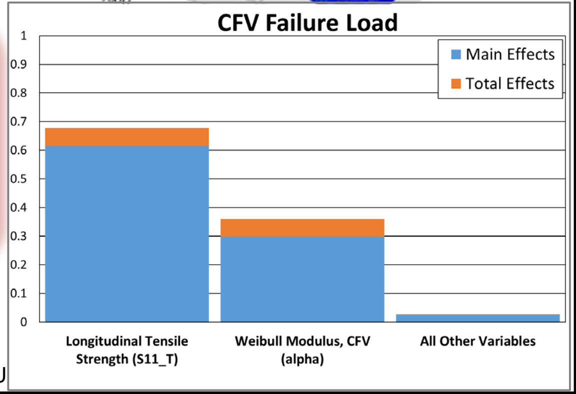
Elastic, Strength, and Fracture Properties

Response Surface Model

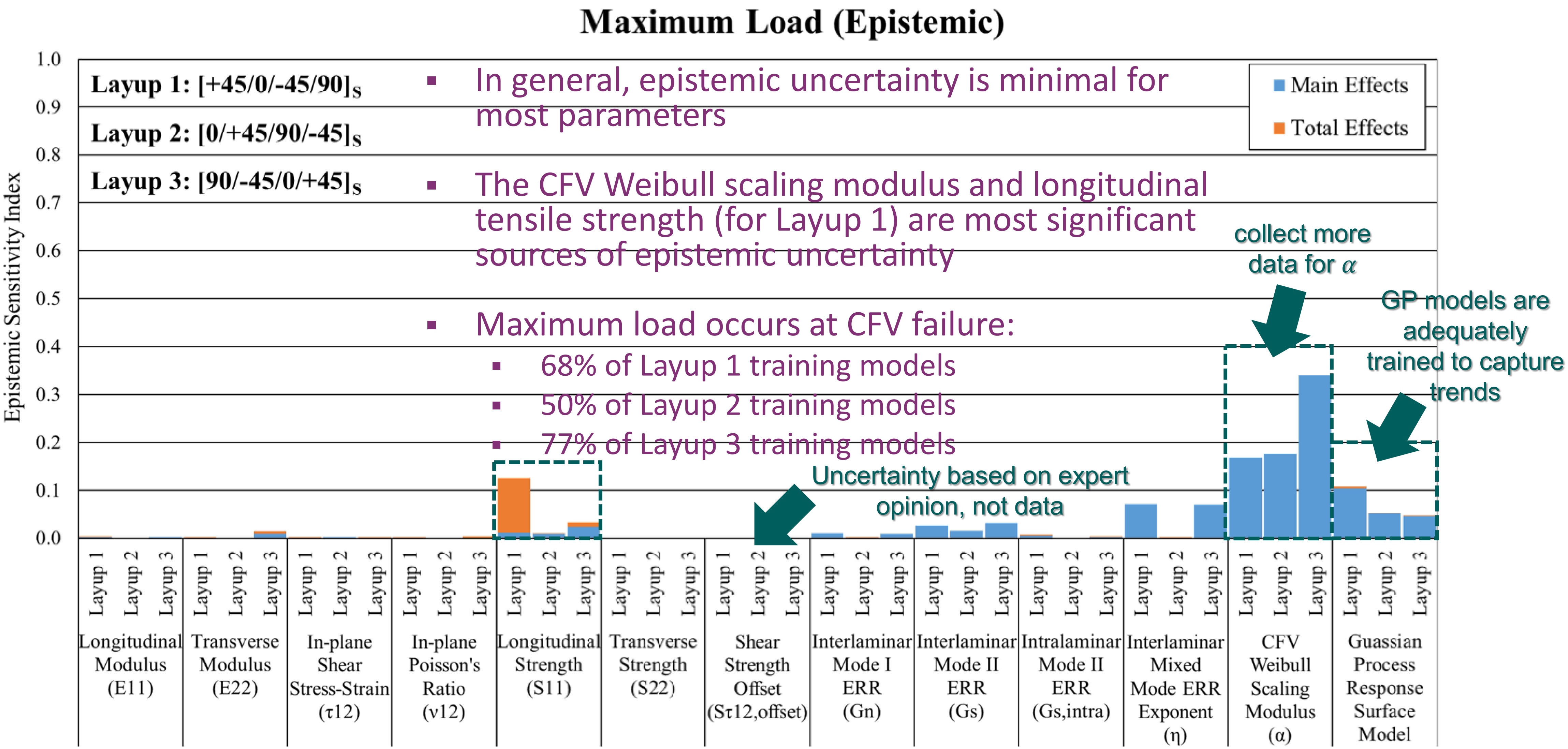
Probabilistic Analysis







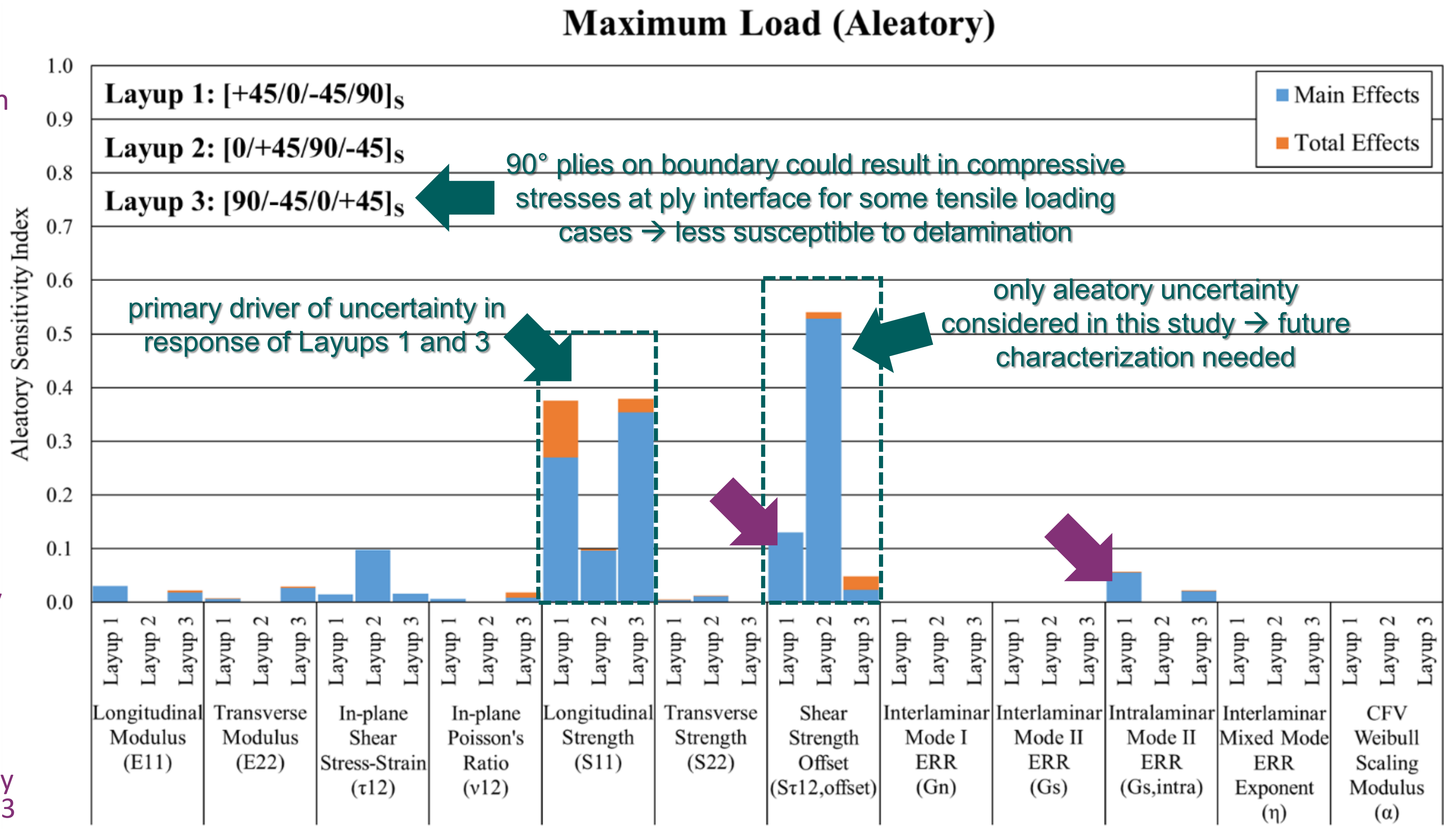
Epistemic Sensitivity Factors



- In general, epistemic uncertainty is minimal for most parameters
- The CFV Weibull scaling modulus and longitudinal tensile strength (for Layup 1) are most significant sources of epistemic uncertainty
- Maximum load occurs at CFV failure:
  - 68% of Layup 1 training models
  - 50% of Layup 2 training models
  - 77% of Layup 3 training models

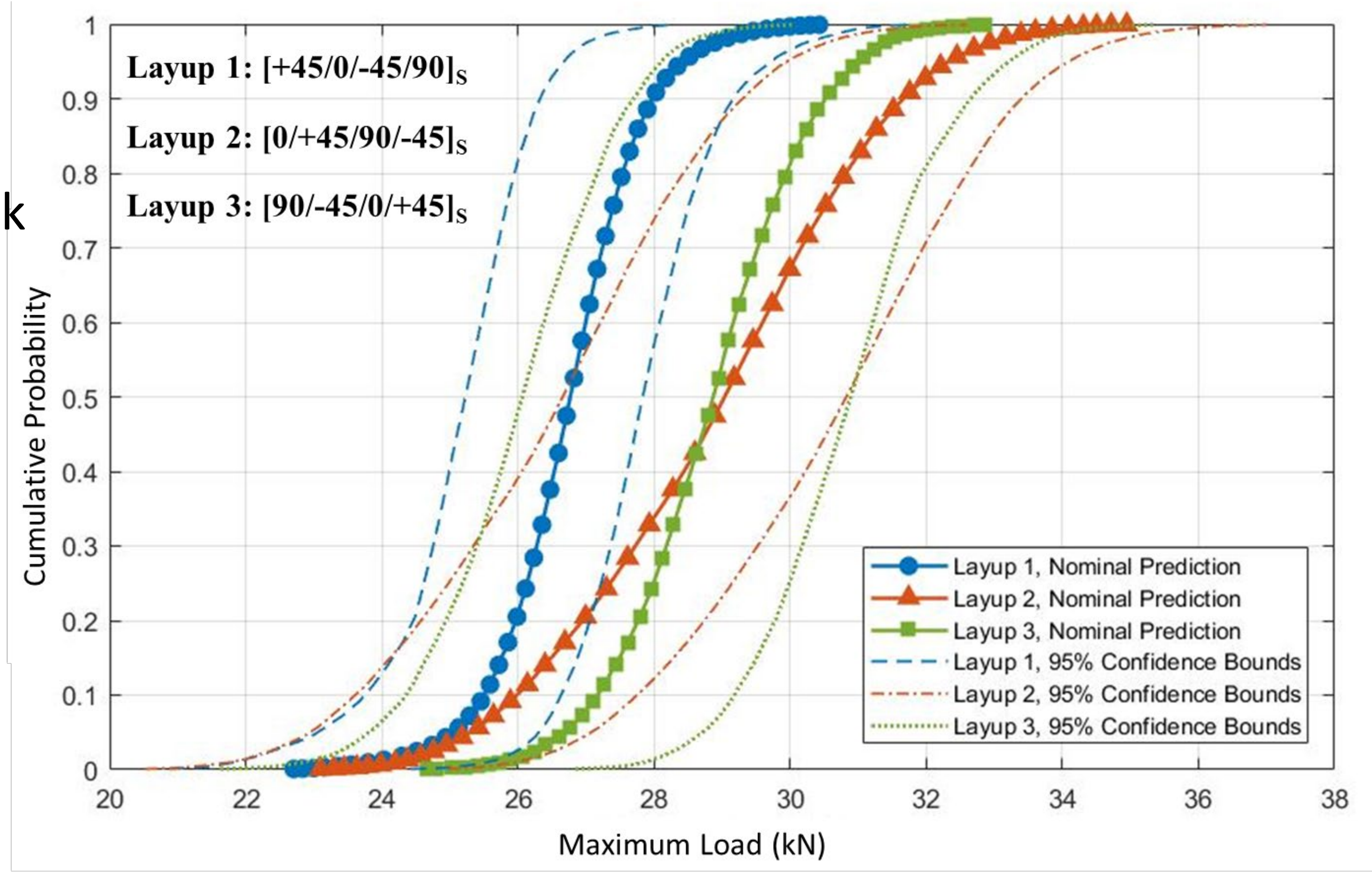
Aleatory Sensitivity Factors

- Differences between layups strongly influenced by position of 0° plies
- **Layup 2** is more sensitive to shear than other layups because 0° plies are on boundary (less constraint on matrix cracking)
- **Layups 1 and 3:**
  - 0° plies positioned between two 45° plies → limit shear cracking initiation and propagation
  - Exhibit similar sensitivity results, but…
  - Differ slightly in sensitivity to intralaminar Mode II fracture and the shear strength offset parameter
  - Layup 1 may be more susceptible to matrix cracking (and subsequently delamination) than Layup 3



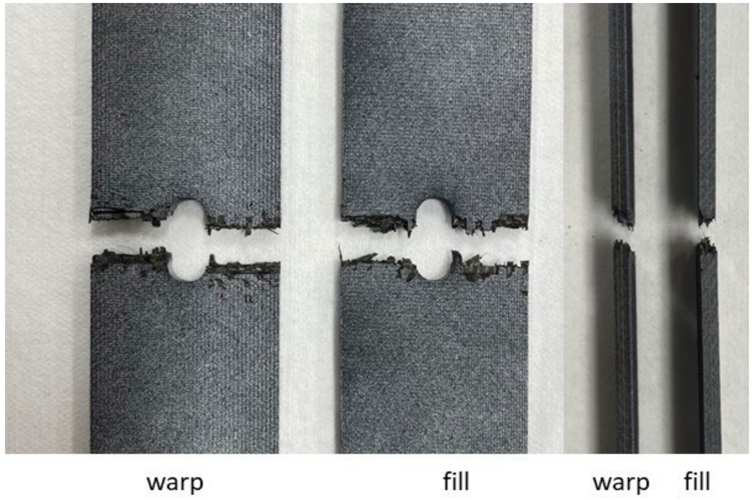
OPPERA Max Load Cumulative Distribution Functions

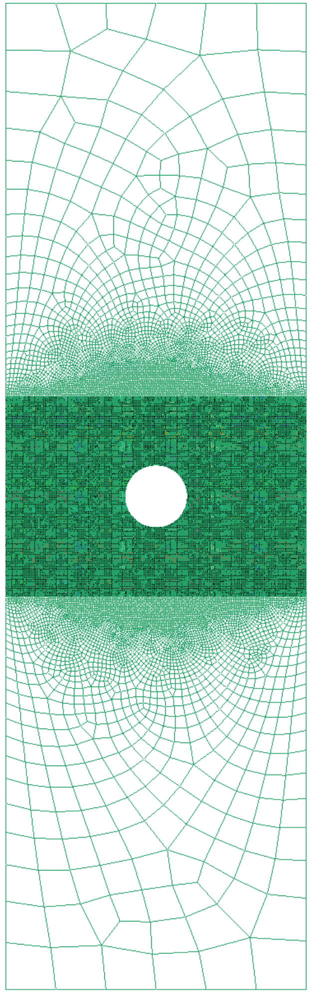
- Range of the nominal prediction represents the aleatory uncertainty
- Layup 2 exhibits the most aleatory uncertainty related to uncertainty in $S_{\tau_{12,offset}}$ → investigate in future work
- Significant difference in max load response between Layup 1 and 3
- Confidence bounds represent the epistemic uncertainty
- Substantial epistemic uncertainty primarily caused by uncertainty in α → additional testing could reduce epistemic uncertainty



Summary and Conclusions

- The response of each layup is strongly influenced by position of 0° plies
  - Layup 2 was more sensitivity to shear → need to characterize shear strength offset
  - Layups 1 and 3 were primarily sensitive to longitudinal tensile strength
  - Significant difference between max load response of Layup 1 and 3 requires additional investigation
- Commonality among all 3 layups = sensitive to epistemic uncertainty in CFV parameter
  - Collecting more data could reduce uncertainty
  - However, this parameter is very hard to measure → consider calibrating directly from open-hole tension experiments
- These types of probabilistic studies can help
  - Identify opportunities for more efficient calibration of progressive damage models
  - Support the development of novel tests or stacking sequences to isolate phenomena
- **Current efforts include:**
  - **Developing framework for rapid calibration of progressive damage models for new materials to augment certification testing**
  - **Multi-scale models of OHT/OHC of 3D textiles.**

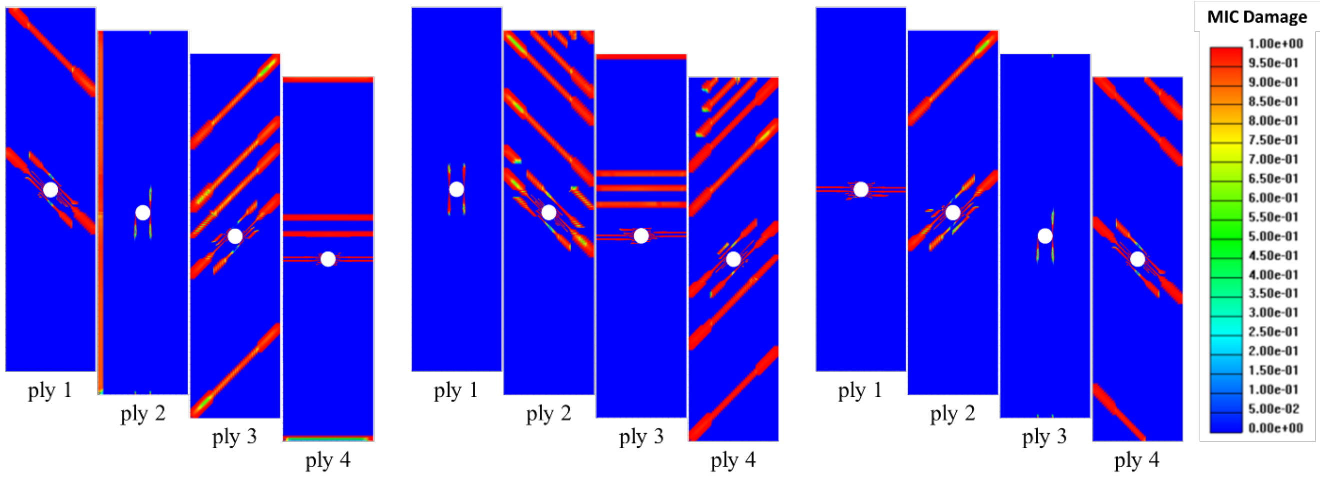




Backup Slides

BSAM Nominal Simulation Results

- Results shown at the maximum load
- Matrix cracks run parallel to ply orientation
- Delamination pattern is more difficult to discern
- In general, more matrix damage appears to have occurred prior to the maximum load than interlaminar damage
- Delamination appears to initiate at free surfaces



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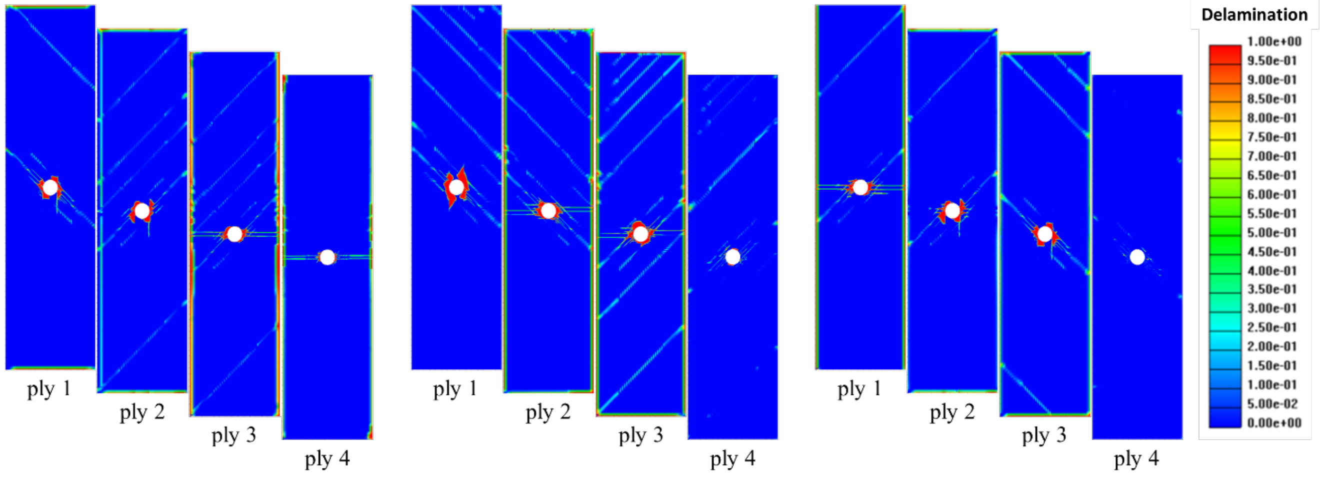

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