Probabilistic Sensitivity Studies of a Multiscale Model for Bonded Composite Pi-joint Performance

OMC Process-to-Performance OPPERA Evaluation, Research, & Analysis

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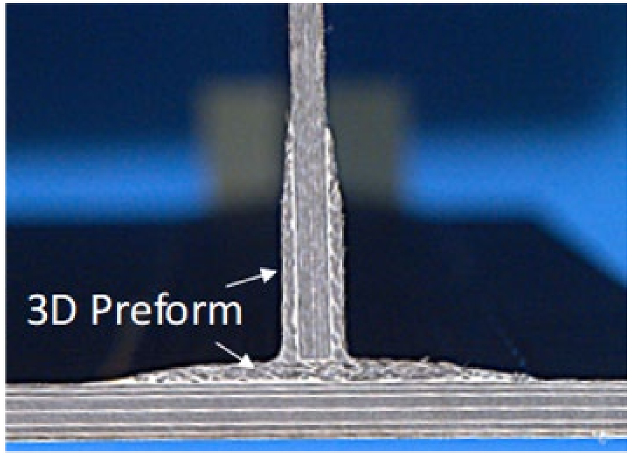
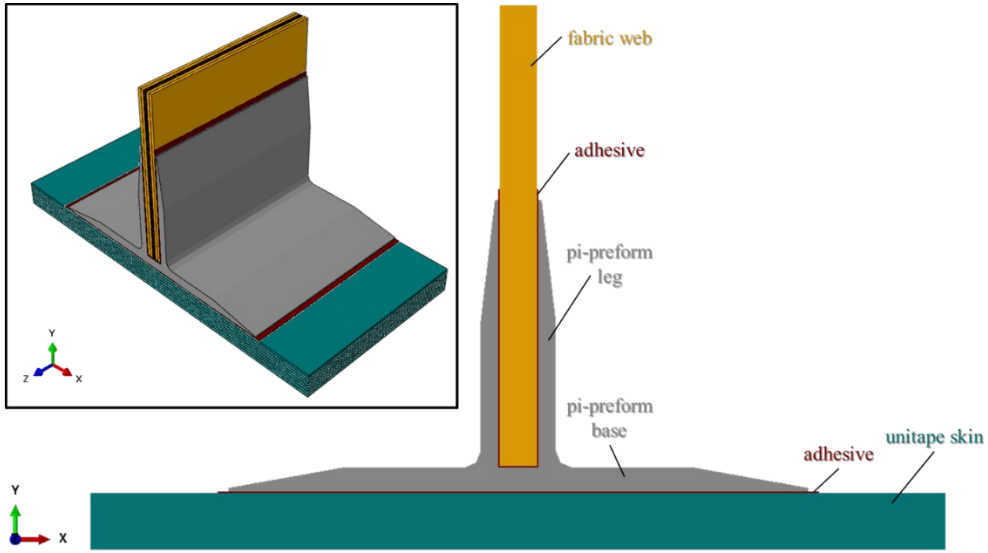
Background and Motivation

- **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:** What is the relationship between textile architecture and the structural response of the Pi-joint?

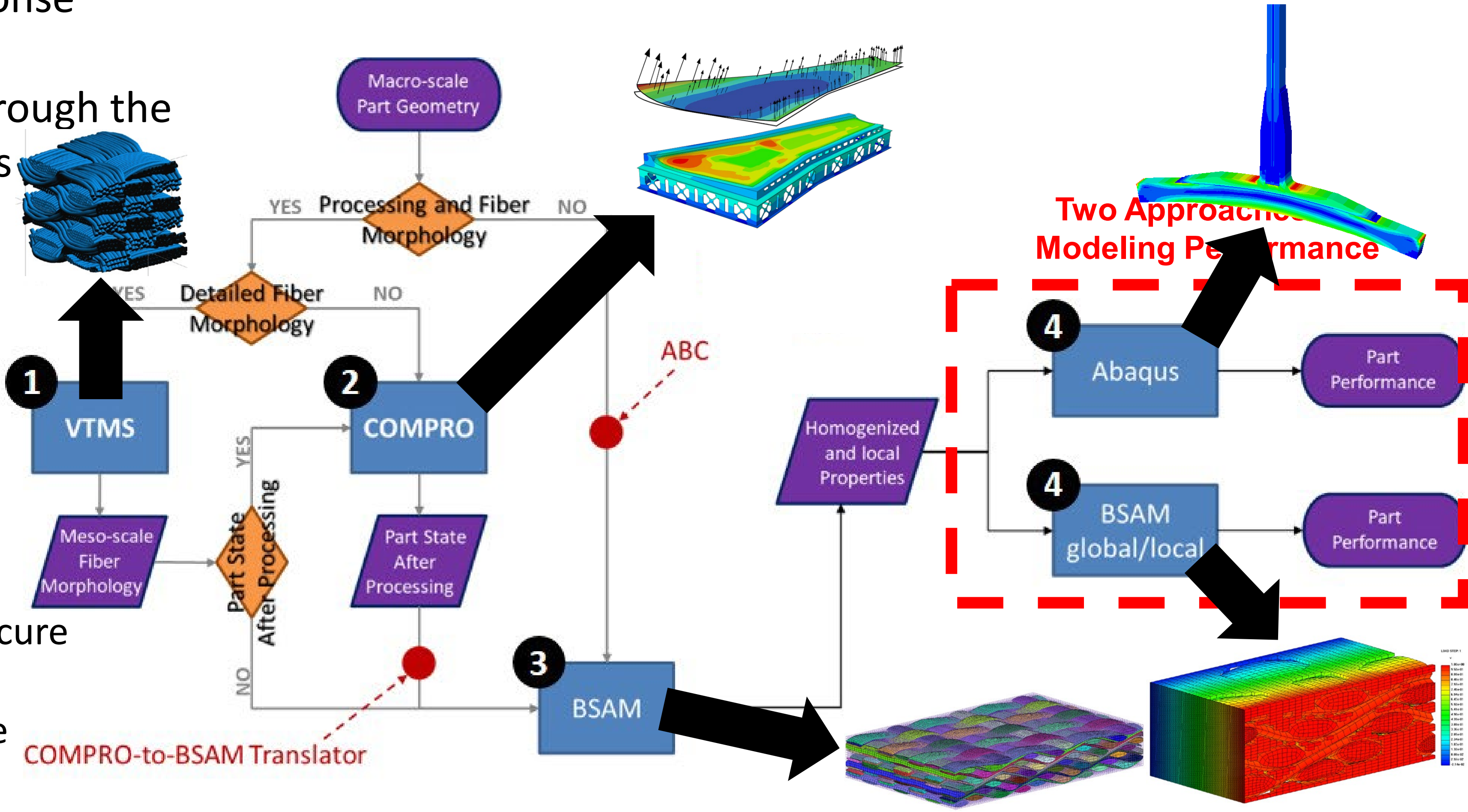
[1] Flansburg et al., AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 2009.
[2] Omairey et al., SN Applied Sciences, 2021.

Overview of OPPERA P2P Framework

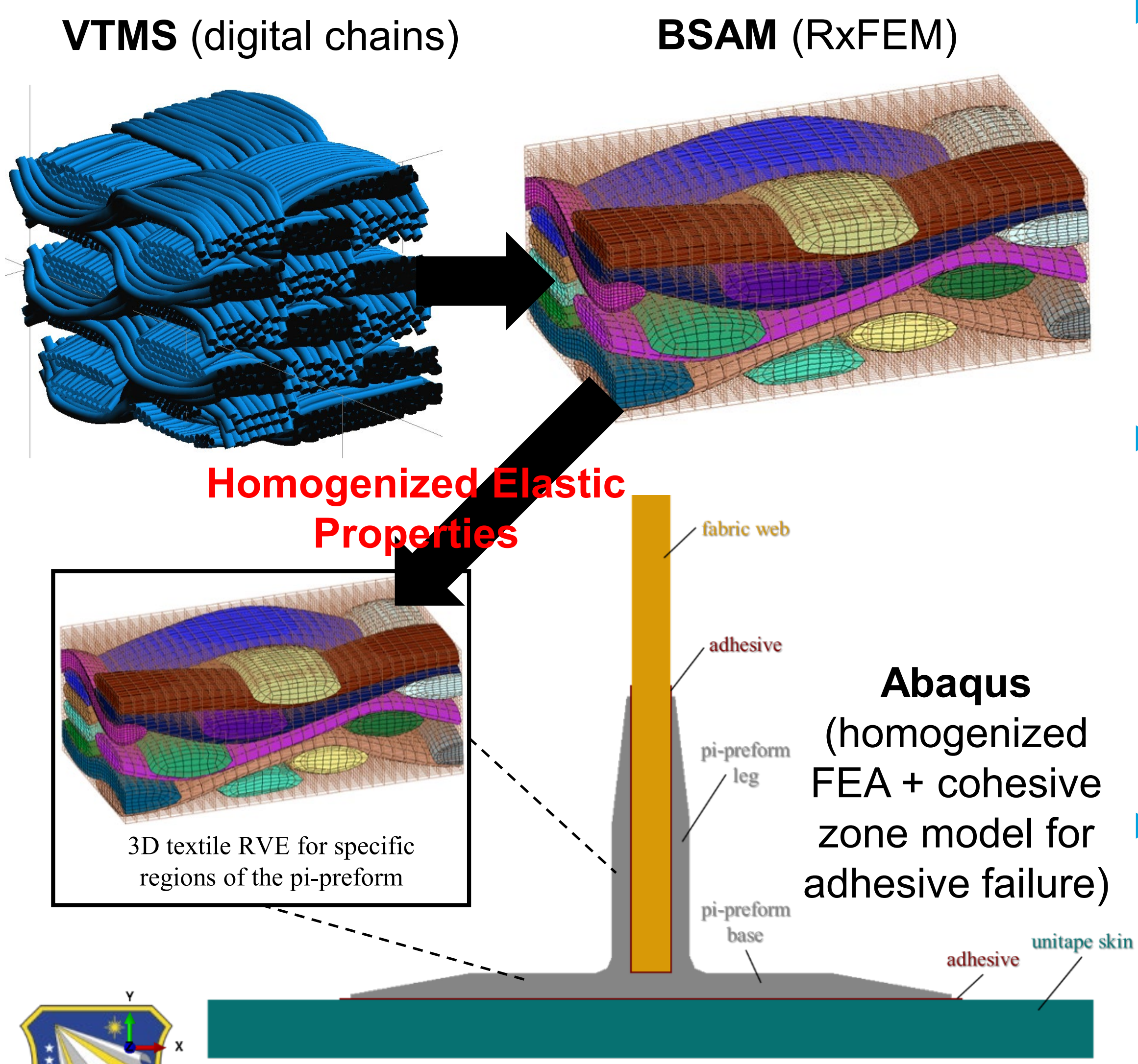
- **Multiscale framework for process-to-performance (P2P) modeling** → mesoscale fiber architecture to macroscale component response

- **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



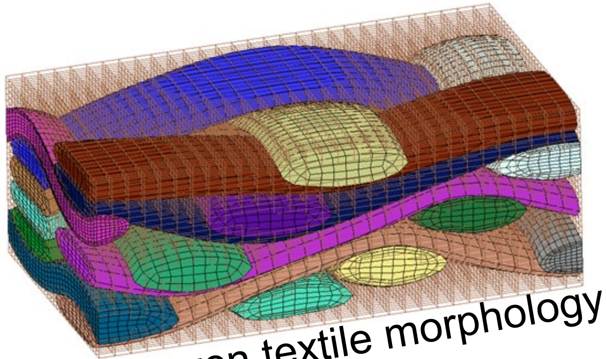
Homogenized Pi-joint Model Approach



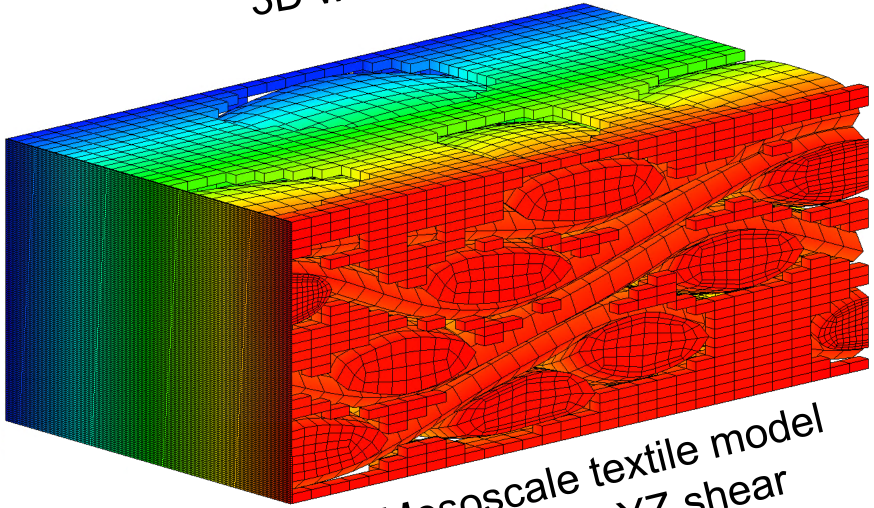
- **VTMS simulates the morphology of the textile RVE after weaving**
  - Digital chains represent bundles of fibers within the tow → used to achieve tow fiber volume fraction without discretely modeling every fiber in the tow
  - Final architecture based on Fiber relaxation and compaction steps
  - Surface smoothing and volume-based approaches to generate the tow geometry for FEA
- **BSAM simulates the mechanical and fracture response of the textile RVE composite**
  - The independent mesh method is used for meshing fiber tows and matrix
  - Employs periodic cluster method (PCM)[3] to address limitations associated with non-conforming mesh for side-to-side
  - Calculate the effective elastic properties from 6 loading state
- **Abaqus simulates the structural response of the Pi-joint**
  - Over 100 geometric, mechanical, and fracture parameters in parametric pi-joint model
  - Linear elastic material properties for pi-preform, web, and skin and cohesive zone model for adhesive bond

[3] Hoos et al. AIAA SciTech, 2022.

OPPERA Textile Homogenization (VTMS + BSAM)



3D woven textile morphology



Mesoscale textile model loaded in YZ shear

- **Conforming mesh is an issue for complicated textile geometries**
- **The independent mesh method (IMM) is used to address this meshing issue**
  - Combination of direct meshing of the tows and a voxel-based methodology within the matrix
  - Integration enrichment for connectivity between the tows and matrix
  - <u>Limitation</u>: requires node-to-node periodicity on opposing sides of the finite element mesh
- **IMM node-to-node periodicity limitation is addressed by periodic cluster method (PCM)[3]**
  - Utilizes additional plates at the edges of the RVE that connect via penalty connection
  - Displacements between opposing periodic clusters are tied together and properties are tailored to provide very little additional stiffness to the model
  - Satisfies node-to-node periodicity requirement and allows RVE mesh to be non-conforming side-to-side
- **Calculate the 9 effective elastic properties from 6 loading states**

[3] Hoos et al. AIAA SciTech, 2022.

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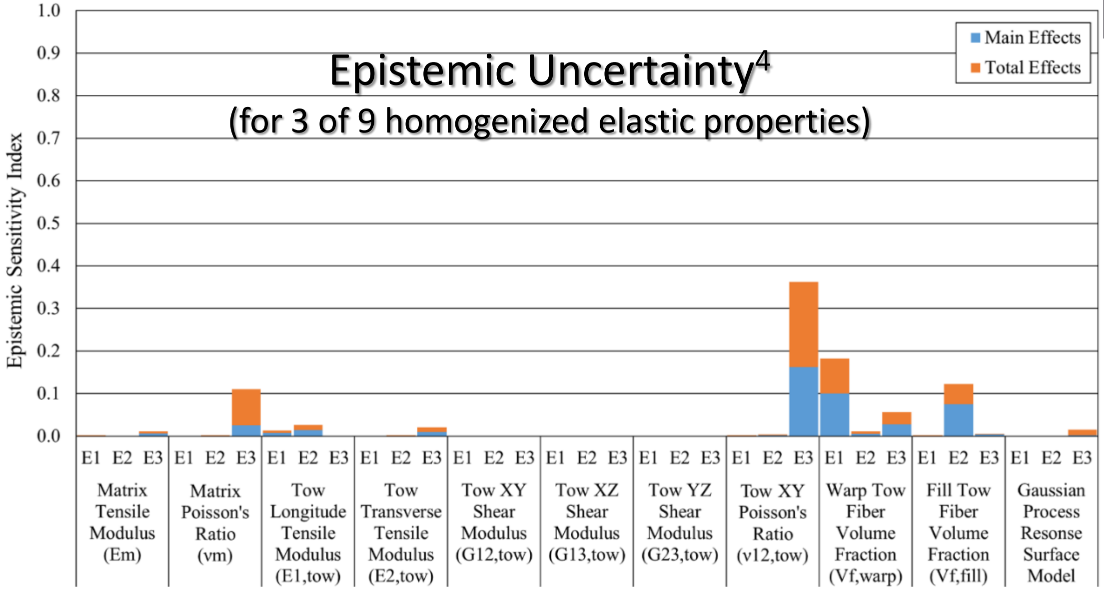
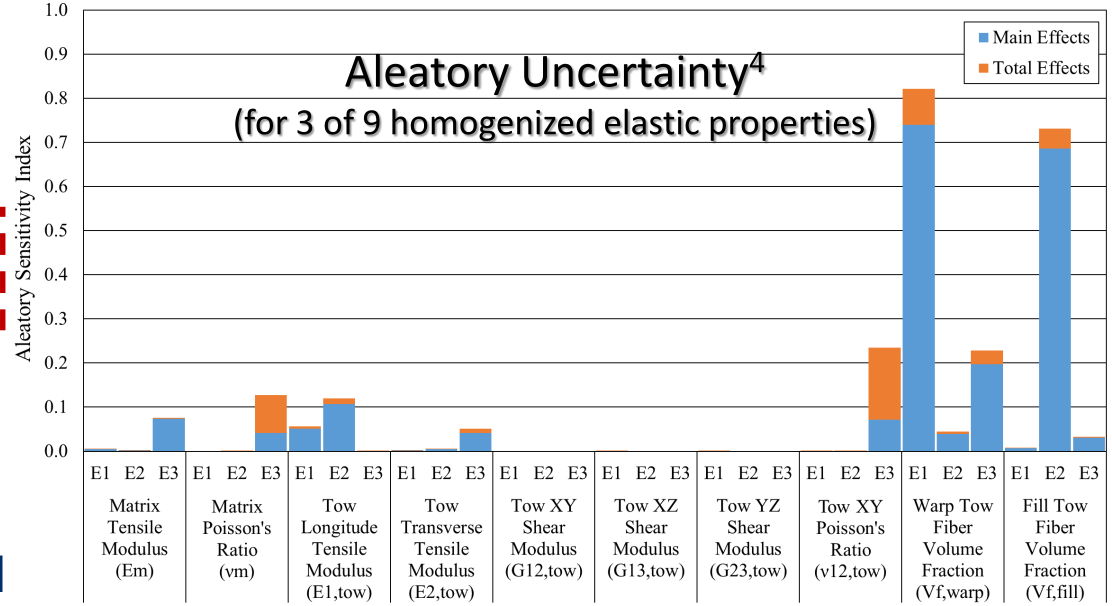
Uncertainty in Homogenized Properties

Findings from Previous Study[4]

$$COV = \frac{standard\ deviation}{mean}$$

- **Largest sources of uncertainty**
  - Tow XY Poisson's ratio ($\nu_{12,tow}$): **8.5% COV**
  - Warp tow fiber volume fraction ($V_{f,warp}$): **6.2% COV**
  - Matrix tensile modulus (E_m): **6.0 % COV**
  - Fill tow fiber volume fraction ($V_{f,fill}$): **5.1% COV**
  - All other mesoscale material properties: **< 5% COV**
- **Each of the nine homogenized properties was primarily sensitive to uncertainty in the tow V_f and/or $\nu_{12,tow}$**
- **Current mesoscale models do not account of intra- or inter-tow spatial variability in tow V_f**
  - One $V_{f,warp}$ and one $V_{f,fill}$ value describe all tows in the model
  - Not accounting for spatial variability yields overly conservative results
- **The value of the sensitivity analyses would be more impactful if mesoscale models were linked to macroscale analyses**
- **Proposed future work from previous study**
  - Additional characterization of $\nu_{12,tow}$ and $V_{f,warp}$
  - Model spatial variability in tow V_f for more realistic simulations
  - Link mesoscale textile model with macroscale pi-joint model

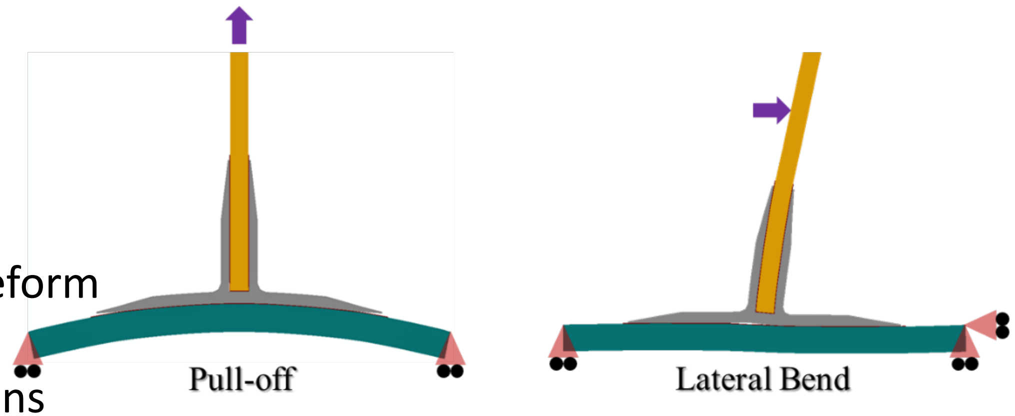




[4] Kirby et al. AIAA SciTech, 2022.

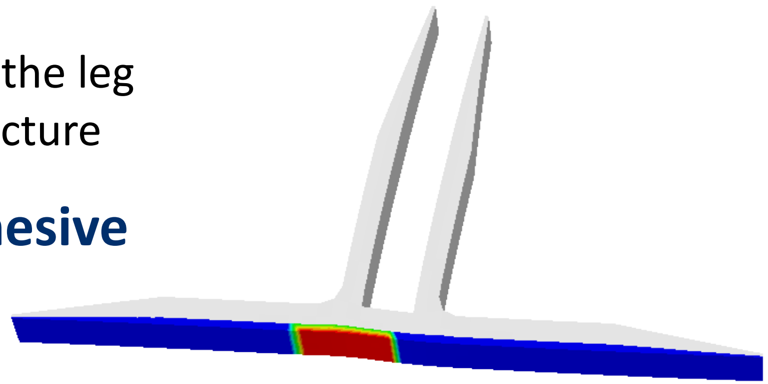
OPPERA Parametric Pi-joint Model Development

- **Parametric model of the pi-joint in Abaqus[5]**
  - Over 100 geometric, mechanical, and fracture parameters
  - Linear elastic material properties for pi-preform, web, and skin
  - Cohesive zone model for adhesive bond
  - Predicts stresses in pi-preform → does not model damage in preform
  - Simulates pure pull-off (PO), pure lateral bend (LB), and combined pull-off plus lateral bend (PO+LB) loading configurations
  - Currently developing capabilities for pure shear (PS) loading configuration



- **Focus of this study is predicting the lateral bend (LB) response of the pi-joint**
  - Only have validated mesoscale model for pi-preform leg architecture
  - LB response is more sensitive to leg architecture than PO due to bending in the leg
  - In this study, the pi-preform base and leg are assumed to have same architecture
- **During LB pi-joint testing, failures have been observed in the adhesive (Mode I fracture) and the pi-preform radius**

Predicted Adhesive Failure During Lateral Bend Testing



[5] Kirby et al. AIAA SciTech, 2023.

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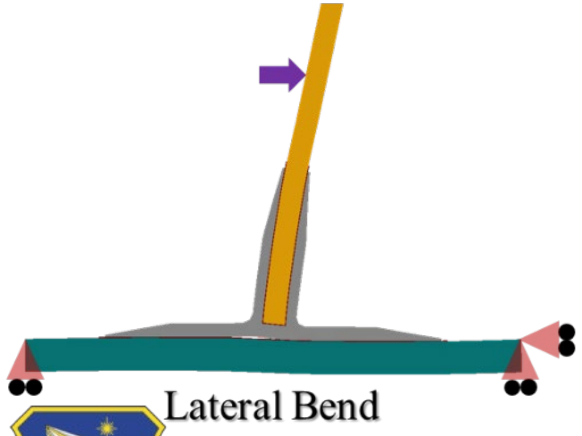
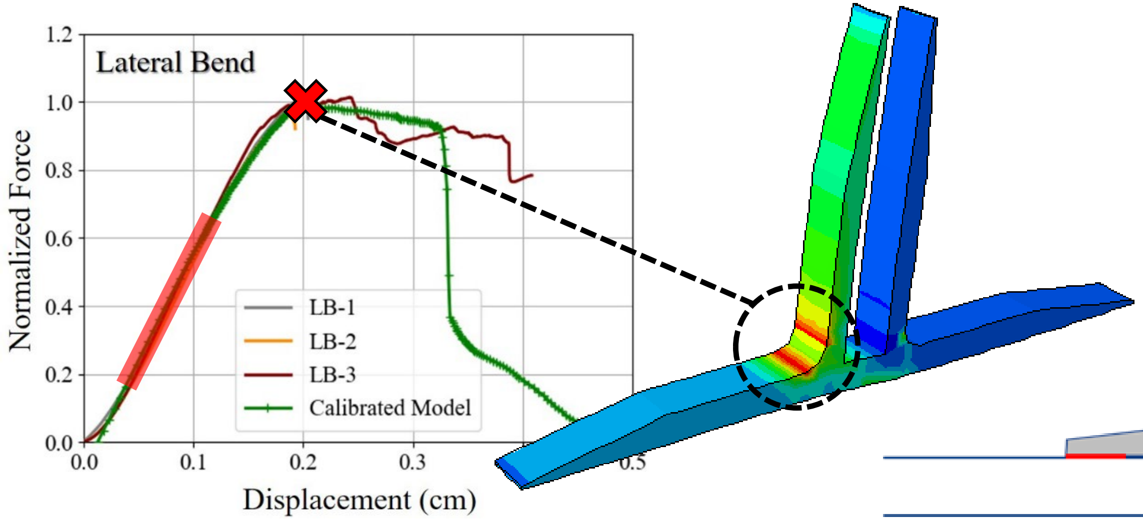
Macroscale Responses of Interest

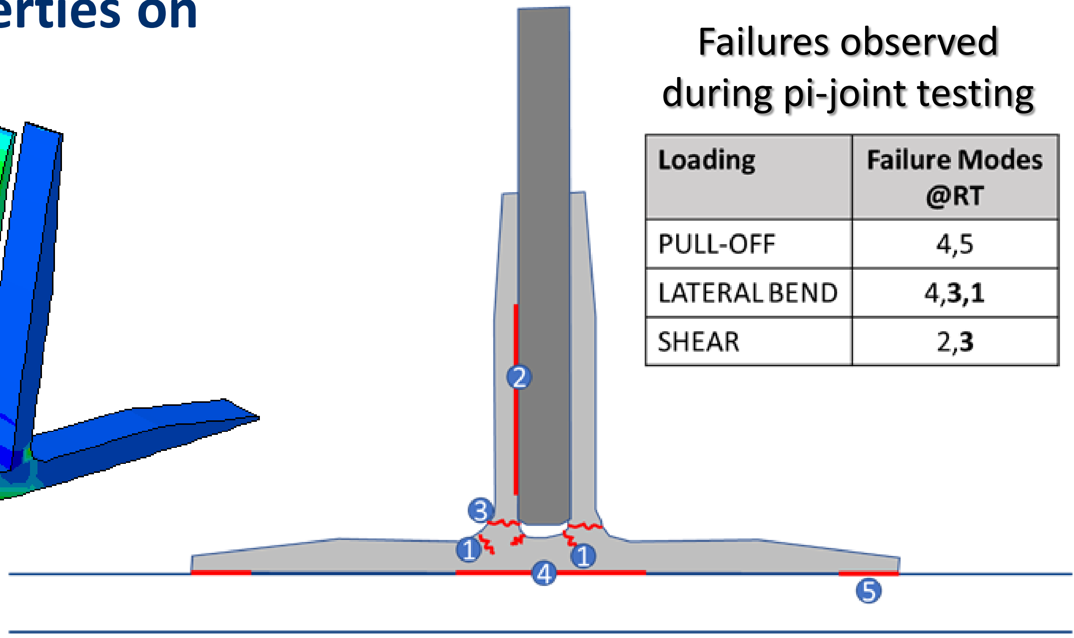
- **Failure of the pi-preform in the radius between base and leg is a concern (failure modes 1 & 3)**
  - The model does not capture pi-preform damage, so max stress & strain in this region are the quantities of interest
  - Future work could involve using homogenized strength or strain-based criteria to predict damage onset in preform
- **Macroscale model responses of interest**
  - Maximum load and stiffness (slope) from force-displacement curve
  - Maximum stress in pi-preform radius at maximum load → associated with failure modes 1 & 3
- **What is the impact of uncertainty in mesoscale properties on uncertainty in the predicted lateral bend response?**





Failures observed during pi-joint testing

Loading	Failure Modes @RT
PULL-OFF	4,5
LATERAL BEND	4,**3**,**1**
SHEAR	2,**3**



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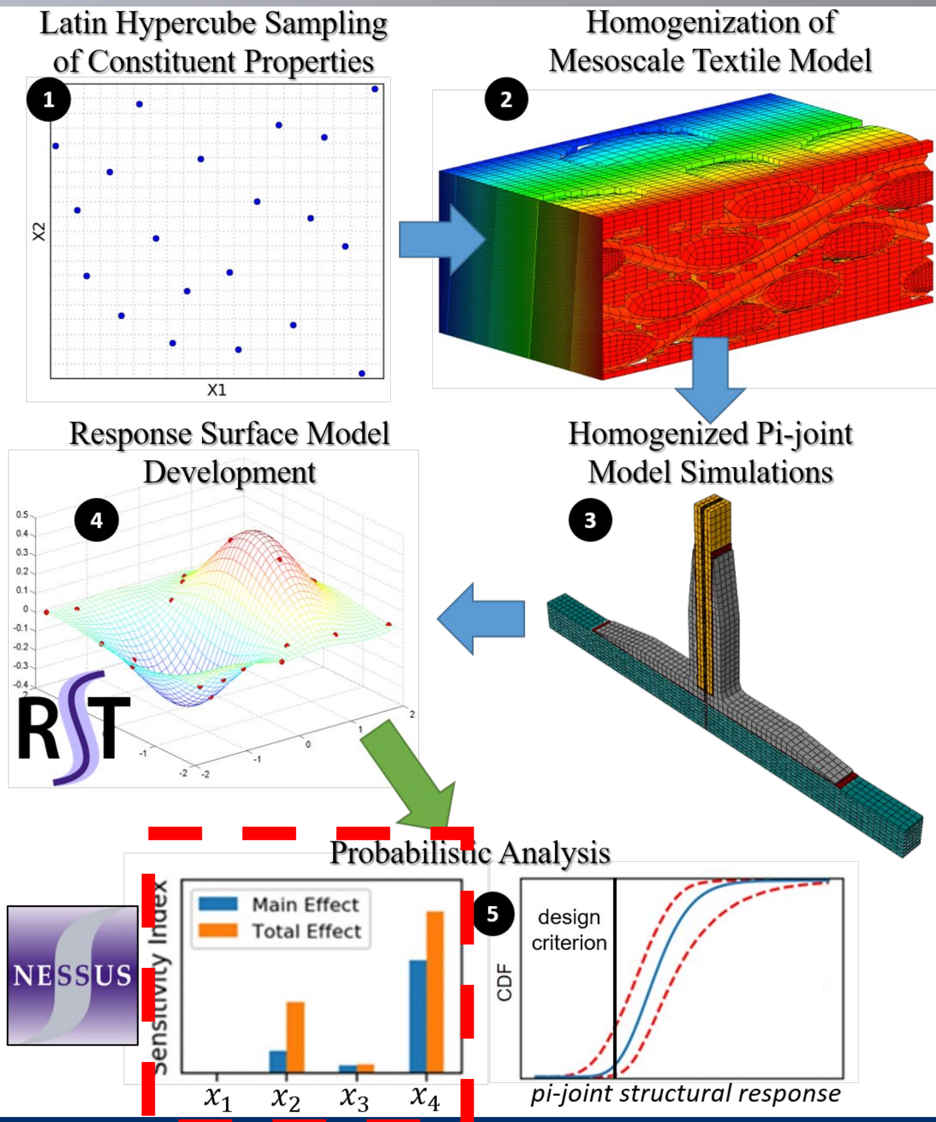
Probabilistic Analysis – Sensitivity Studies

- **NESSUS® 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 the 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
- **Sensitivity analysis objectives**
  - Elucidate relationship between mesoscale architecture and macroscale pi-joint response
  - Identifying steps to reduce uncertainty in model predictions and mature the P2P framework



Characterization and Uncertainty Quantification

Mesoscale Textile Model[4]

Constituent Material Property	COV (%)	Number of Measurements (N)	Characterization Method	Layup
Matrix Tensile Modulus (E_m)	5.98	12	ASTM D638	N/A
Matrix Poisson's Ratio (ν_m)	1.66	4	ASTM D638	N/A
Tow Longitudinal Tensile Modulus ($E_{1,tow}$)	2.17	8	ASTM D3039	$[0]_8$
Tow Transverse Tensile Modulus ($E_{2,tow}$)	3.16	5	ASTM D3039	$[90]_{16}$
Tow XY Shear Modulus ($G_{12,tow}$)	3.80	4	non-standard PTS15	$[0]_{48}$
Tow XZ Shear Modulus ($G_{13,tow}$)	1.49	6	modified ASTM D2344	$[0]_{48}$
Tow YZ Shear Modulus ($G_{23,tow}$)	2.30	4	non-standard PTS15	$[0]_{48}$
Tow XY Poisson's Ratio ($\nu_{12,tow}$)	8.45	3	ASTM D3039	$[0]_8$
Warp Tow Fiber Volume Fraction ($V_{f,warp}$)	6.17	8	optical microscopy	N/A
Fill Tow Fiber Volume Fraction ($V_{f,fill}$)	5.14	10	optical microscopy	N/A

Macroscale Pi-joint Model[5]

Pi-joint Model Parameter Description	Parameter	Approx. COV (%)	Uncertainty Quantification
Pi-joint Geometry			
Base Thickness	*tb*	3	calibration
Base Taper Thickness	*tb_taper*	5	conservative assumption
Full Base Width, including taper	*wb_taper*	5	calibration
Leg Thickness	*tl*	3	calibration
Leg Taper Thickness	*tl_taper*	5	conservative assumption
Leg Width, including taper	*wl_taper*	4	calibration
Unitape Skin Ply Thickness	*tply_uni*	3.75	calibration
Fabric Web Ply Thickness	*tply_fab*	5	calibration
Unitape and Fabric Mechanical Properties			
Unitape Skin Shear Modulus G23	*G23_u*	10	conservative assumption
Quasi-isotropic Unitape Mod. E11 Tension	*E11_tqu*	10	calibration
Quasi-Isotropic Fabric Mod. E11 Tension	*E11_tqf*	10	conservative assumption
Adhesive Cohesive Zone Law			
Normal Strength, Mode I	*S_n*	20	calibration
Shear Strength, Mode II	*S_s*	20	calibration
Mode I Strain Energy Release Rate	*G_n*	20	calibration
Mode II Strain Energy Release Rate	*G_s*	20	calibration
Mixed-mode Exponent	*BK*	10	calibration
Compliance Constant, Mode I	*alpha_n*	20	calibration
Compliance Constant, Mode II	*alpha_s*	20	calibration

$$COV = \frac{standard\ deviation}{mean}$$

[4] Kirby et al. AIAA SciTech, 2022. [5] Kirby et al. AIAA SciTech, 2023.

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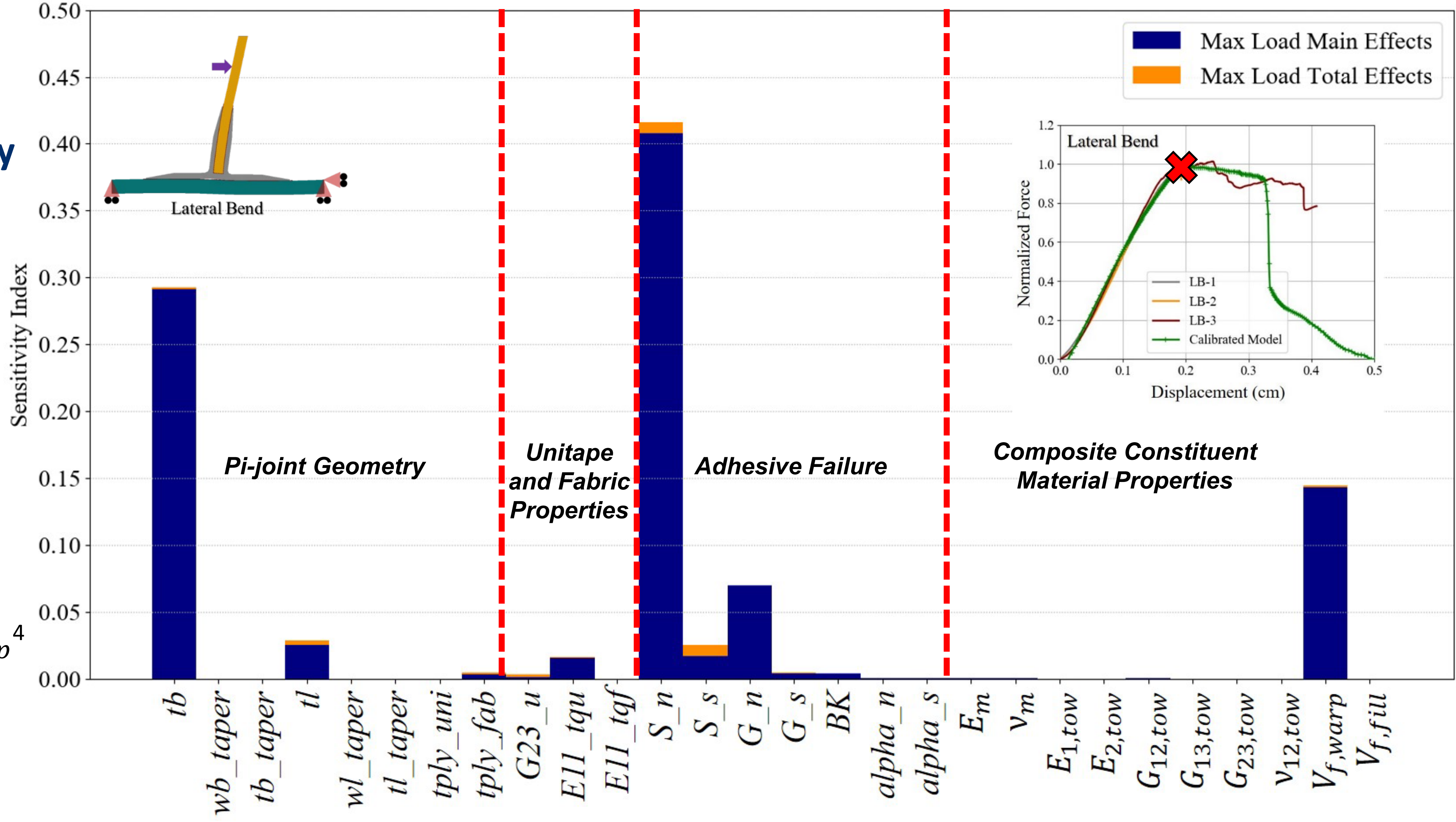
Maximum Load Response

- Max load is primarily governed by **failure of the adhesive but also influenced by geometry**
- Most sensitive to the Mode I cohesive zone strength → **unexpected for a bending test**
- Of constituent properties, only sensitive to $V_{f,warp}$
  - E_1 in the leg is most sensitive to uncertainty in $V_{f,warp}$ [4]
  - Beam theory → **bending stress is a function of E_1 in the leg**



[4] Kirby et al. AIAA SciTech, 2022.

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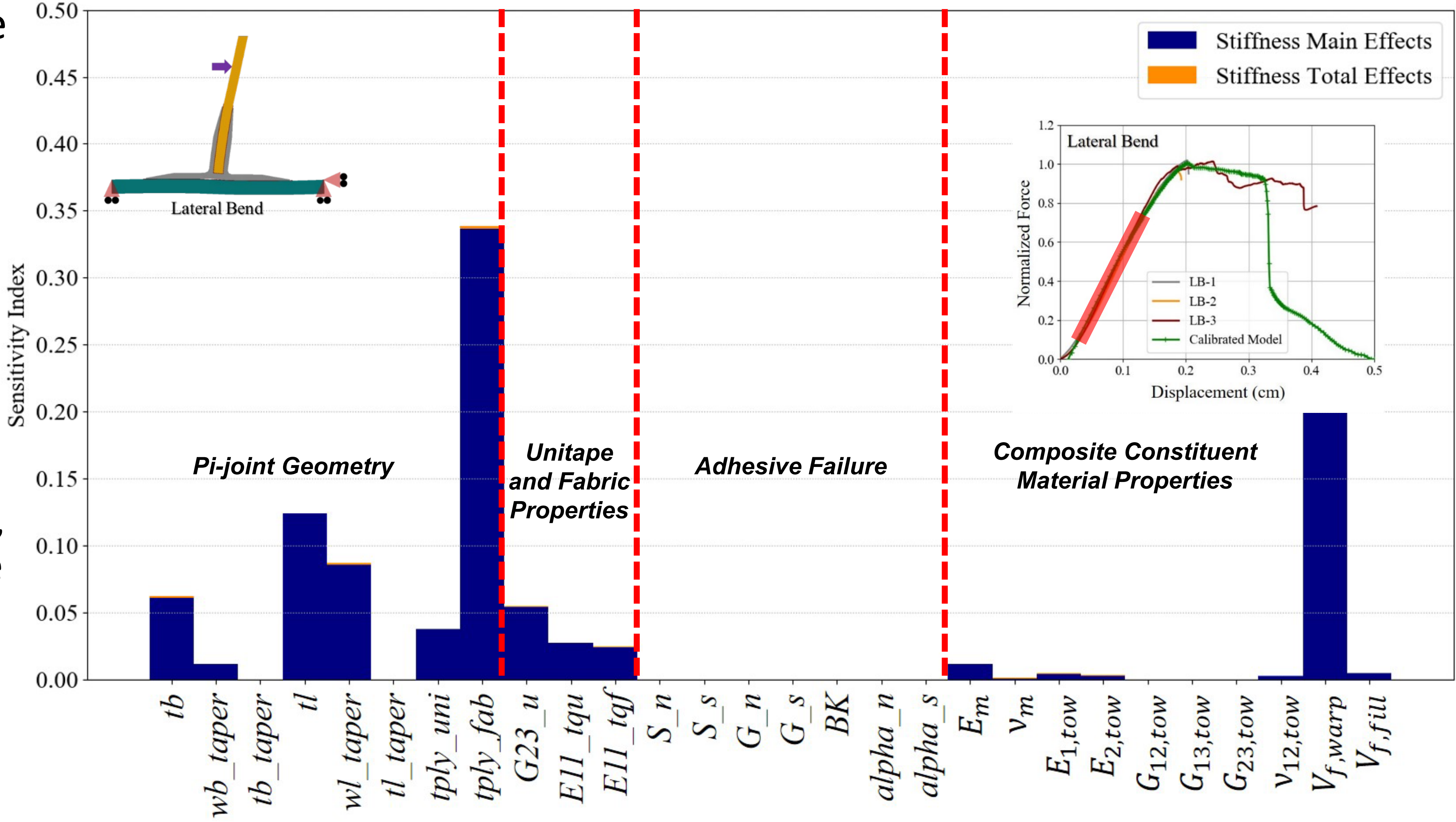
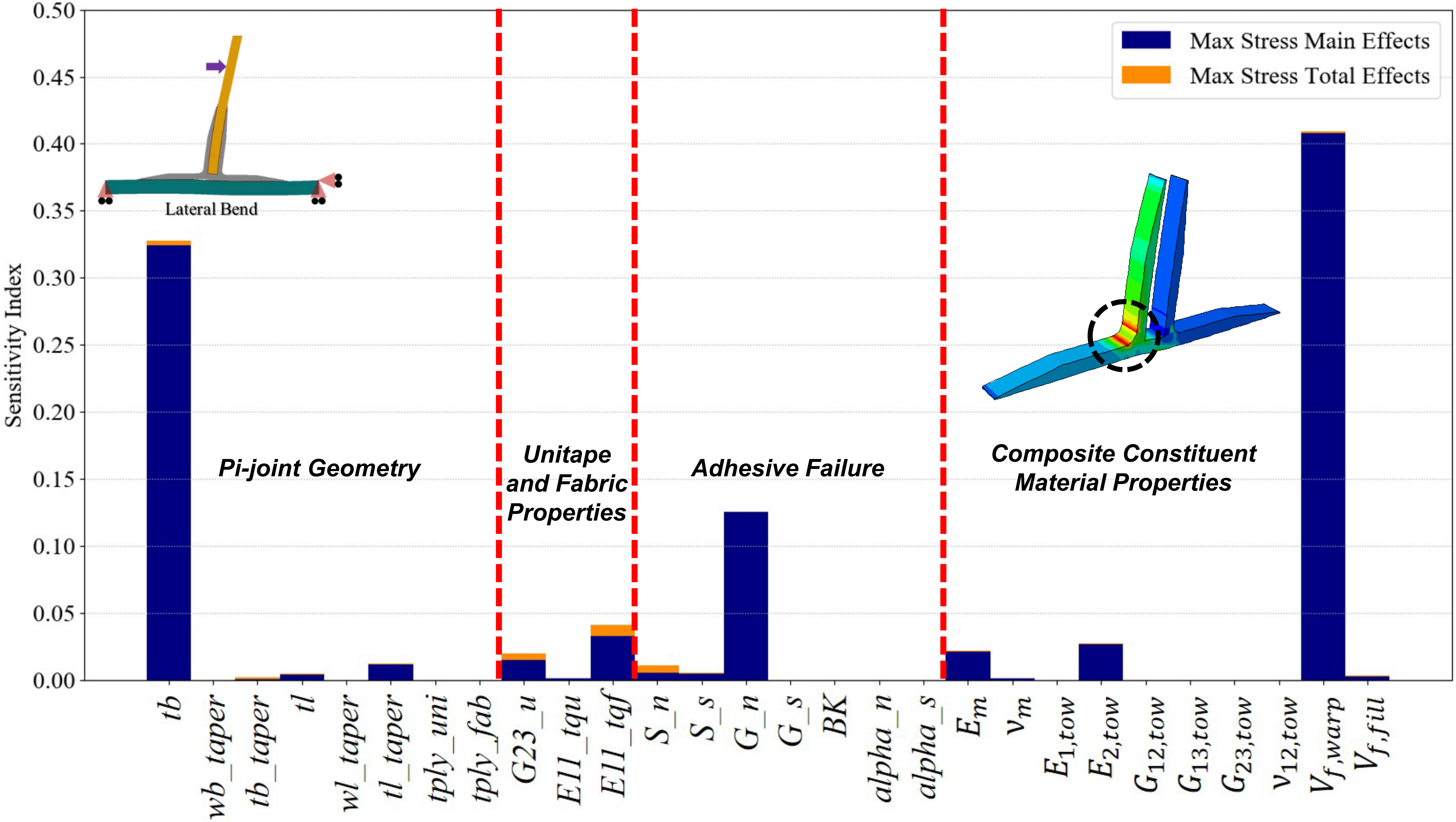
Stiffness Response

- Stiffness is sensitive to pi-joint geometry, not adhesive failure
- Bending stiffness directly related to **fabric web thickness** and $\boldsymbol{E_1}$ **in leg**
- Similar to max load, stiffness is sensitive to $V_{f,warp}$ → **significance of** $\boldsymbol{E_1}$ **in leg**



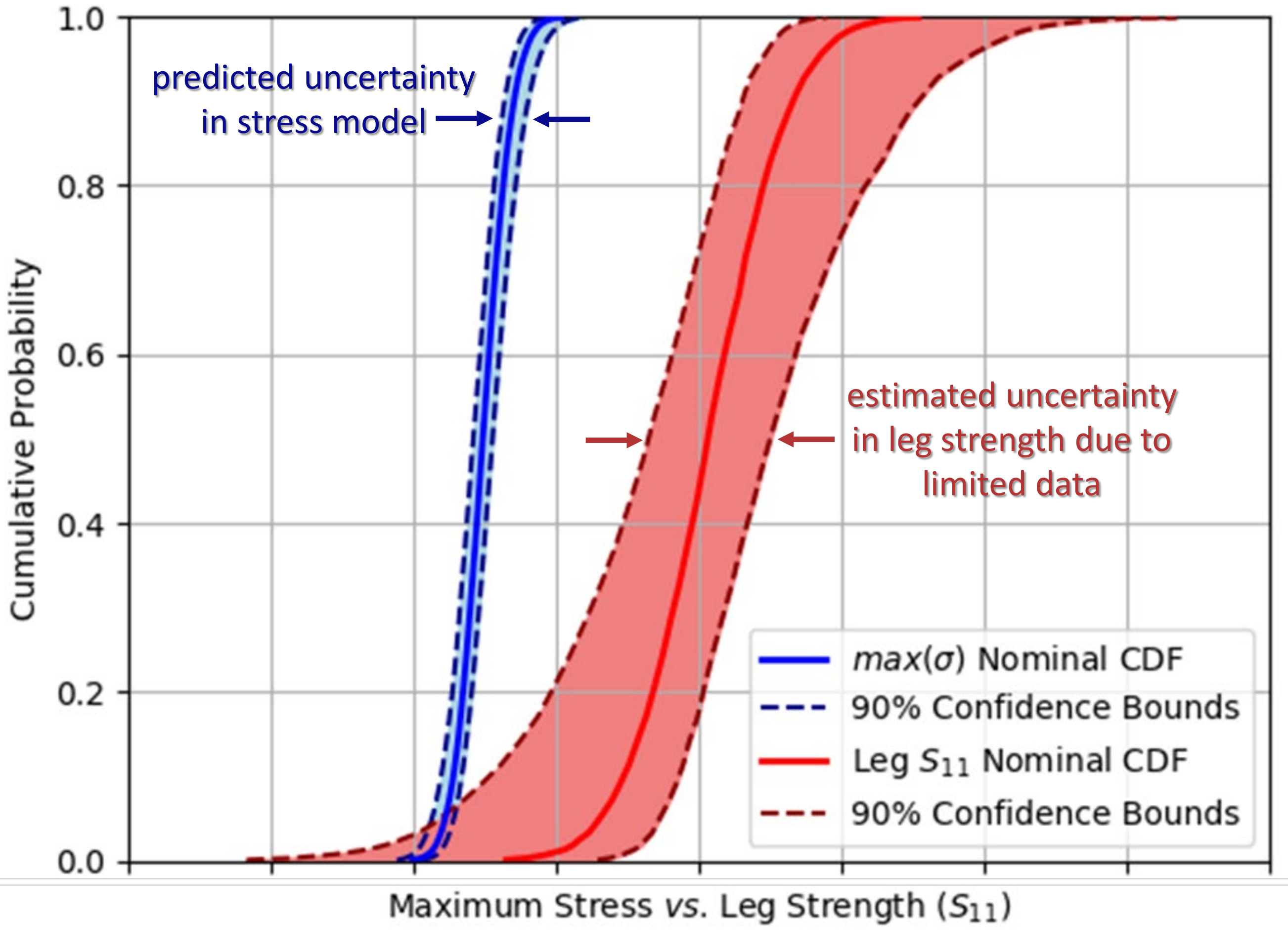
Maximum Stress Response

- Max stress in the pi-preform during LB is in the radius btwn base and leg
- **Max stress is primarily sensitive to constituent properties ($V_{f,warp}$)** and is also influenced by geometry
- Should pursue efforts to reduce uncertainty in $V_{f,warp}$ and tb
- Interaction btwn pi-preform fracture and adhesive failure is not captured in model



Cumulative Distribution Function Analysis

- Can use model for max stress or max load to compare to experimental data → **reliability analysis**
  - Could compute the probability that the max stress exceeds the strength
  - Could estimate probability of pi-preform fracture *vs*. failure in the adhesive for pristine pi-joints
- Limited data for leg strength (5 tests) is a significant source of uncertainty → **recommend additional tests to reduce uncertainty**
- Future work → **how does predicted uncertainty using mesoscale model compare to measured uncertainty?**



Summary and Next Steps

- Developing a multiscale 3D textile pi-joint model to aid in design and analysis of textile architectures and investigate their impact on component performance
- Sensitivities provide an understanding of the impact of uncertainty at the constituent level on uncertainty in the predicted pi-joint response
- Limitation of the parametric pi-joint model = damage only modeled in the adhesive → global force-displacement response does not show sensitivity to constituent properties other than $V_{f,warp}$
- Future work:
  - Use separate textile models for base, leg, and transition region
  - Compare and contrast different fiber weave architectures and constituent materials (different fiber and resin)
  - Look at additional loading cases → only looked at lateral bend so far
  - Further investigation of uncertainty in fiber volume fraction → all responses sensitive to $V_{f,warp}$
- **The homogenized model approach is only one piece of the larger P2P framework that is being developed under OPPERA**

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