Estimation of 3D Woven Design Sensitivities Using a Rapid Multiscale Analysis Technique

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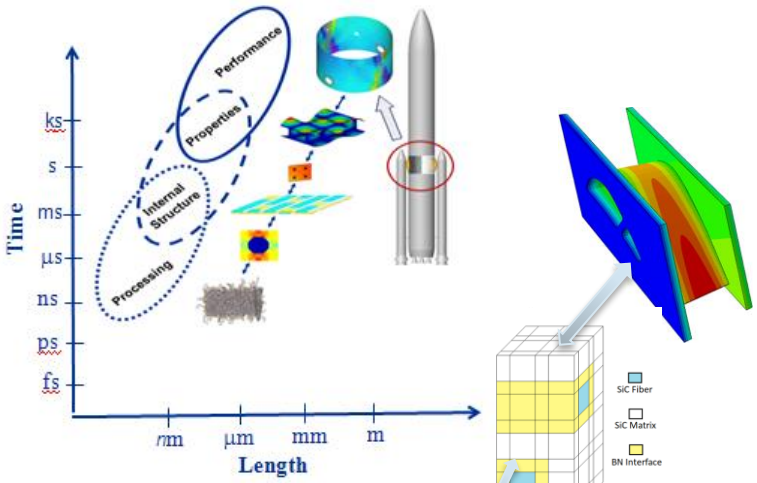
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Introduction

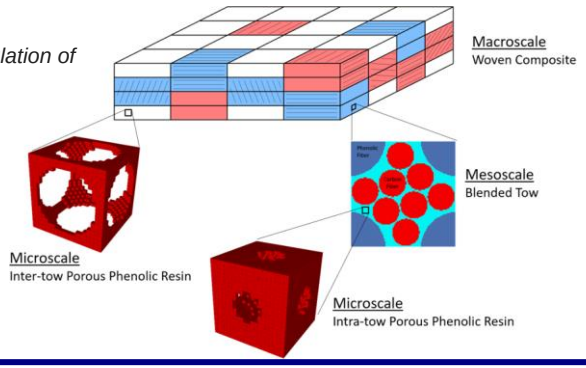
- Increasing use of 3D woven composites in recent years
- Enhanced damage tolerance and customizability
- Multiple systems explored by NASA for space missions:
  - Adaptive Deployable Entry Placement Technology (ADEPT)
  - 3D Multifunctional Ablative Thermal Protection System (3D-MAT)
  - Heatshield for Extreme Entry Environment Technology (HEEET)
  - 3D Medium Density Carbon Phenolic (3MDCP)
  - Several systems for Composite Technologies for Exploration (CTE)
- Significant body of experimental work, few multiscale modeling studies
- Predominant modeling approach in the literature:
  - Single-scale analysis
  - Highly-refined finite element analysis
  - Effective property prediction

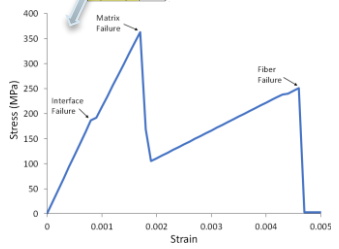
NASA Multiscale Analysis Tool (NASMAT)

- Successor to MAC/GMC and FEAMAC toolsets
- A framework designed to support massively multiscale modeling (M3) on high-performance computing (HPC) sy
  - Solves real, large-scale, non-linear, thermo-mechanical problems
- Modular design to support “plug-and-play” capabilities
  - Operational components categorized into NASMAT procedures
    - Each procedure has access to a library of modules
- Developed for enhanced interoperability
  - Integrates with 3rd party structural analysis codes (e.g., FEA)
  - Library of constitutive laws/damage models
  - Data output in HDF5 file format
- Ideal for “design with” or “design of” the material
  - Enables Integrated Computational Materials Engineering (ICME)
  - Developed to support NASA Vision 2040



Multiscale localization/homogenization



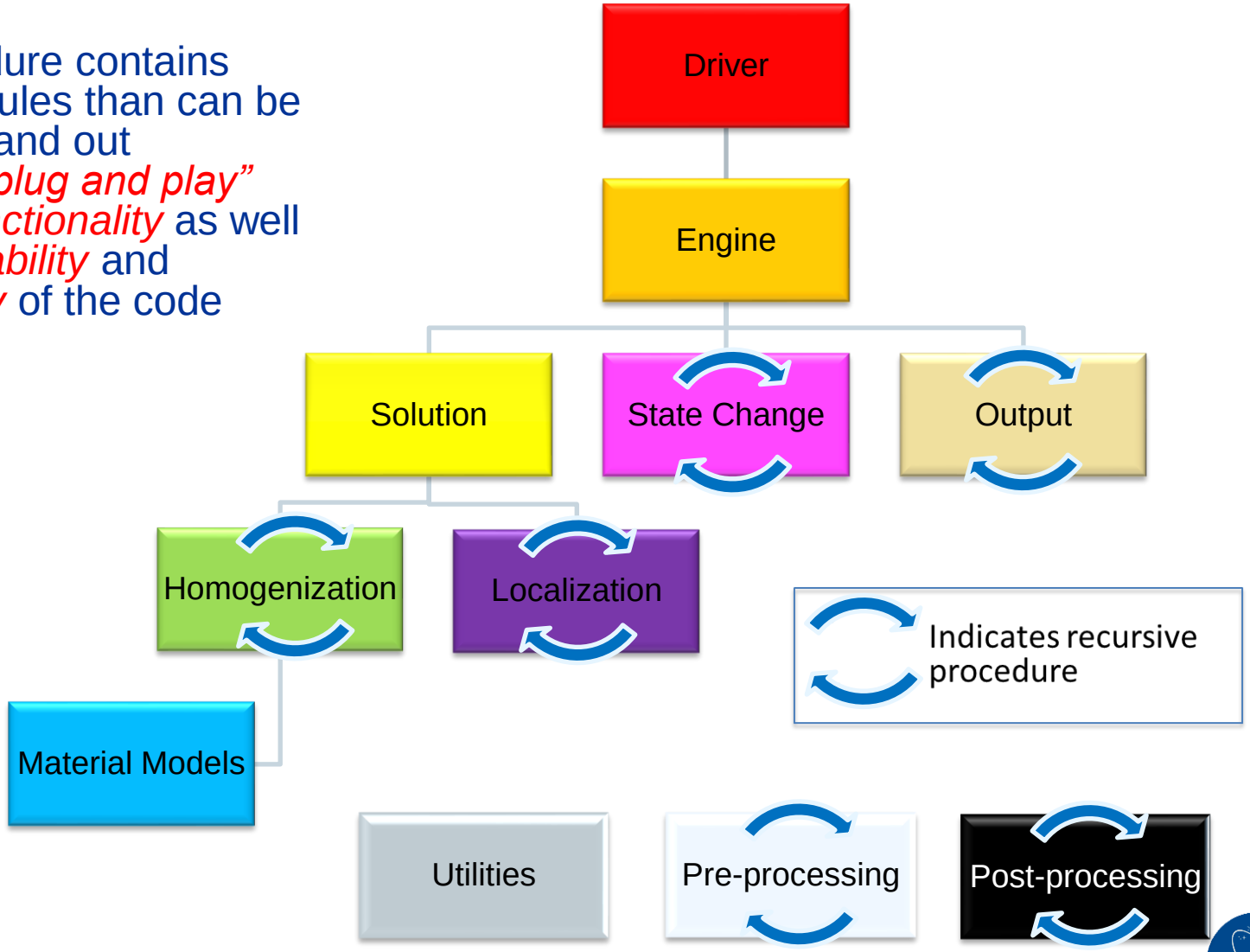


Liu, Xuan, et al. *Vision 2040: a roadmap for integrated, multiscale modeling and simulation of materials and systems*. NASA/CR-2018-219771.

NASMAT
NASA Multiscale Analysis Tool

NASMAT Workflow

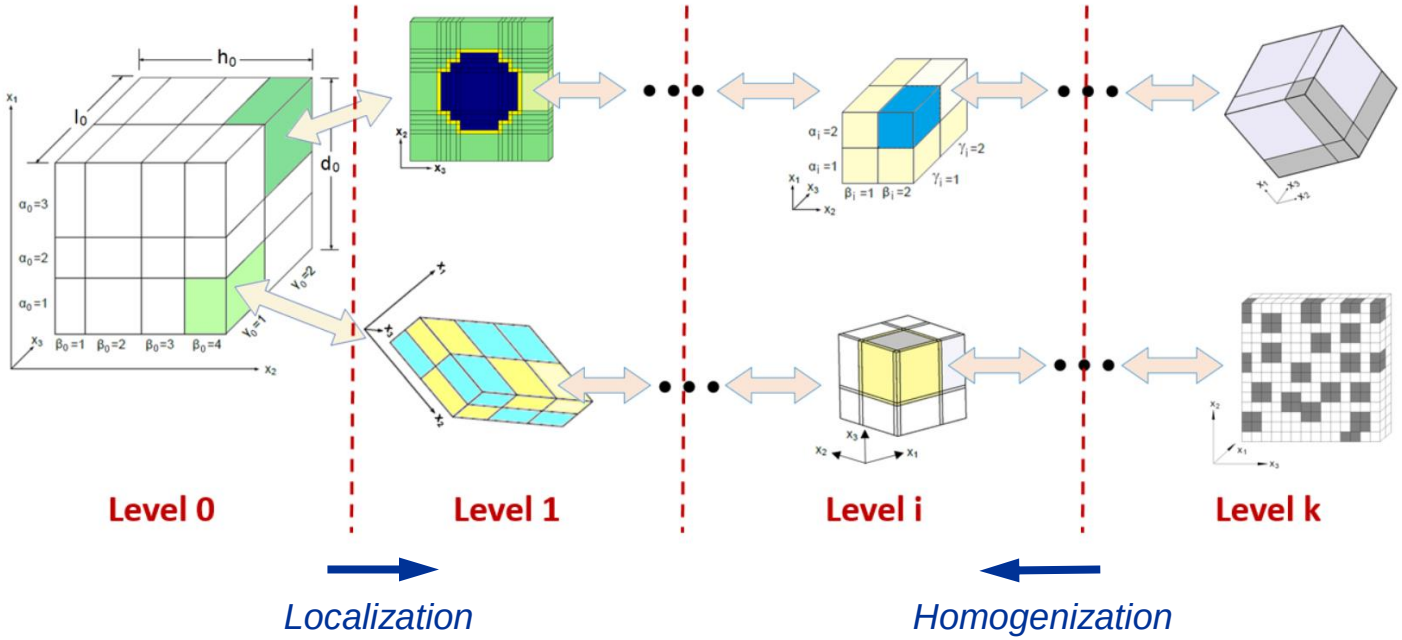
- Each procedure contains various modules than can be swapped in and out supporting *"plug and play"* and *user functionality* as well as *maintainability* and *upgradability* of the code



Multiscale Recursive Micromechanics (MsRM)

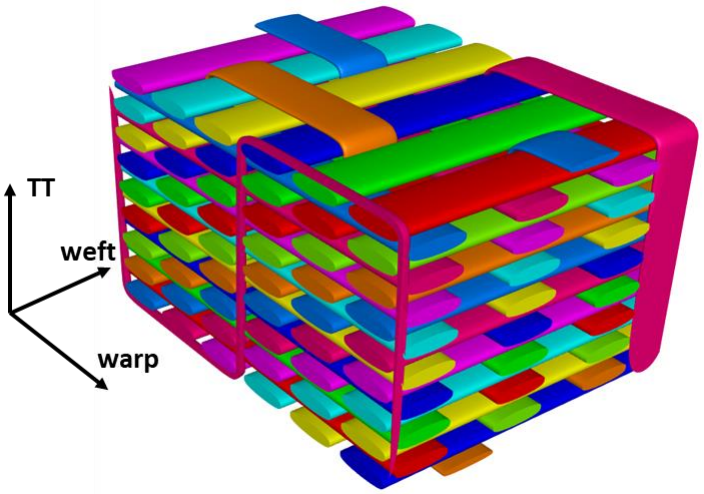
- Multiple available micromechanics theories
- Call each other (or themselves, recursively)
- Captures microstructure on any number of scales
- No limit on depth of scales

NASMAT
NASA Multiscale Analysis Tool



3D Woven Architecture

- IM7-6k/RTM6 3D orthogonal weave
  - Preform: Bally Ribbon Mills
  - Resin infusion: North Coast Composites
- 24 warp tows (8 layers, 3 columns)
- 54 weft tows (9 layers, 6 columns)
- 3 binder tows
- Approximate designed unit cell size:
  - 8.23 mm (warp)
  - 4.80 mm (weft)
  - 3.18 mm (thickness)
- Characterization methods
  - Standard coupon testing
  - X-ray computed tomography (CT)



Coupon Test Data

- Tensile testing in warp/weft directions performed by the National Institute for Aviation Research (NIAR)
  - Five 254.0 mm x 25.4 mm specimens (ASTM D3039) per direction
  - Modulus and strength data utilized
  - Strain gage (SG) and digital image correlation (DIC) data available
- In-house acid-digestion testing (ASTM D3171 Procedure B)
  - 9 specimens
  - Fiber volume fraction (mean: 0.48, std: 0.01)
  - Void content (mean: 1.7%, std: 0.3%)

Specimen	Warp-Direction			Weft-Direction		
	Modulus (MPa) SG	Modulus (MPa) DIC	Strength (MPa)	Modulus (MPa) SG	Modulus (MPa) DIC	Strength (MPa)
1	58066	57549	915	67754	-	970
2	58497	56173	892	67088	68137	933
3	59778	56537	906	66680	-	905
4	58575	57864	871	69624	70919	894
5	58960	-	924	69198	70481	909
Average	**58775**	**57031**	**902**	**68069**	**69846**	**922**
St. Dev.	**644**	**805**	**21**	**1293**	**1496**	**30**

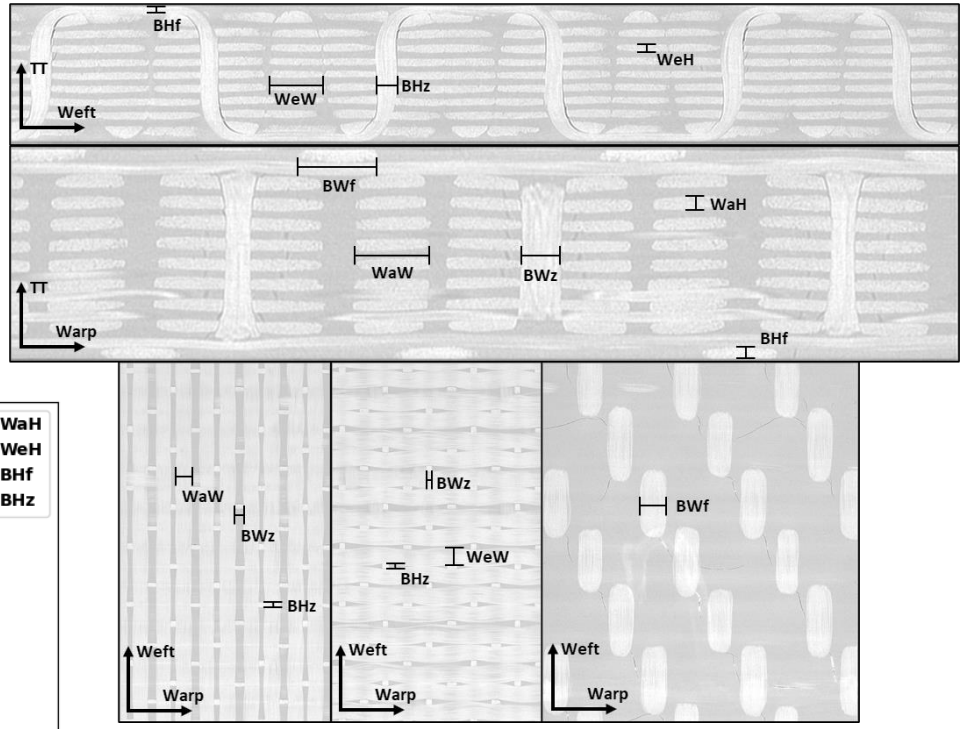
Geometric Characterization

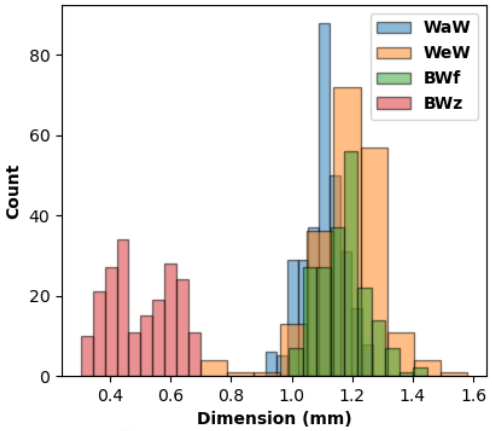
- X-ray CT performed by NIAR prior to testing
  - Different specimens from same test panel
  - 13.4 µm resolution
  - Various dimensions identified and measured

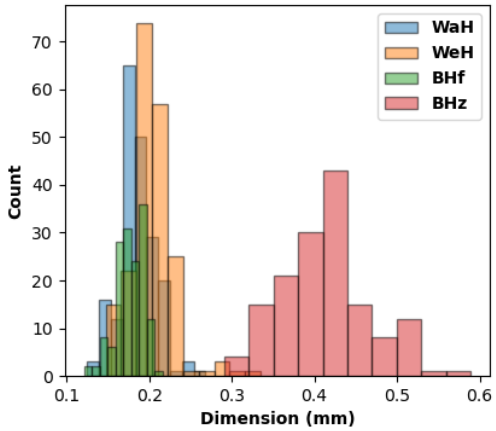
See reference for more info:

Jackson, W.C.; Bergan, A.; Rose, C.A.; Segal, K.N; Gardner, N.W.; Waas, N.W. Experimental Observations of Damage States in Unnotched and Notched 3D Orthogonal Woven Coupons Loaded in Tension. in the proceedings of the AIAA SCITECH 2022 Forum, Jan 3-7, 2022. San Diego, CA.

Variable	Description
WaW	warp tow width
WaH	warp tow height
WeW	weft tow width
WeH	weft tow height
BWf	binder tow width (flat region)
BHf	binder tow height (flat region)
BWz	binder tow width (TT region)
BHz	binder tow height (TT region)







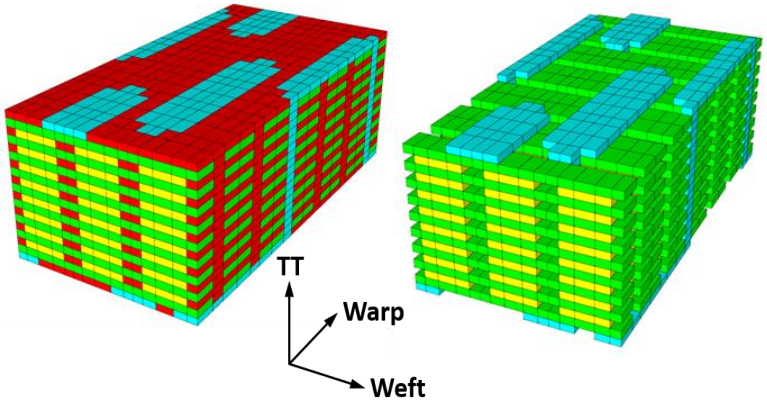
Sensitivity Analysis

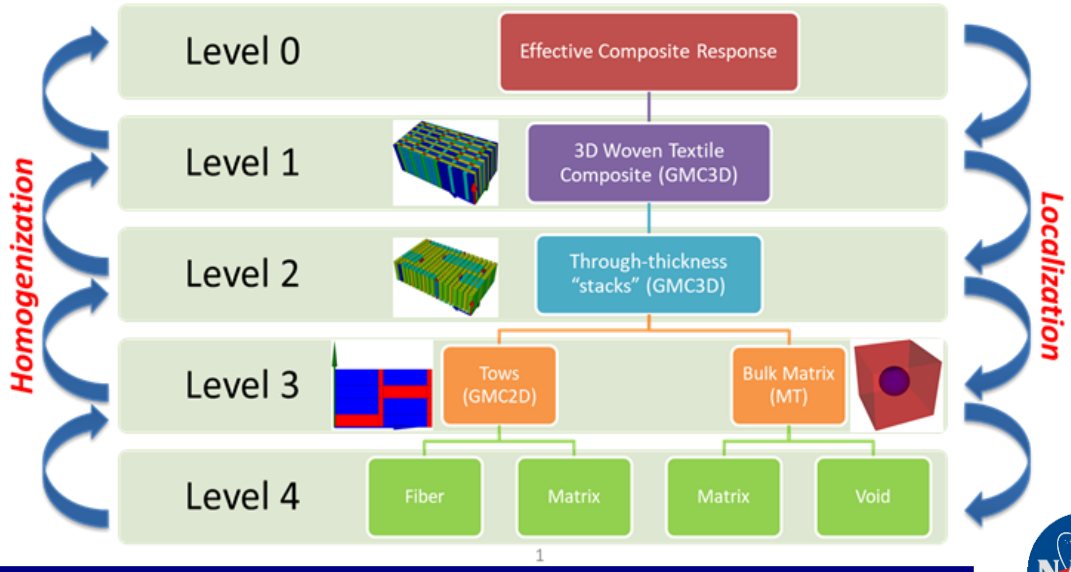
- Goal: quantify which inputs contribute most to a particular output
- Can be used to downselect quantities of interest or prioritize characterization tests
- Multiple approaches available
- Pearson Correlation Coefficients calculated (as implemented in MATLAB)
  - Measured linear correlation of input A to output B
- Generated 50,000 sets of inputs, 100,000 NASMAT analyses run (warp/weft loading)
- Leveraged a high computing performance (HPC) cluster to speed up calculations
  - 120 Intel Xeon E5-2698 v4 CPUs
- Approximate runtimes:
  - Pre-processing: 31 min
  - NASMAT runs: 6.25 hours
  - Post-processing: 40 min
- Serial pre-/post-processing

$$\rho(A,B) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{A_i - \mu_A}{\sigma_A}\right)\left(\frac{B_i - \mu_B}{\sigma_B}\right)$$

NASMAT Modeling Strategy

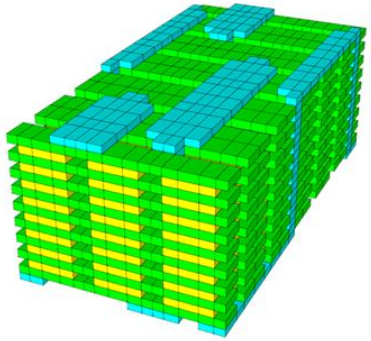
- Added flexibility with NASMAT to balance model accuracy with computational cost at each scale
- Textile modeled with GMC3D (5130 subcells)
  - Levels 1 and 2
- Tows modeled with GMC2D (16 subcells)
  - Level 3 – contains tow orientations
- Inter-tow matrix modeled with Mori-Tanaka
  - Level 3
  - Only void location
- Transversely isotropic fiber
- Isotropic matrix
- Max stress failure criteria
- Binder/warp overlap modeled





Input Variables

- All inputs assigned a truncated normal distribution with a prescribed coefficient of variation (CV)
- Lower/upper bounds set for ±3 standard deviations
- 25 total inputs
  - 10 geometric variables (dimensions, volume fractions)
  - 7 elastic material properties (fiber, matrix), 10% CV assumed
  - 8 failure properties (6 fiber, 2 matrix), 20% CV assumed



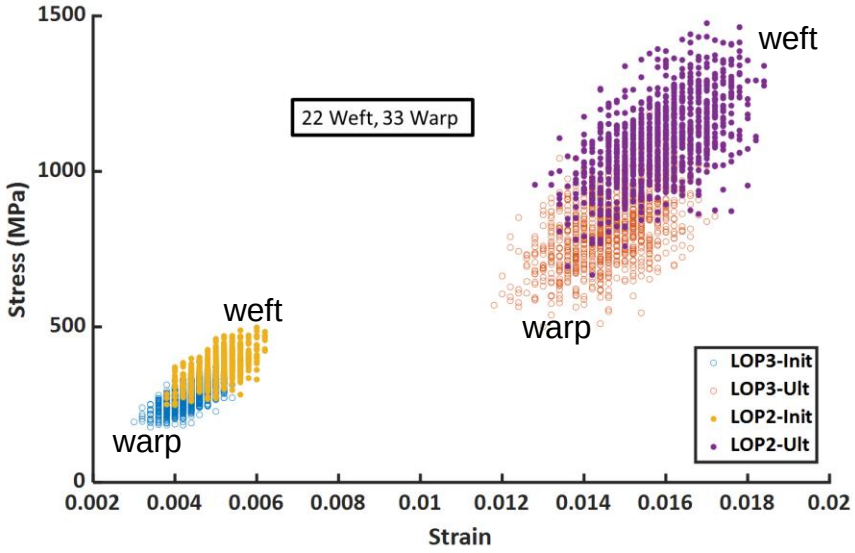
Category	Variable	Description	Units	Mean	St. Dev.	Lower Bound	Upper Bound
Geometric inputs	WaW	warp tow width	mm	1.108	0.068	0.904	1.312
	WaH	warp tow height	mm	0.186	0.022	0.121	0.251
	WeW	weft tow width	mm	1.186	0.118	0.831	1.541
	WeH	weft tow height	mm	0.202	0.026	0.124	0.281
	BWf	binder tow width (flat region)	mm	1.171	0.081	0.928	1.413
	BHf	binder tow height (flat region)	mm	0.174	0.017	0.123	0.225
	BWz	binder tow width (TT region)	mm	0.501	0.105	0.186	0.817
	BHz	binder tow height (TT region)	mm	0.413	0.052	0.256	0.569
	Vv	overall void volume fraction	-	0.017	0.003	0.008	0.026
	Vf	tow fiber volume fraction	-	0.700	0.070	0.490	0.910

Input Variables

Category	Variable	Description	Units	Mean	St. Dev.	Lower Bound	Upper Bound
Elastic properties	M-E	matrix modulus	MPa	2755.0	275.5	1928.5	3581.5
	M-v	matrix Poisson's ratio	-	0.380	0.038	0.266	0.494
	F-Ea	fiber axial modulus	MPa	262200.0	26220.0	183540.0	340860.0
	F-Et	fiber transverse modulus	MPa	11800.0	1180.0	8260.0	15340.0
	F-va	fiber axial Poisson's ratio	-	0.270	0.027	0.189	0.351
	F-vt	fiber transverse Poisson's ratio	-	0.210	0.021	0.147	0.273
	F-Ga	fiber axial shear modulus	MPa	18900.0	1890.0	13230.0	24570.0
Failure parameters	F-SIGF-FT	fiber tensile failure parameter (axial)	MPa	4335.0	867.0	1734.0	6936.0
	F-SIGF-TT	fiber tensile failure parameter (transverse)	MPa	113.0	22.6	45.2	180.8
	F-SIGF-X23	fiber shear failure parameter (in-plane)	MPa	128.0	25.6	51.2	204.8
	F-SIGF-X13	fiber shear failure parameter (out-of-plane)	MPa	138.0	27.6	55.2	220.8
	F-SIGF-FC	fiber compressive failure parameter (axial)	MPa	2608.0	521.6	1043.2	4172.8
	F-SIGF-TC	fiber compressive failure parameter (transverse)	MPa	354.0	70.8	141.6	566.4
	M-SIGFT	matrix normal failure parameter	MPa	87.0	17.4	34.8	139.2
	M-SIGFS	matrix shear failure parameter	MPa	76.1	15.2	30.4	121.8

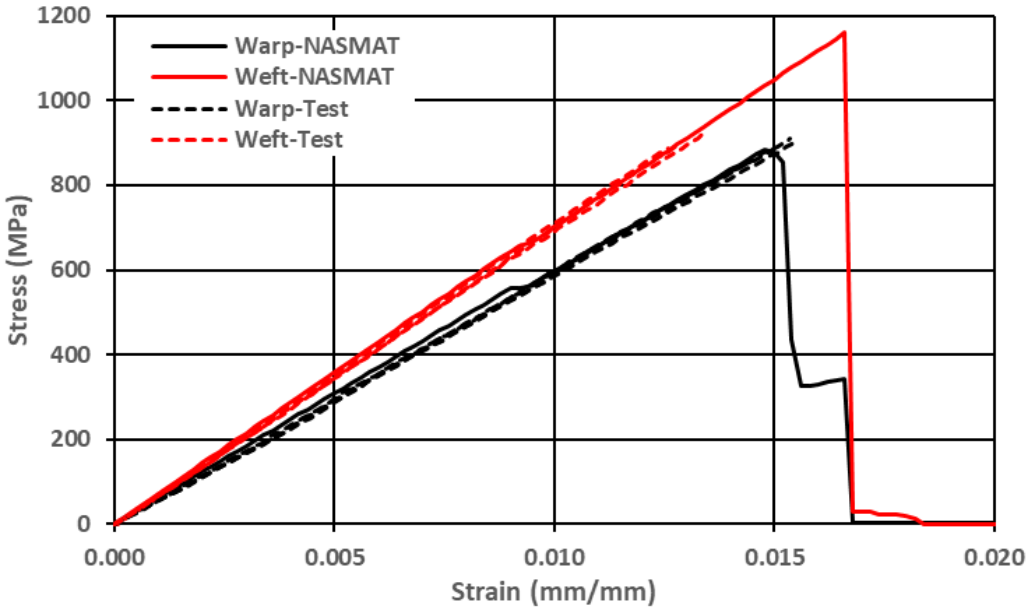
Output Variables

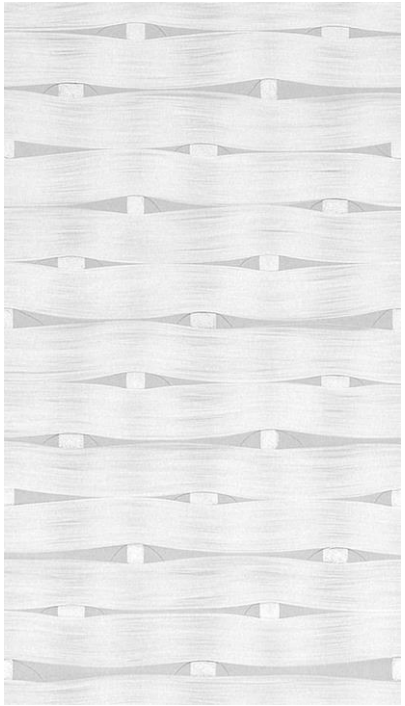
- Warp-direction
  - Stiffness
  - Damage initiation stress
  - Ultimate strength
- Weft-direction
  - Stiffness
  - Damage initiation stress
  - Ultimate strength
- Many other outputs available



Baseline NASMAT Results

- NASMAT model evaluated at mean input values
- Strain-control loading in warp and weft-directions
- Strain increment chosen based on convergence study
- Runtime for each analysis: ~30s
- Good agreement in stiffnesses, warp strength
- Over-prediction in weft-direction strength
  - Likely due to not modeling weft-tow waviness

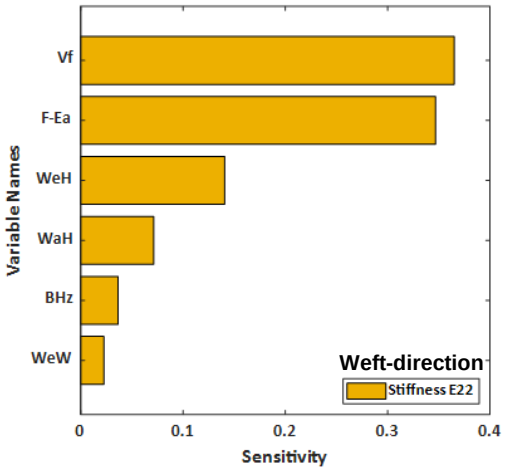


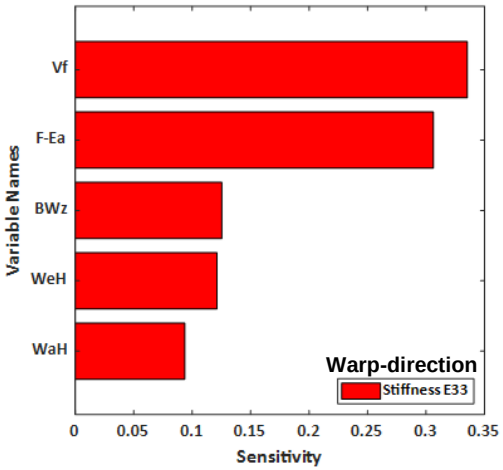


Sensitivity Analysis

- Pearson Correlation Coefficients calculated and ranked
- Values less than 0.01 not shown
- For stiffnesses:
  - Similar results between warp and weft
  - Tow fiber volume fraction and fiber axial modulus dominant
  - Various tow dimensions also important

Variable	Description
BHz	binder tow height (TT region)
BWz	binder tow width (TT region)
F-Ea	fiber axial modulus
Vf	tow fiber volume fraction
WaH	warp tow height
WeH	weft tow height
WeW	weft tow width

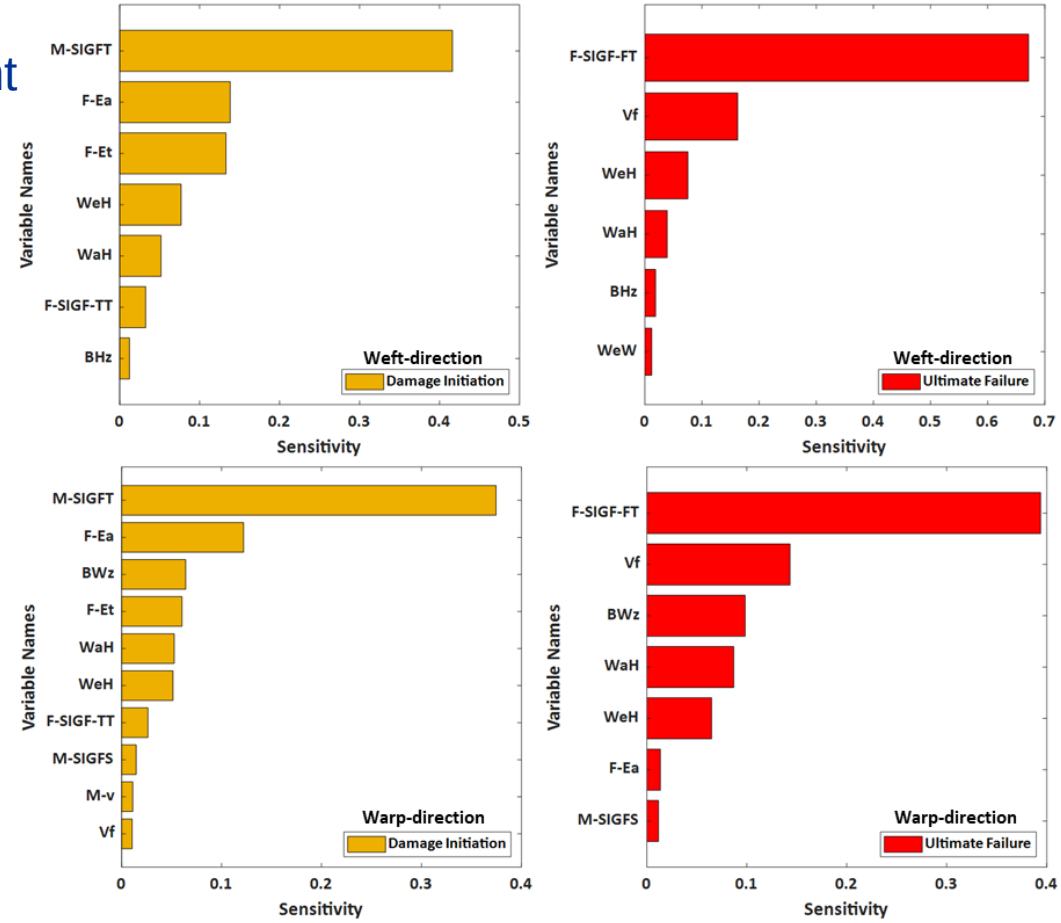




Sensitivity Analysis

- Similar results between warp and weft
- Damage initiation stress
  - Matrix tensile strength dominant
- Ultimate strength
  - Fiber axial tensile strength dominant
- Mix of dimensions, fiber properties, and tow fiber volume fraction with less importance

Variable	Description
BHz	binder tow height (TT region)
BWf	binder tow width (flat region)
BWz	binder tow width (TT region)
F-Ea	fiber axial modulus
F-Et	fiber transverse modulus
F-SIGF-FT	fiber axial tensile strength
M-SIGFT	matrix tensile strength
Vf	tow fiber volume fraction
WaH	warp tow height
WeH	weft tow height
WeW	weft tow width



Summary and Conclusions

- Presented a methodology for performing rapid sensitivity analyses of three-dimensional (3D) woven composites
- Accurate and efficient NASMAT models of 3D woven composites able to be obtained
  - Demonstrated for an IM7-6k/RTM6 orthogonal weave
  - Incorporated a large amount of x-ray computed tomography (CT) data
- Calculated sensitivities of different model outputs to a wide variety of inputs
  - 50,000 unique sets of inputs
  - 100,000 individual NASMAT analyses (~6 hours runtime)
  - Results consistent with theoretical expectations
- NASMAT readily able to be applied to uncertainty quantification, optimization, and machine learning problems

Acknowledgements

- Work performed as part of NASA's Entry Systems Modeling Project within the Space Technology Mission Directorate (STMD)

- Test data generated as part of NASA's Composite Technologies for Exploration Project within the STMD

Thank You For Your Attention



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