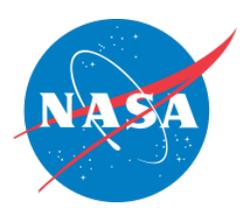


Application of the NASA Multiscale Analysis Tool: Multiscale Integration and Interoperability

Trenton M. Ricks, Evan J. Pineda,
Brett A. Bednarczyk, Steven M. Arnold

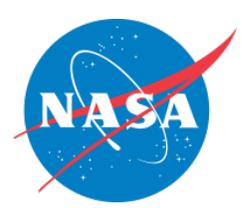


NASA Glenn Research Center, Cleveland, OH, USA



Outline

- Historical Context
- Overview of NASMAT
- Input Syntax
- Output Data and Visualization
- Example 1: Running a Single Scale Analysis in NASMAT
 - Unidirectional Ceramic Matrix Composite
- Example 2: Running a Multiscale Analysis in NASMAT
 - 3D Woven Textile Composite Including Failure
- Example 3: Calling NASMAT from an External Software
 - Multiscale Simulation of a Polymer Matrix Composite
- Profiling of NASMAT
- Future development
- Conclusions



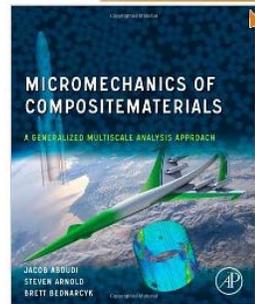
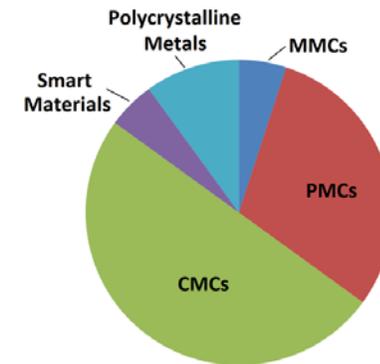
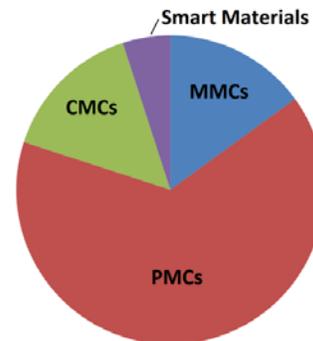
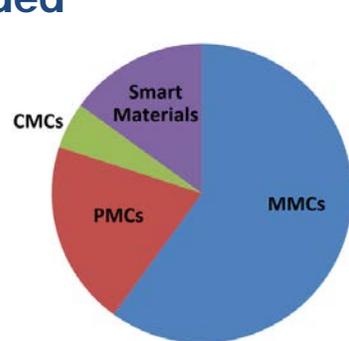
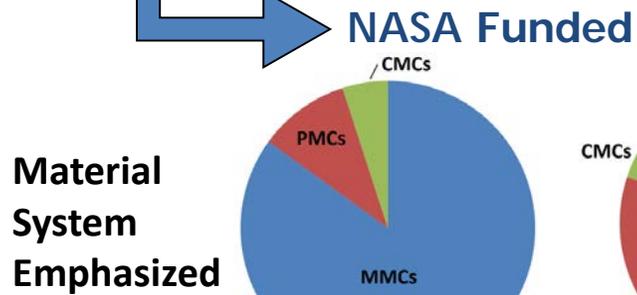
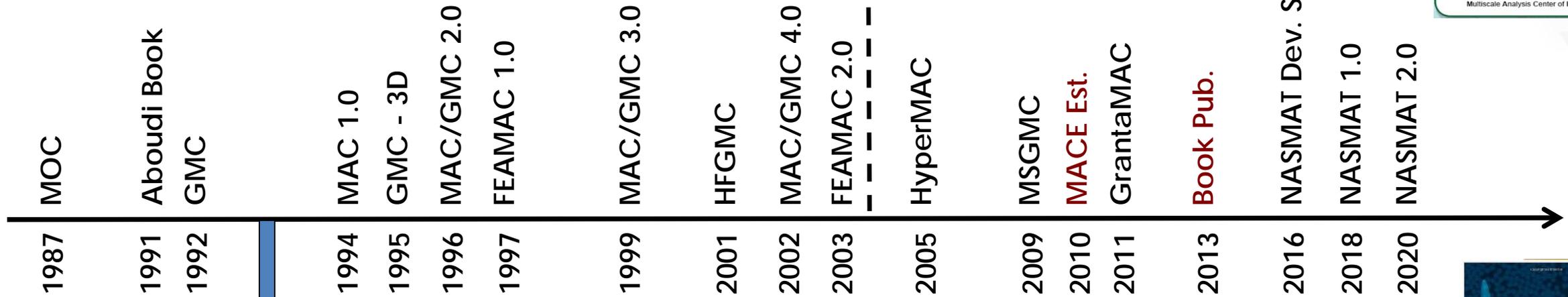
Micromechanics Analysis Code (MAC) Development Timeline History

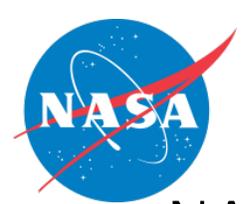
1992 – 2002: Development of basic tools/theories/methods

- Inelastic deformation/constitutive model development
- Fiber-matrix debonding/interfaces
- Fatigue, creep fatigue
- Laminate dominated

Focus shift:

- Woven/braided composites
- Multiscale
- Visualization tools
- Damage/failure

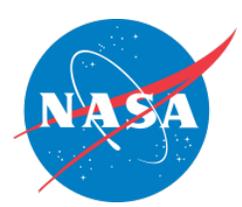




What is NASMAT?

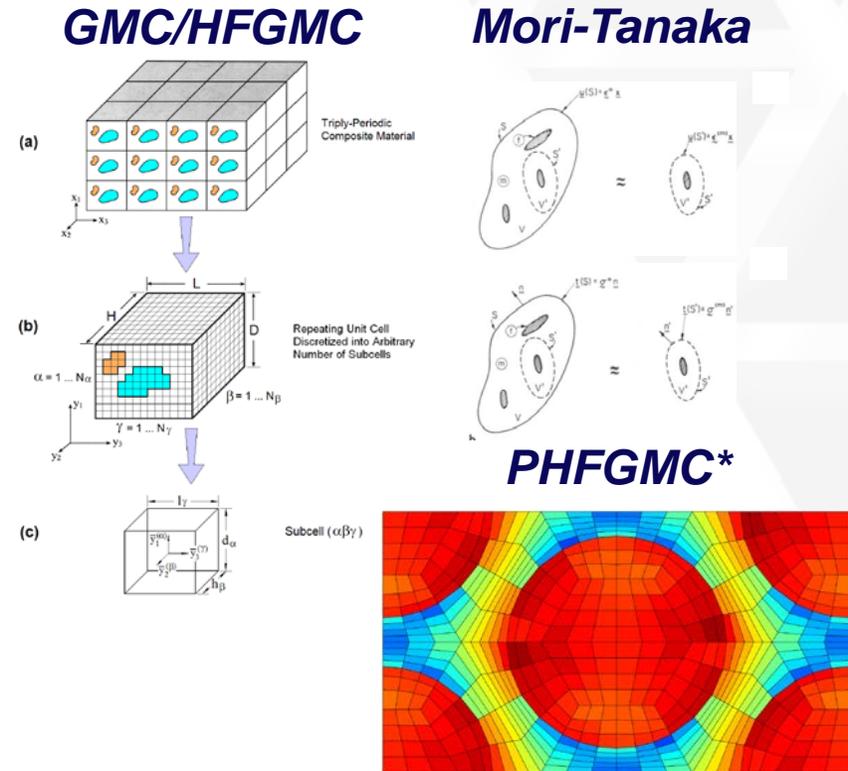
- NASA Multiscale Analysis Tool
 - a state-of-the-art, parallelized, “plug-and-play”, computational platform for performing multiscale analysis of heterogeneous materials
- **A framework designed to support massively multiscale modeling (M^3) on high-performance computing (HPC) systems**
 - Recursive procedures, subroutines, and data structures employed
- Modular design to support “*plug-and-play*” capabilities
 - Operational components categorized into 11 NASMAT procedures
 - Each procedure has access to a library of modules
 - Facilitates robust user functionality
 - User structural analysis, user micromechanics, user constitutive laws, user damage models
- Software architecture focused in *utility, upgradability, maintainability, and interoperability* of code
- NASMAT v2.0 scheduled for release 10/2020



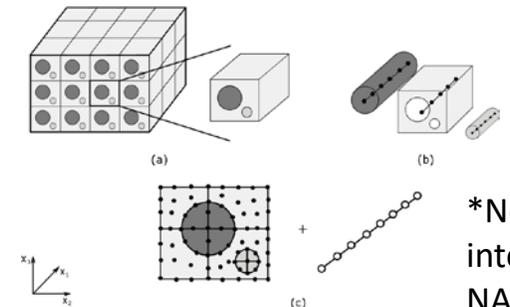
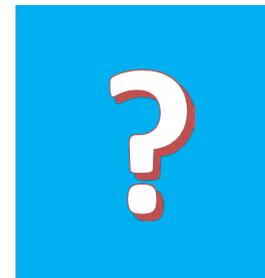


Rapid Development of NASMAT

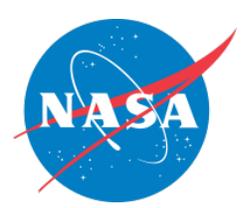
- NASMAT v2.0 (scheduled release – 10/20)
 - Demonstrated support of user micromechanics
 - Parametric HFGMC (PHFGMC), Carrera Unified Formulation (CUF) finite element, Mori-Tanaka (MT)
 - Multiscale recursive micromechanics (MsRM)
 - Any available micromechanics theory can be employed at any scale
 - Macroscale Application Program Interface (Macro API)
 - Structural analysis software capable of calling Fortran, C, or C++ code can easily call NASMAT
 - Demonstrated with Abaqus, Calculix, in-house GE FEM code
 - Referenceable and recursive output data
 - Improved progressive damage and failure analysis (PDFA) capabilities – (6/20)
 - Viscoplasticity – (9/20)
 - Multiscale visualization tool (MsViz) – (9/20)



User-Defined* Carrera Unified Formulation (CUF)*



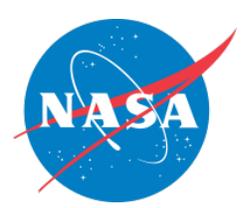
*Not yet fully integrated in NASMAT



Using 26 Years of Lessons Learned to Guide Future Development

- MAC software development has been ***actively*** occurring at NASA for over ***two decades***.
- Actively porting MAC/GMC keywords into NASMAT
- Merging keywords where appropriate
- Removing under utilized keywords
- Verifying accuracy by comparing to MAC/GMC

MAC/GMC KEYWORD IMPLEMENTATION IN NASMAT	
STATUS	Fully/Partially Implemented
	To Be Implemented
	No Plans to Implement
ALLOWABLES	MECH
CHECK	MICRO_MODELS
CONDUCTIVITY	MSGMC
CONSTITUENTS	MSMATS
CONVERT	MULTISCALE_OPTIONS
CURTIN	PATRAN
DAMAGE	PINNED
DEBOND	PLASTICITY
DISTRIBUTION	PRESSURE
ELECTROMAG	PRINT
FAILURE_CELL	PROGRESSIVE_DAMAGE
FAILURE_LAM	RUC
FAILURE_SUBCELL	SOLVER
FOAM	STIFFNESS_PRINT
HYPERSIZER	SURF
LAMINATE	THERM
LOADMARGIN	TMAC
MATLAB	WOVEN
MBDPATH	XYPLOT

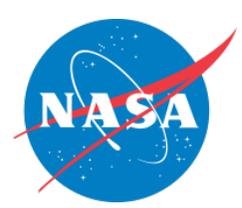


NASMAT Input Syntax

- ASCII-based text file
- NASMAT controlled through keywords (*KEYWORD)
- Simple, easy to construct input file (often <50 lines total)
- Supports legacy *.mac keywords
- Manually generated (by hand or by script)
- Plans for interactive pre-processor development for more complicated models

Hallmark of MAC: Simple Input File

```
1 # - THIS IS A NASMAT INPUT FILE
2 *CONSTITUENTS
3   NMATS=2
4 # -- RTM6 Matrix
5   M=1 CMOD=6 MATID=U MATDB=1 &
6   EL=  2.89E+03,2.89E+03,0.35,0.35,1.070370370370E+03,0.0,0.0
7 # -- AS4 Fiber
8   M=2 CMOD=6 MATID=U MATDB=1 &
9   EL=231.0E3,15.0E3,0.21,0.3,15.8E3,0.00000E+00,0.00000E+00
10 *RUC
11   MOD=102 ARCHID=13 VF=0.25 F=2 M=1 R=1
12 *MECH
13   LOP=3
14   NPT=2 TI=0.,1. MAG=0.,0.02 MODE=1
15 *SOLVER
16   METHOD=1 NPT=2 TI=0.,1. STP=0.01 ITMAX=50 ERR=1.E-6
17 *FAILURE_SUBCELL
18   NMAT=2
19   MAT=2 NCRIT=2
20     CRIT=1 X11=3350 COMPR=DIF XC11=2500 ACTION=1
21     CRIT=2 X11=0.01488 COMPR=DIF XC11=0.0111 ACTION=1
22   MAT=1 NCRIT=1
23     CRIT=1 X11=75.0 X22=75.0 X33=75.0 COMPR=SAM ACTION=1
24 *HDF5
25   MAXLEV=2
26 *XYPLOT
27   FREQ=1
28   MACRO=1
```



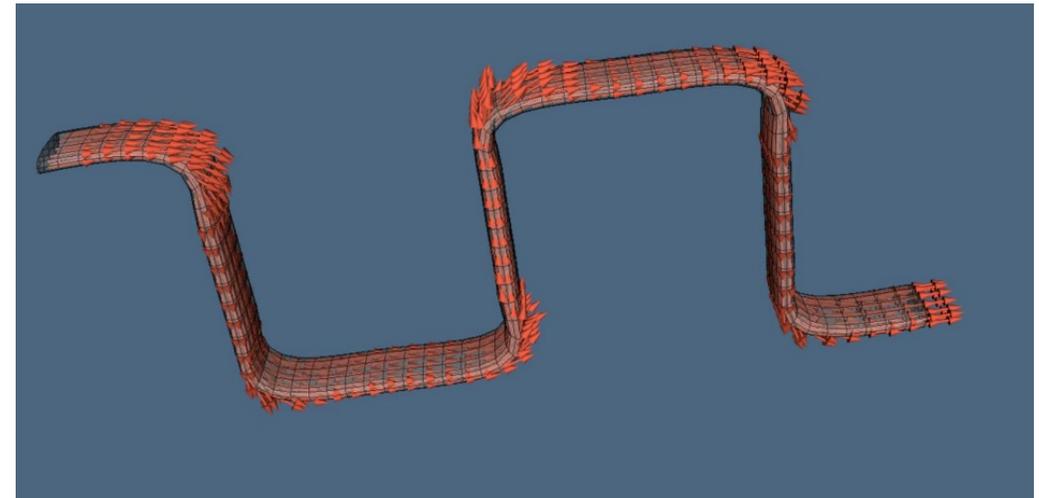
Output Data and Visualization

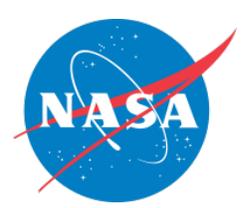
Output Data

- ASCII-based text file (*.out)
 - Echoing of keywords
 - Summary information
 - Results
 - Error messages
- Keyword-controlled text files
 - *XYPLOT (manually added individual curves)
 - *MATLAB (legacy visualization)
- Database (*HDF5)
 - Hierarchical Data Format version 5 (HDF5) open source file format
 - Both automatically and manually added fields/properties

Visualization

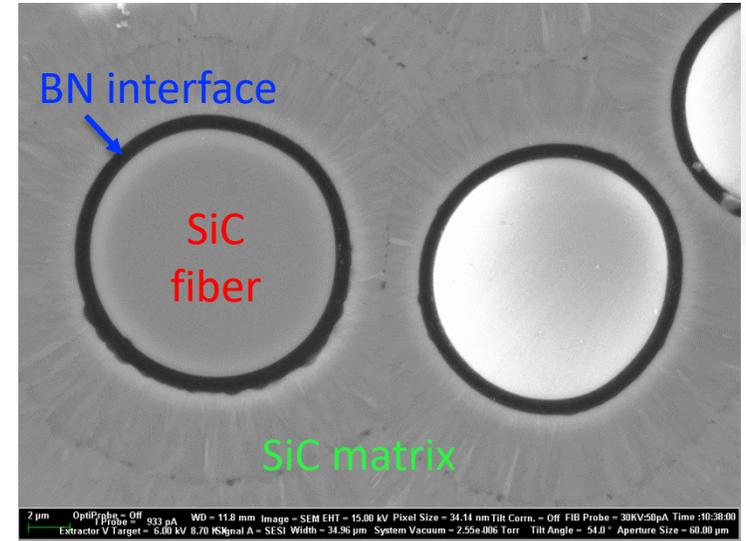
- Python
- Open source Visualization Toolkit (VTK)
- Plans to create a graphical user interface (GUI)



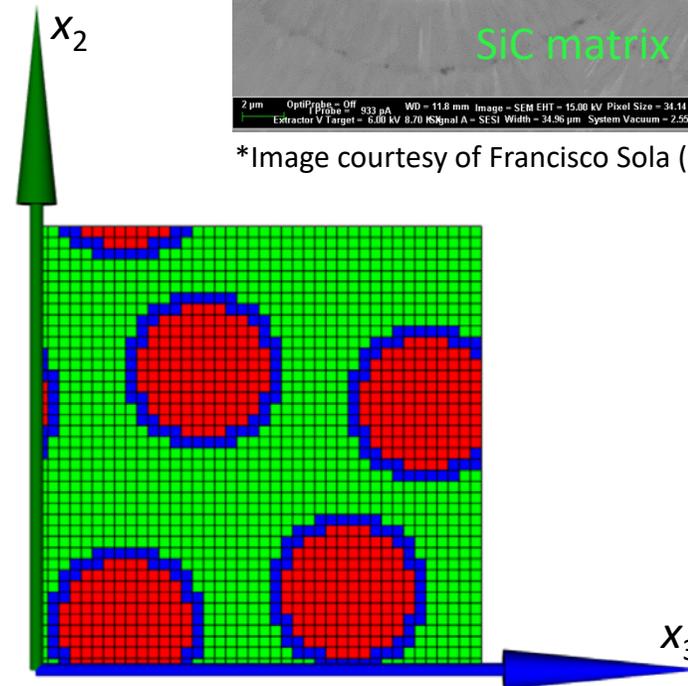


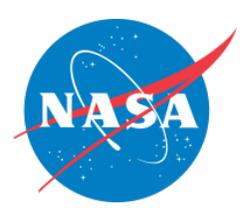
#1) Single Scale Analysis of Unidirectional Ceramic Matrix Composite (CMC)

- Silicon Carbide (SiC) fiber, SiC matrix, Boron Nitride (BN) interface
- Transverse loading ($\epsilon_{33} = 0.5\%$) in x_3 -direction
- Random arrangement of four fibers
- Compare predicted stress and strain fields from GMC and HFGMC techniques



*Image courtesy of Francisco Sola (NASA GRC)

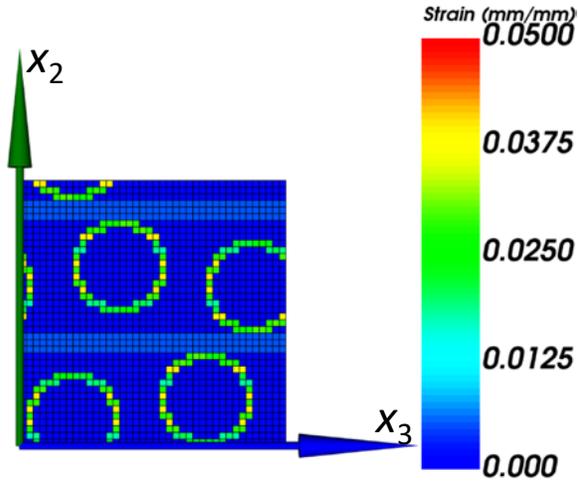




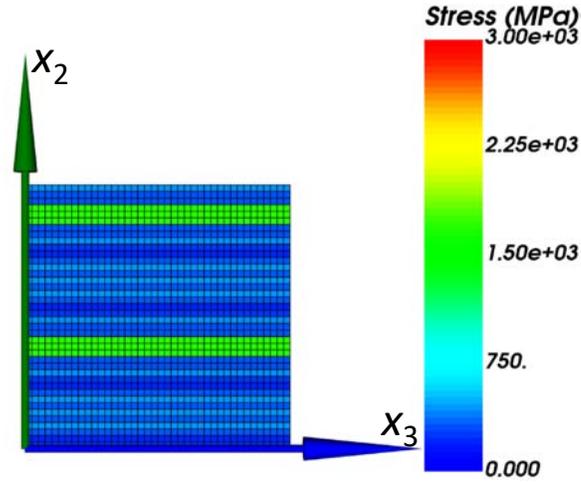
#1) Single Scale Analysis of a Unidirectional CMC

GMC2D

Strain (ϵ_{33})



Stress (σ_{33})

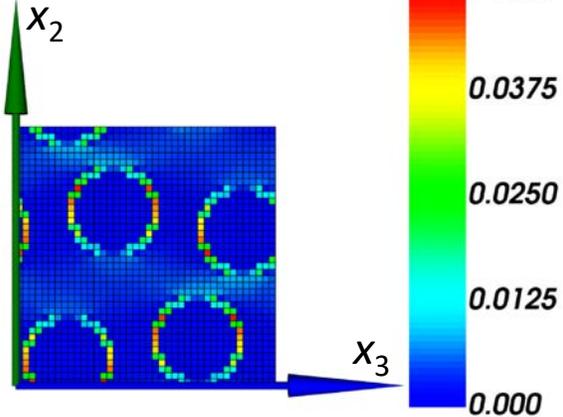


Elastic Constants

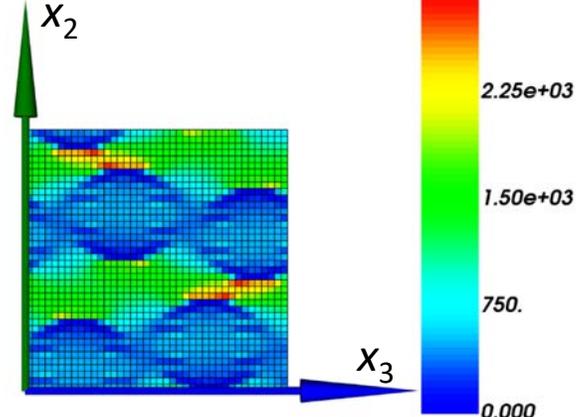
E_{11} (MPa)	302044
E_{22} (MPa)	84547
E_{33} (MPa)	104644
ν_{23}	0.180
ν_{13}	0.212
ν_{12}	0.206
G_{23} (MPa)	26258
G_{13} (MPa)	40918
G_{12} (MPa)	32347

HFGMC2D

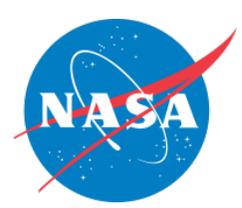
Strain (mm/mm)



Stress (MPa)

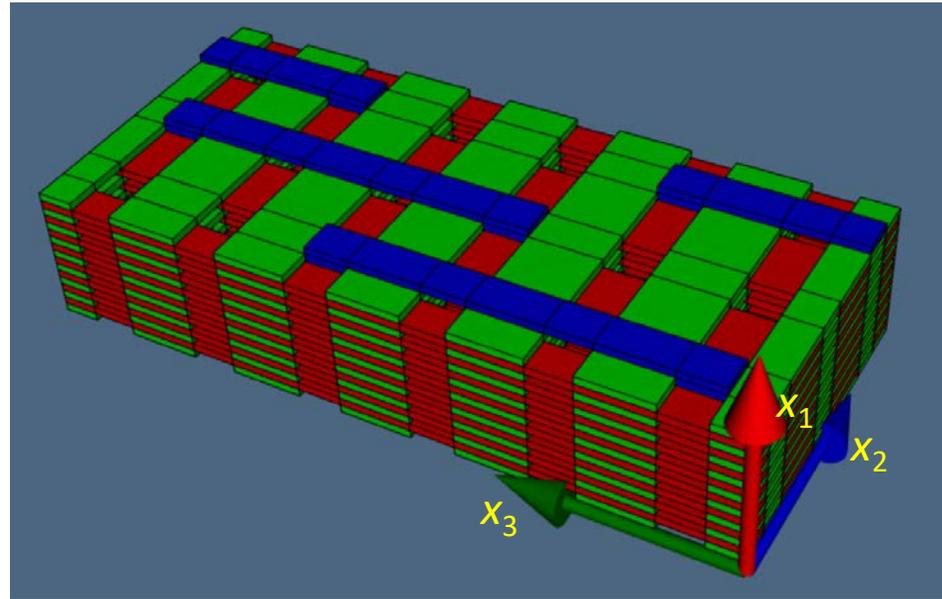


E_{11} (MPa)	302077
E_{22} (MPa)	152098
E_{33} (MPa)	154927
ν_{23}	0.222
ν_{13}	0.214
ν_{12}	0.213
G_{23} (MPa)	50652
G_{13} (MPa)	70177
G_{12} (MPa)	69654

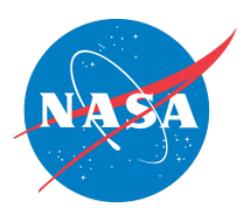


#2) Multiscale Analysis of a 3D Woven Polymer Matrix Composite (PMC)

- Consider an orthogonal weave geometry
- Assume each tow to have a hexagonal unit cell architecture with $v_f = 0.8$
- Assume voids are present in the bulk matrix, but not in the matrix within tows

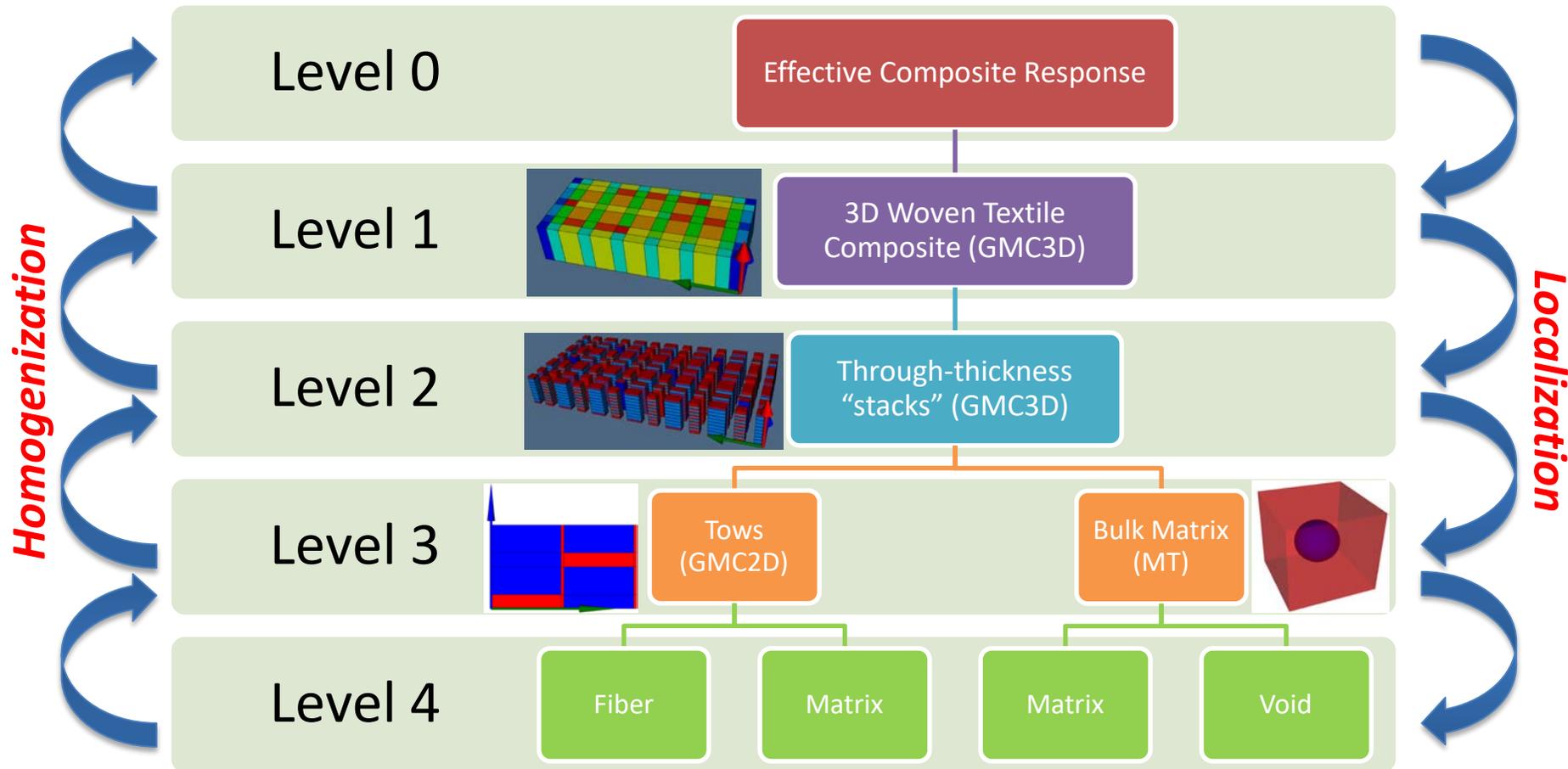


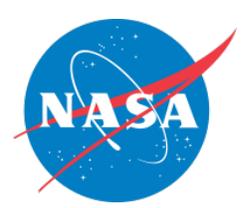
*matrix subcells not shown for clarity



Multiscale Modeling Strategy

- Multiple scales, modeling approaches seamlessly handled within the Multiscale Recursive Micromechanics (MsRM) approach





Valuable Insights Into Material Performance

- Various types of data available to output and utilize

Processing/Fabrication

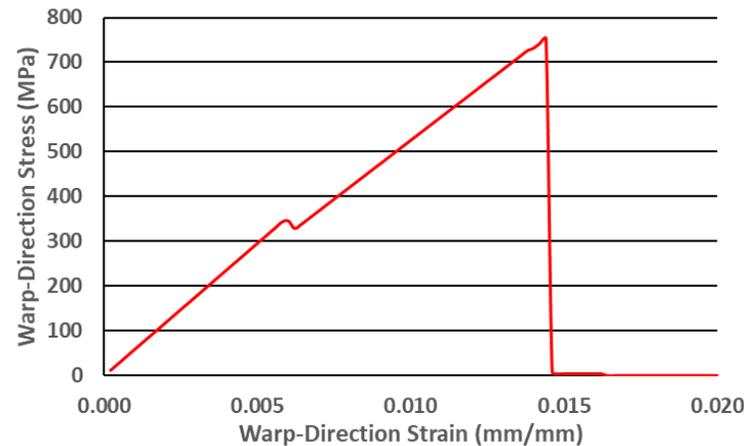
Simulated Volume Fractions		
3D Woven Composite	Fiber	0.503
	Matrix	0.493
	Void	0.004
Tow	Fiber	0.800
	Matrix	0.200
Bulk Matrix	Matrix	0.989
	Void	0.011

Elastic Constants

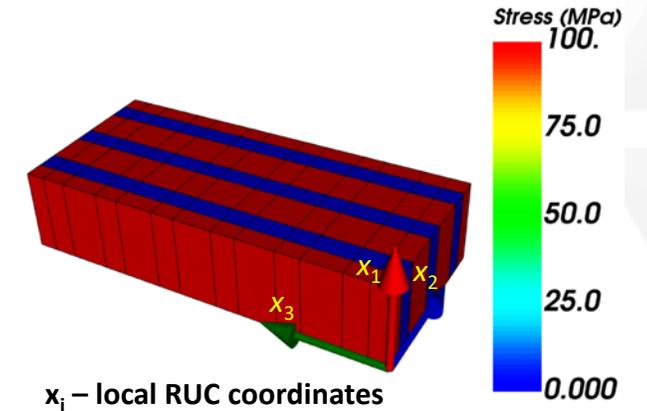
E_{11} (MPa)	9301
E_{22} (MPa)	59032
E_{33} (MPa)	59293
ν_{23}	0.037
ν_{13}	0.052
ν_{12}	0.050
G_{23} (MPa)	3989
G_{13} (MPa)	2014
G_{12} (MPa)	2058

1-direction – through-thickness
 2-direction – weft
 3-direction – warp

Stress/Strain Curves



Local Fields/Properties

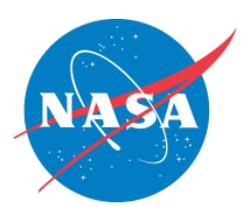


Damage/Failure Data

Damage Initiation Strain (mm/mm)	0.006
Damage Initiation Strain (MPa)	346
Failure Strain (mm/mm)	0.014
Failure Stress (MPa)	753

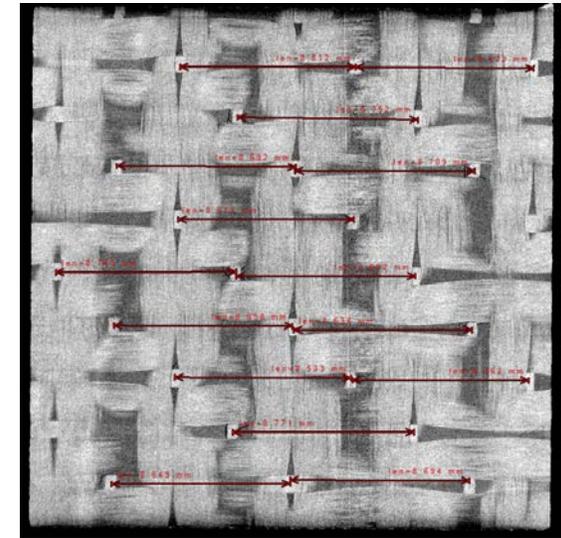
Runtime/File Data

To complete 100 load increments with:	Runtime (s)	HDF5 File Size (MB)
No multiscale data output	25	-
Up to Level 1 multiscale data output	82	22
Up to Level 2 multiscale data output	1588	75
Up to Level 4 multiscale data output	17141	1207

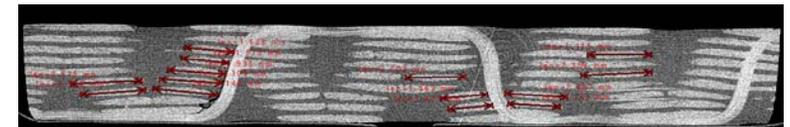


A Demonstration of NASMAT's Predictive Capability in Action

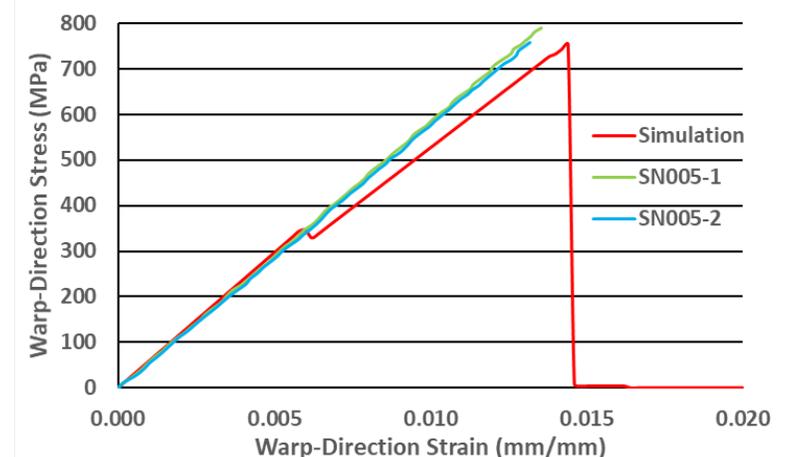
- 3D woven example – from a NASA project
- X-ray computed tomography conducted to determine as-fabricated weave geometry
- Acid digestion tests (3) performed to determine overall fiber volume fraction and void content
- Tensile tests (5) performed to determine warp-direction modulus and strength
- Coarse, simplified model generated
- Three assumptions made in NASMAT model:
 - Idealized yarn geometries and spacing
 - Yarn fiber volume fraction
- Predicted properties closely matched test data



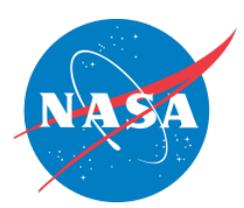
Images courtesy of Babak Farrokh (NASA GSFC)



		Overall Fiber Volume Fraction	Warp Tensile Modulus (GPa)	Warp Tensile Strength (MPa)
Simulation		0.503	59.3	753
Experiments*	Average	0.474	57.6	769
	St. Dev.	0.003	3.3	41
Difference		6.1%	2.9%	-2.1%

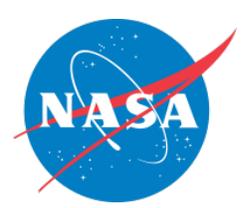


*Farrokh, B., et al. "Uniaxial Tensile Properties of AS4 3D Woven Composites with Four Different Resin Systems: Experimental Results and Analysis – Property Computations," CAMX 2019.



Multiscale Implementation of NASMAT within an External Software

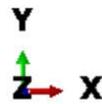
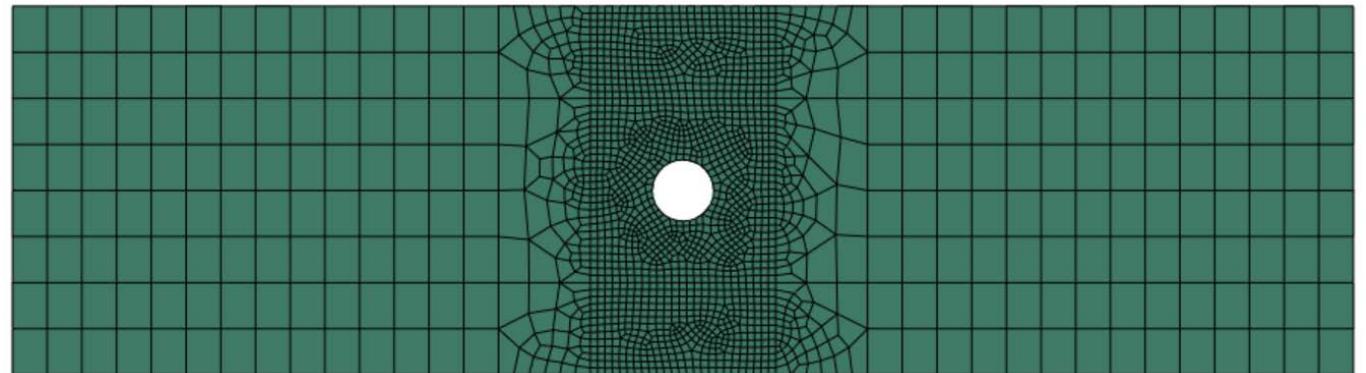
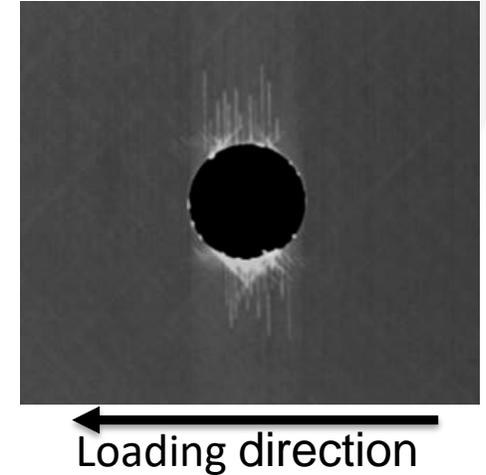
- Demo of the NASMAT MacroAPI
 - “Hook-ups” for NASMAT to act as a material point
 - Interface between NASMAT and external code
 - Handles all input/output
 - Does not have to utilize micromechanics/multiscale methods
- External Code: ABAQUS finite element software
 - Assembles/solves finite element problem
 - Handles all material point coordinate transformations
- Available support for additional external codes



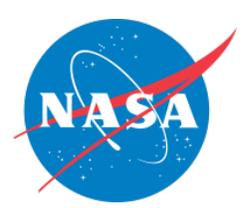
#3) Multiscale Implementation of NASMAT within an External Software

- PMC with variable fidelity micromechanics approaches
- Finite element problem definition
 - Open-hole tension specimen, single ply, 90°
 - Loaded in axial direction (x)
 - 1988 reduced integration brick elements
- Material definition
 - Orthotropic fiber
 - Isotropic matrix
 - No failure allowed

90° ply within a [0,45,90,-45]_{2s} laminate*



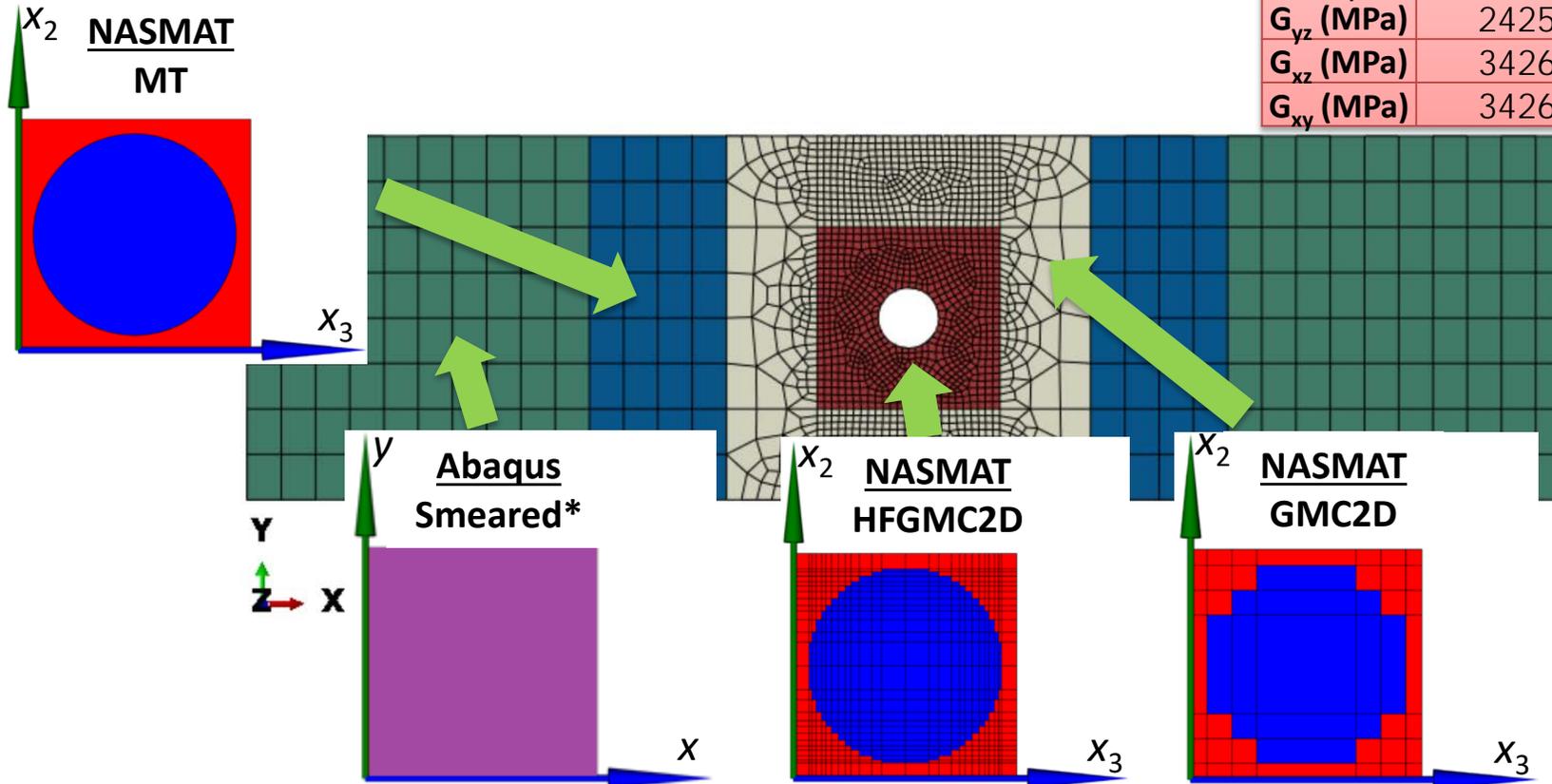
*Naghipour, P., et al. 2017. Multiscale static analysis of notched and unnotched laminates using the generalized method of cells. Journal of Composite Materials. 51(10), 1433-1454. NASA/TM-2016-219084



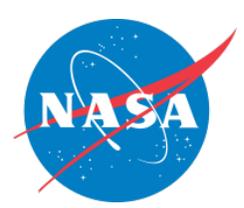
Multiscale Problem Definition

- Multiple zones defined
- Each zone assigned a unique material

	ABAQUS	NASMAT		
	Smearred*	MT	GMC	HFGMC
E_{xx} (MPa)	139773	139773	139773	139774
E_{yy} (MPa)	6963	6963	7719	7861
E_{zz} (MPa)	6963	6963	7719	7861
ν_{yz}	0.435	0.435	0.375	0.366
ν_{xz}	0.260	0.260	0.260	0.260
ν_{xy}	0.260	0.260	0.260	0.260
G_{yz} (MPa)	2425	2425	2093	2196
G_{xz} (MPa)	3426	3426	3423	3568
G_{xy} (MPa)	3426	3426	3423	3568

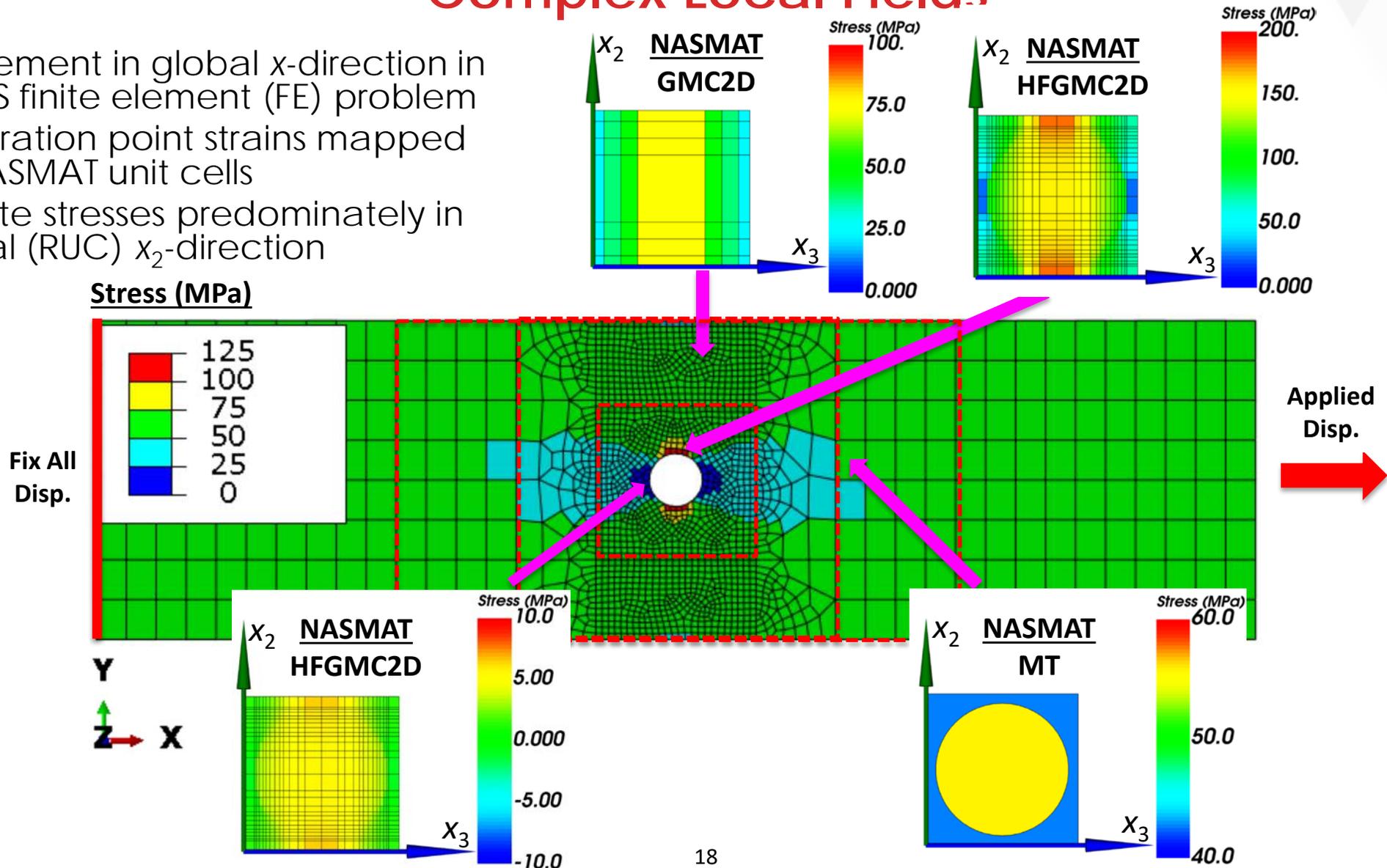


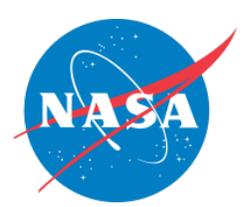
*Based on MT Results



Robust and Flexible Approach to Capture Complex Local Fields

- Displacement in global x -direction in ABAQUS finite element (FE) problem
- FE Integration point strains mapped onto NASMAT unit cells
- Generate stresses predominately in the local (RUC) x_2 -direction

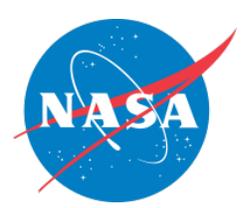




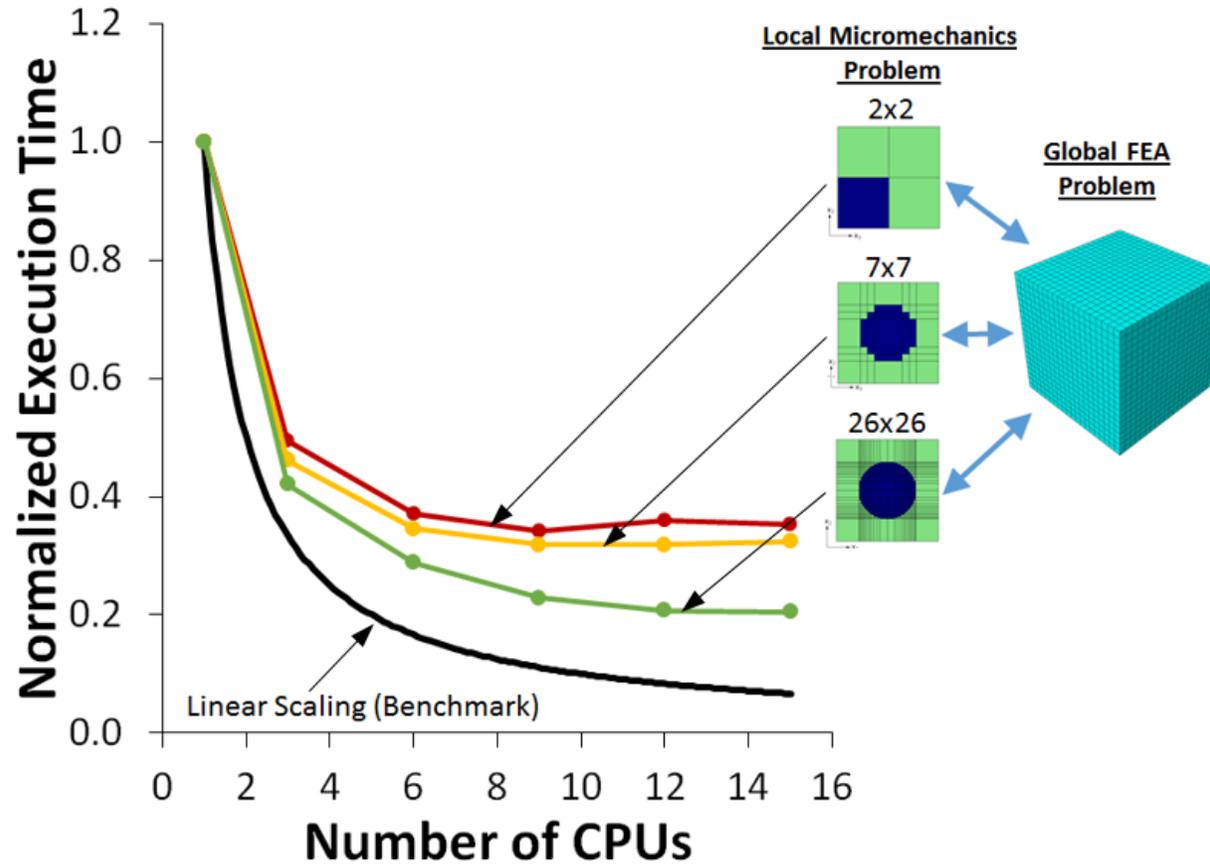
NASMAT Outperforms Legacy FEAMAC Tool

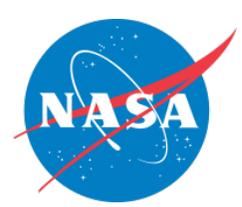
- Additional simulations run to assess performance:
 - ABAQUS only model using smeared properties
 - NASMAT/ABAQUS multiscale model (1 and 20 CPUs)
 - FEAMAC/ABAQUS multiscale model (1 CPU)
 - FEAMAC restricted to only 1 CPU due to implementation
 - MT replaced with smeared properties
- Well-known, significant penalty associated with performing multiscale analyses
- Pre-preprocessing required reading/processing NASMAT and ABAQUS input decks
- Multi-CPU run capability in NASMAT enables more sophisticated multiscale problems to be solved.
- NASMAT significantly faster than legacy FEAMAC tool when run on one CPU
- Currently profiling NASMAT for various examples to identify programming inefficiencies

		ABAQUS	NASMAT		FEAMAC
Number of Processors		1	1	20	1
Runtime (s)	Pre-Processing	-	10	10	-
	Total	0.6	111	26	279



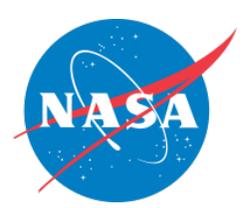
Profiling of NASMAT v1.0





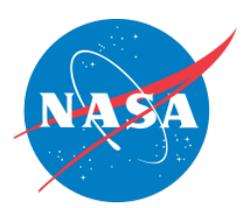
Future Development of NASMAT

- **NASMAT v2.0 (scheduled release – 10/20)**
 - Driver modules:
 - Quasi-static thermomechanical loading
 - MacroAPI
 - Solution modules:
 - MsRM
 - Classical lamination theory
 - Homogenization/Localization modules:
 - Generalized method of cells (GMC),
 - High fidelity GMC (HFGMC)
 - Parametric HFGMC (PHFGMC)
 - Mori Tanaka (MT)
 - Carrera Unified Formulation (CUF)
 - Material Models modules
 - Anisotropic linear elasticity
 - Subcell elimination (SE) failure
 - Progressive damage models
 - transversely isotropic SE, Crack band theory, enhanced Schapery theory (EST)
 - Viscoplasticity
 - State Change modules:
 - Failure criteria
 - Maximum (stress/s, Tsai-Wu (stress/strain), Hashin (stress/strain)
 - Output modules:
 - ASCII
 - HDF5
 - Preprocessing modules
 - “.mac” input file
 - Post-processing modules
 - VTK based multiscale visualization
- **NASMAT v3.0 (scheduled release – 10/21)**
 - Homogenization/Localization modules:
 - MicroAPI
 - Material Models modules:
 - Plasticity
 - User defined MPI parallelization of NASMAT
 - State Change modules:
 - Subcell debonding
- **Development schedule is tentative and subject to change based on user/project needs**

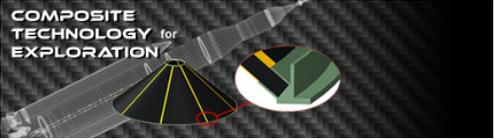


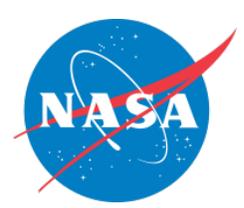
Summary and Conclusions

- The NASA Multiscale Analysis Tool (NASMAT) is a **flexible** and **versatile** tool capable of solving **practical** and **challenging** engineering problems.
- Capabilities demonstrated for single scale and multiscale standalone composite problems
- Capabilities demonstrated for a multiscale composite problem when interfacing with an external software



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 - Integration of CUF
- Prof. Rami Haj-Ali (Georgia Tech/Tel Aviv University)
 - Integration of PHFGMC



Questions

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