Uniaxial Tensile Properties of AS4 3D Woven Composites with Four Different Resin Systems: *Experimental Results and Analysis* – Property Computations

Babak Farrokh[1], Kenneth N. Segal[1], Trent M. Ricks[2], Sandi G. Miller[2], Benjamin T. Rodini [3], and David W. Sleight[4]

[1]NASA Goddard Space Flight Center, Greenbelt, MD
[2]NASA Glenn Research Center, Cleveland, OH
[3]ATA Aerospace LLC, Greenbelt, MD
[4]NASA Langley Research Center, Hampton, VA

THE COMPOSITES AND ADVANCED MATERIALS EXPO

Outline

- Introduction and Objectives
- Materials, Processes, and Weave Architectures
- Material Characterizations and Mechanical Testing
- Experimental Results and Discussion
- Material Modeling and Mechanical Property Computations
- Summary
- Acknowledgements

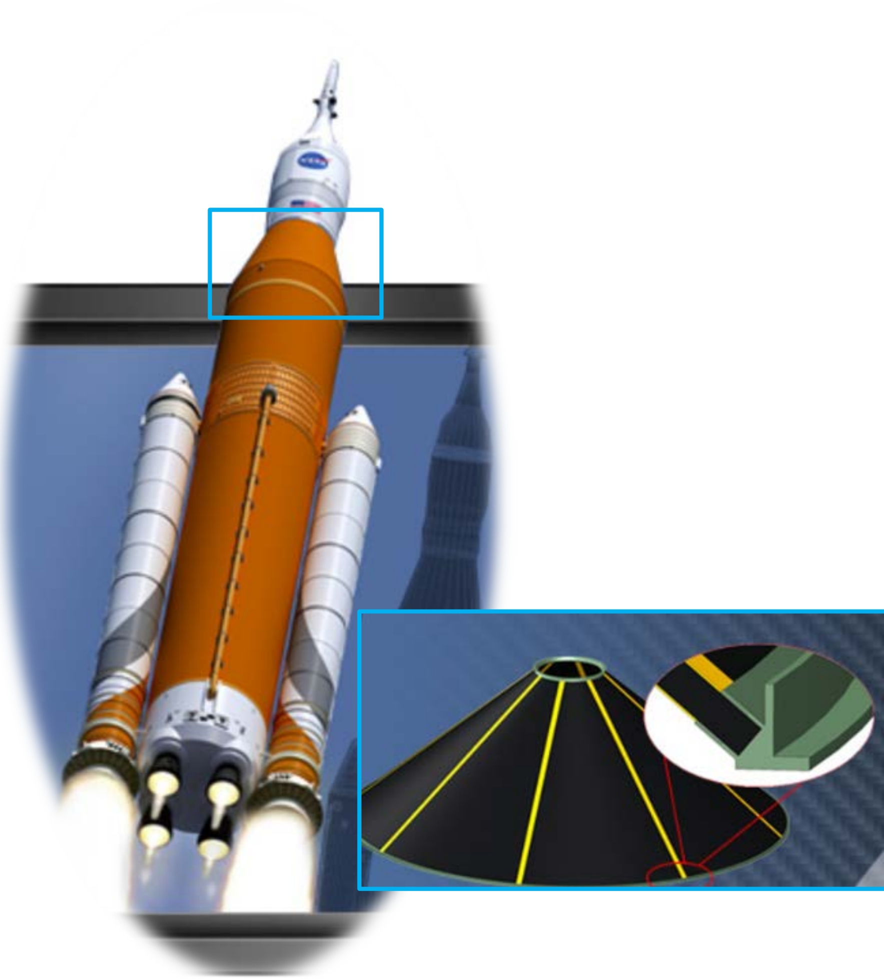
Introduction/ Objectives

Composite Technology for Exploration (CTE)

- Aimed to further advance the state-of-the-art in areas related to ***composite bonded joints*** technology
- Through case studies, the applications of ***composite bonded joints*** in heavy lift launch vehicles can reduce the mass and part counts by around 50% and 80%, respectively

3D Woven Composites [1, 2]

- Identified to offer good potentials in circumferential joints and end-fittings:
  - Enhanced performance (*e.g.,* delamination resistance)
  - Possibility of being woven in curved sections
  - Damage tolerance and fatigue resistance
- Known to exhibit micro-cracking
- Important to understand the evolution of micro-cracking and the influence on the 3D woven parts



Objectives

- Studying the evolution of micro-cracking as a function of four different resin systems, finer vs. coarser fiber yarns, and thermal cycling after processing
- Exploring how these parameters influence mechanical properties/ performance
- As an added value, taking advantage of the collected test data, modeling and computing elastic properties of the weave architectures using a finite element and a analytical technique and comparing with the test data

[1] Tsukrov, I., Bayraktar, H., Giovinazzo, M., Goering, J., Gross, T., Fruscello, M., Martinsson., L. "Finite element modeling to predict cure-induced microcracking in three-dimensional woven composites". *International Journal of Fracture* 172 (2011): 209-216.
[2] Bayraktar, H., Tsukrov, I., Giovinazzo, M., Goering, J., Gross T., Fruscello, M., Martinsson, L. "Predicting cure-induced microcracking in 3d woven composites with realistic simulation technology". *Proceeding of International SAMPE Tech. Conf.* Baltimore, MD, May 21-24, 2012.

Material Systems

- **AS4 carbon fiber with two different tow sizes (6K and 12K)**
- **Four different resin systems**

8 Flat Panels
3.175 mm thick

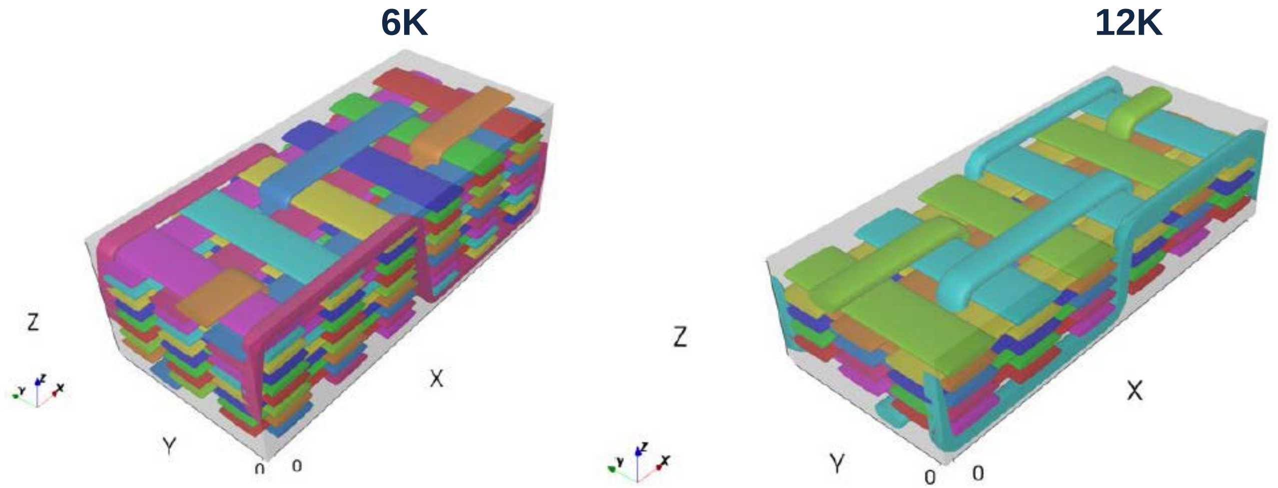
SN#	Fiber Material	Tow Size	Resin System	Panel /Material Designation
SN001	AS4	6K	KCR-IR6070	AS4 6K/KCR-IR6070
SN002		12K		AS4 12K/KCR-IR6070
SN003		6K	EP2400	AS4 6K/EP2400
SN004		12K		AS4 12K/EP2400
SN005		6K	RTM6	AS4 6K/RTM6
SN006		12K		AS4 12K/RTM6
SN007		6K	RS-50	AS4 6K/RS-50
SN008		12K		AS4 12K/RS-50

- **Some coupons subjected to thermal cycling: -55 ºC to 80 ºC for 400 cycles (an 18 day process, ~1 hour per cycle)**

Weave Architecture/ Parameters

- **Two weave configurations proposed by Bally Ribbon Mills (BRM)**
  - 3D orthogonal
  - One Z per dent arrangement

Repeating Unit Cells (RUCs) – TexGen Illustration



Weave Parameters:

Configuration	Fiber	Per Layer		# of Warp Layers	# of Weft Layers	Unit Cell Dims *mm*	% Fiber Fraction			% Fiber Volume	Z Fiber per Dent
		Warp Yarns Per *cm*	Weft Yarns Per *cm*				WARP	WEFT	Z		
1	AS4-6K	3.93	3.54	8	9	16.8 x 7.6 x 3.2	46.6	46.6	7.3	50.9	1
2	AS4-12K	3.54	3.14	4	5	19.1 x 8.5 x 3.2	41	46.4	12.6	52.6	1

Material Characterizations & Mechanical Testing

- **Fiber volume fraction and void content (ASTM D3171) prior to thermal cycling**
- **Optical microscopy and X-Ray Computed Tomography (CT) prior and after thermal cycling**

- **Mechanical Testing (in <u>Warp direction</u>) at National Institute for Aviation Research (NIAR):**

Tension (ASTM D3039) with strain gages and DIC, Compression (ASTM D6641) with extensometer, Short Beam Shear (ASTM D2344), and Single Shear Bearing (ASTM D5691) with extensometer and DIC

- **Room Temperature Ambient (RTA)**
  - As-processed (AP)
  - Thermally cycled (TC)
- **Elevated Temperature Wet (ETW)**
  - AP

Measurement Results: V_f

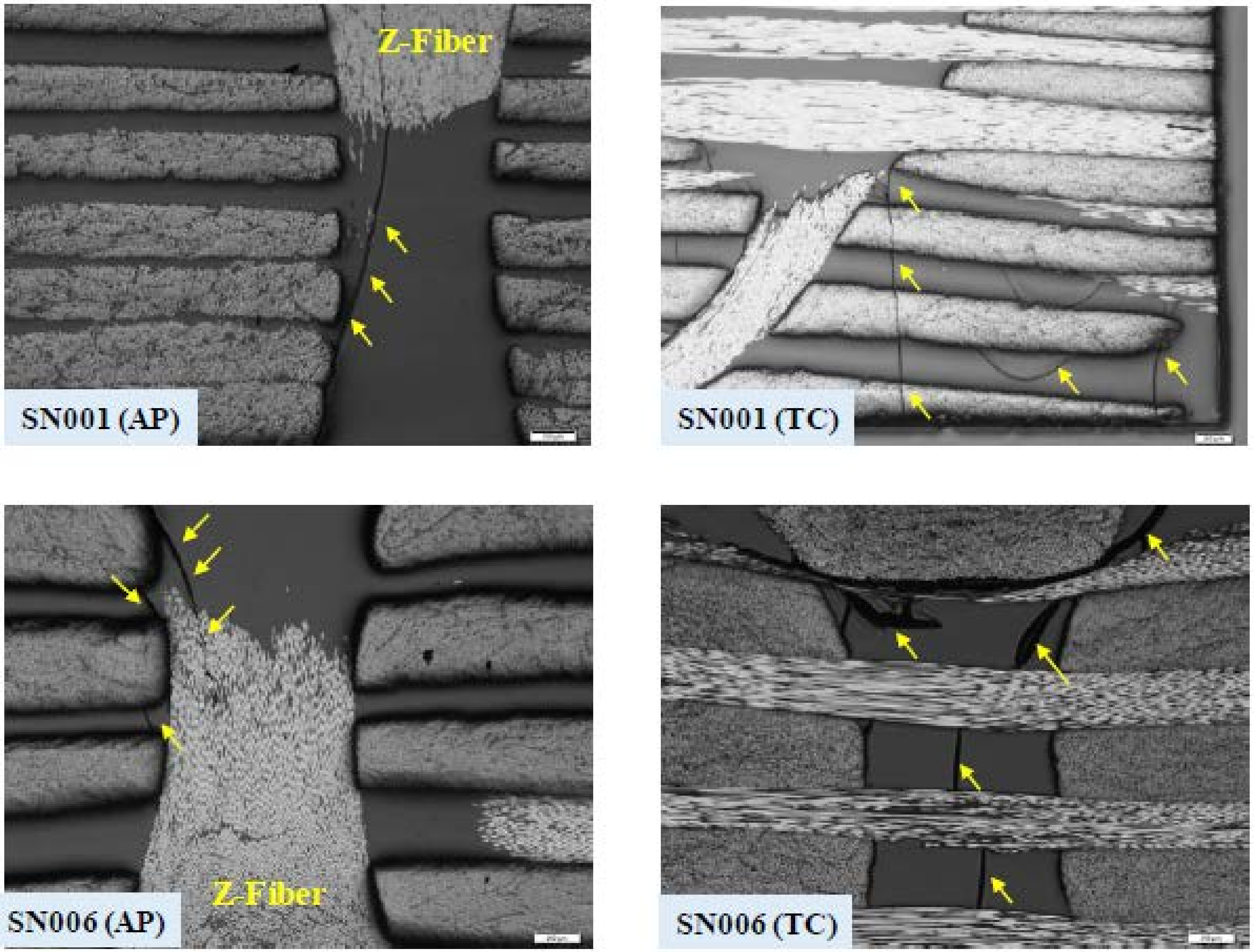
Panel	Resin	% Void Content		% Fiber Volume	
		Avg.	SD	Avg.	SD
SN001	KCR-IR6070	~ 0	0.2	47.3	0.3
SN002		~ 0	0.4	50.6	0.8
SN003	EP2400	1.4	0.2	49.7	0.5
SN004		1.1	0.4	51.5	0.9
SN005	RTM6	0.4	0.3	47.4	0.3
SN006		~ 0	0.5	48.4	1.2
SN007	RS-50	1.1	0.2	47.3	0.6
SN008		1.2	0.1	48.6	0.9

- BRM estimated Vf for 6K and 12K weave architectures to be 50.9% and 52.6%, respectively
  - Nominal thickness of 3.175 mm vs. as-built thickness (3.175 mm to 3.327 mm)
- **Consistent:** V_f (12K) > V_f (6K)

Micro-cracking Assessment: Optical Microscopy

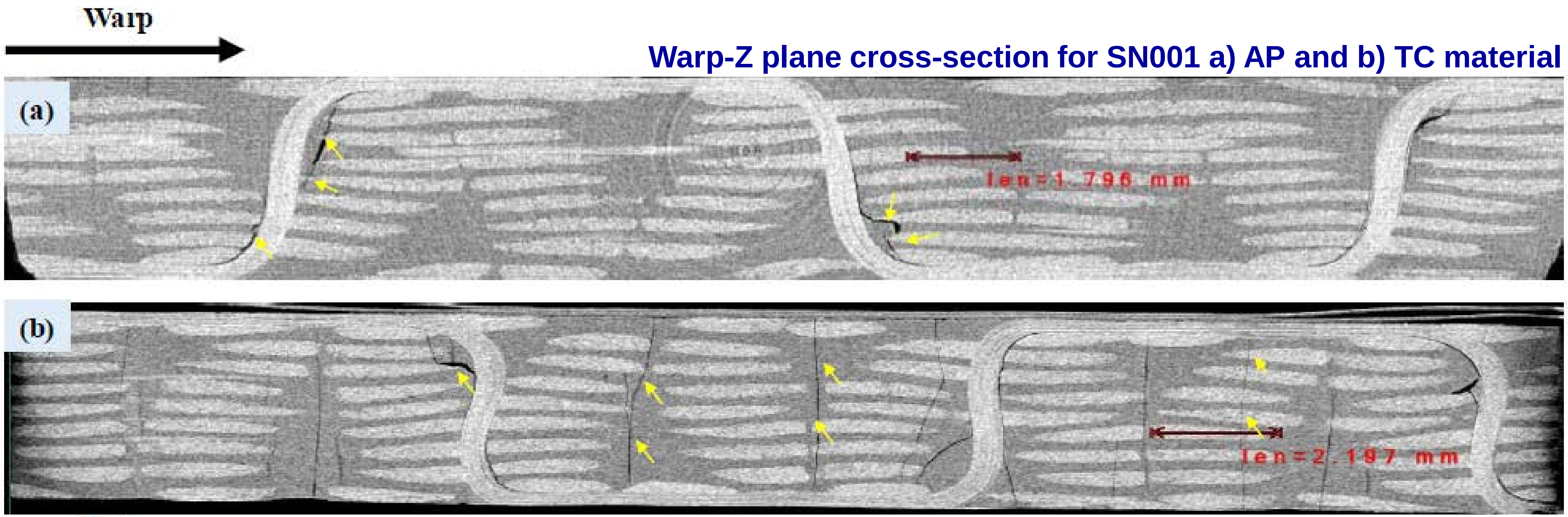
- Micro-cracks developed in all panels likely during curing process and cool down
- Micro-cracking observed mainly near the Z-fibers
- Density of micro-cracks increased after thermal cycling
    - In addition to Z-fibers vicinities, cracks distributed within the material, including individual fiber tows

- Developing an imaging technique to measure the cumulative volumes of the micro-cracks within these samples is an ongoing work at NASA

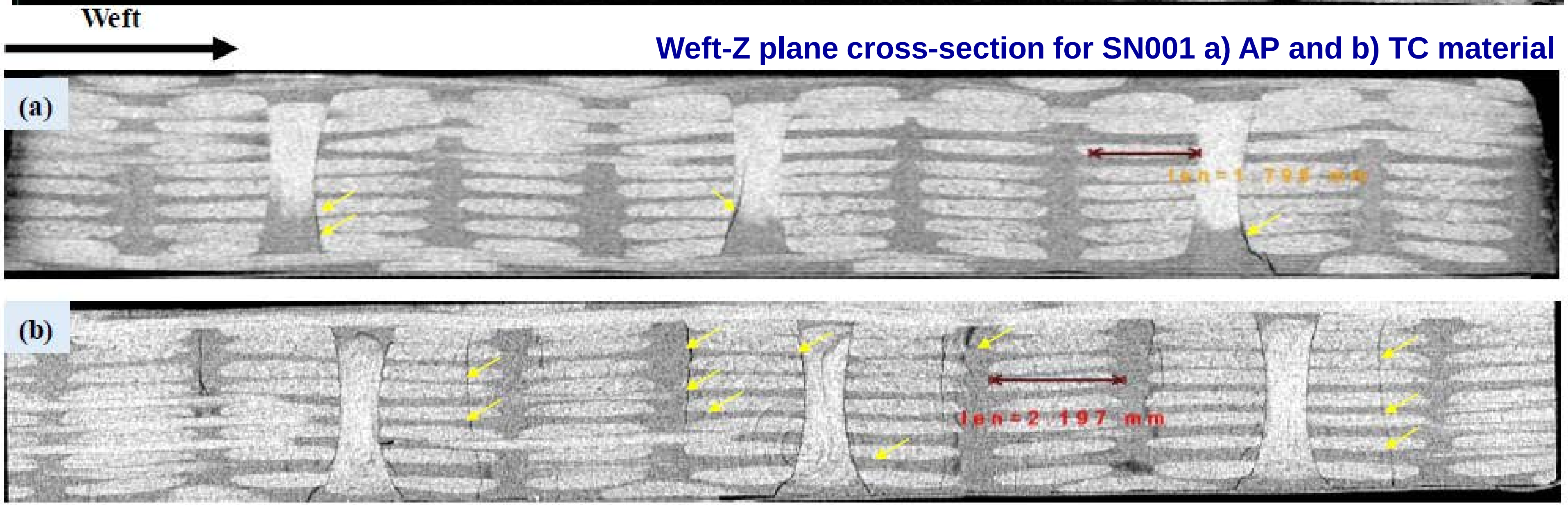


Micro-cracking Assessment: X-Ray CT

Warp-Z plane cross-section for SN001 a) AP and b) TC material



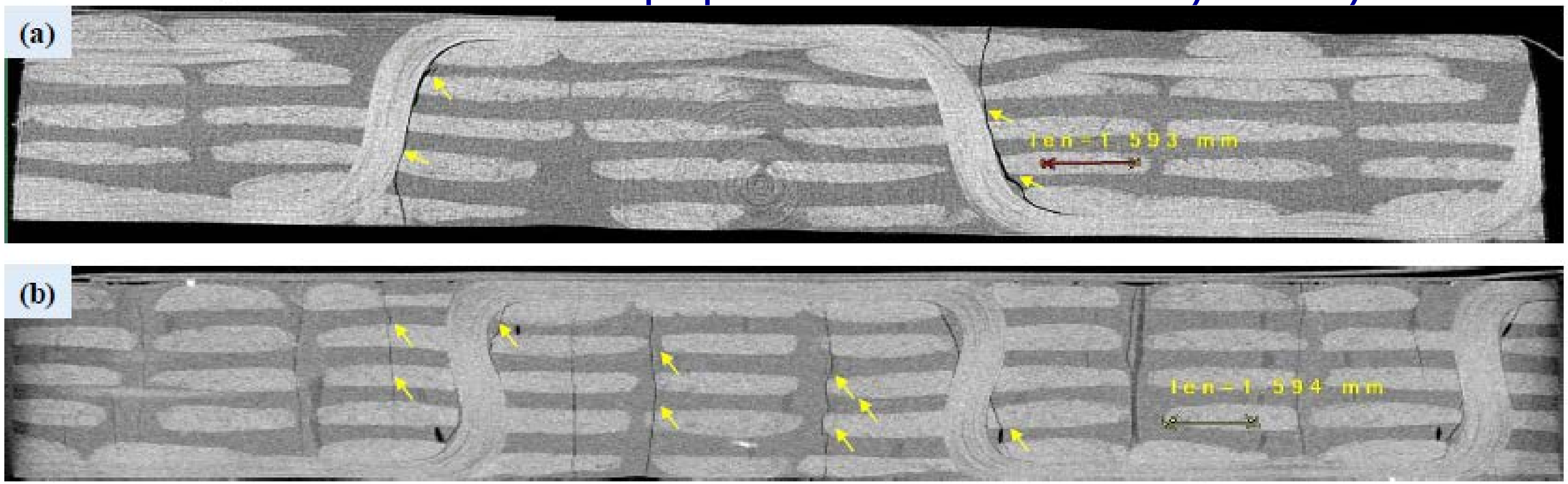
Weft-Z plane cross-section for SN001 a) AP and b) TC material



Micro-cracking Assessment: X-Ray CT

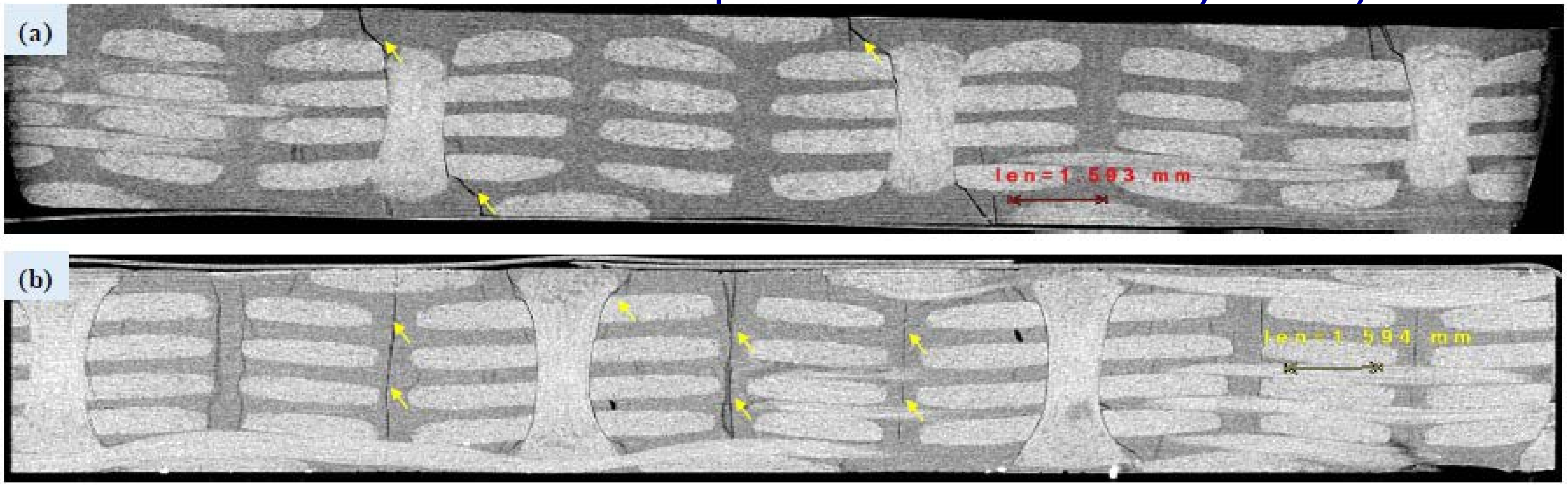
Warp →

Warp-Z plane cross-section for SN006 a) AP and b) TC material

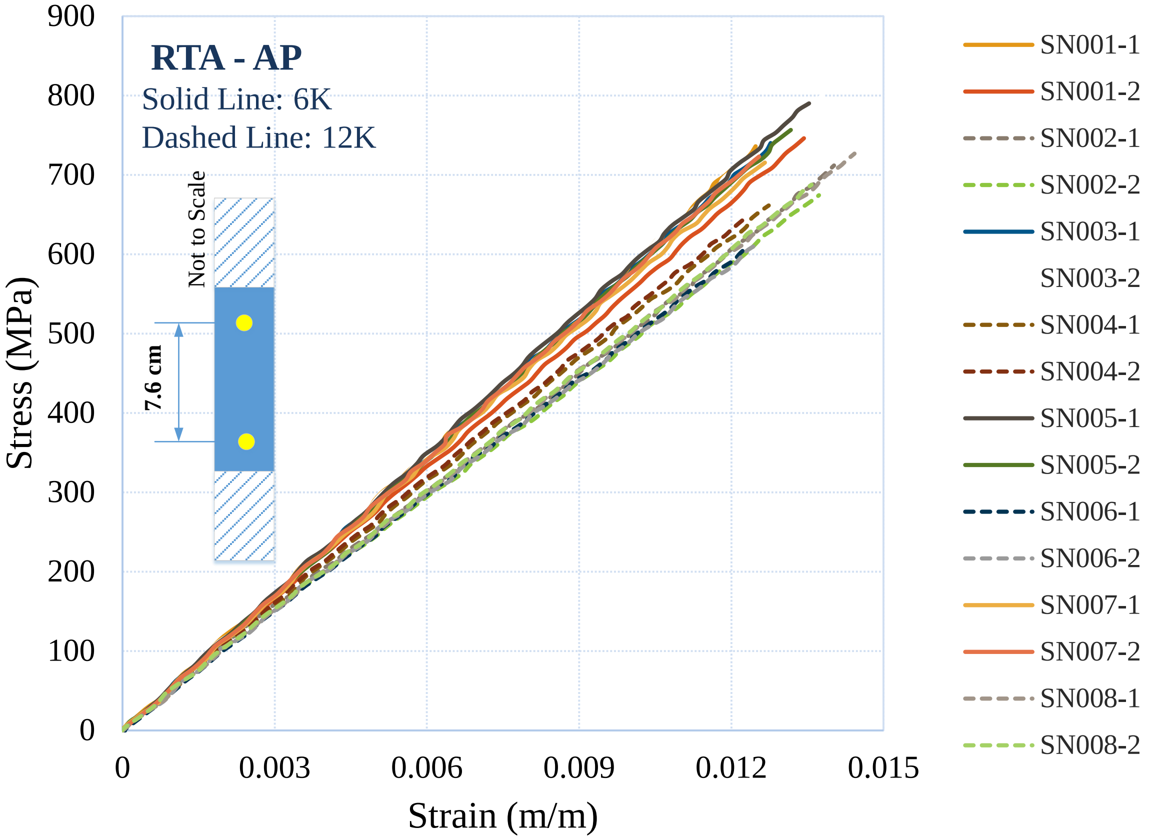


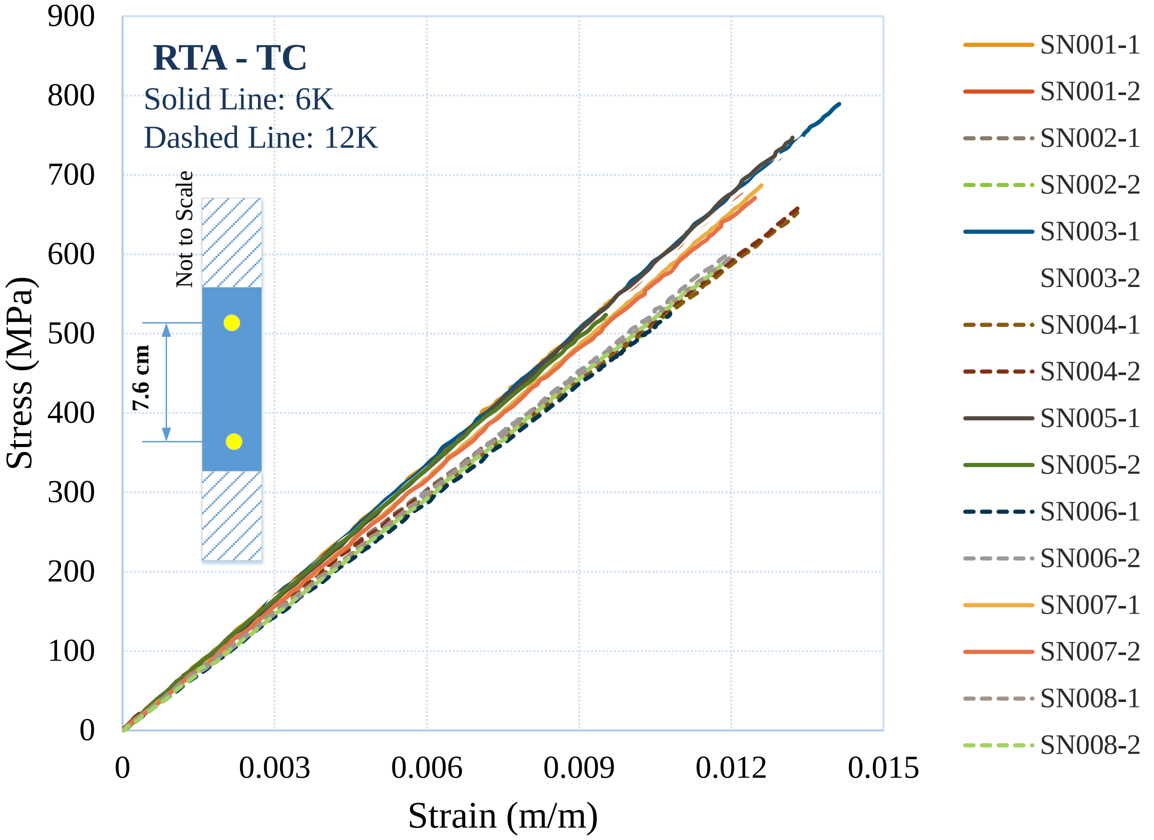
Weft →

Weft-Z plane cross-section for SN006 a) AP and b) TC material



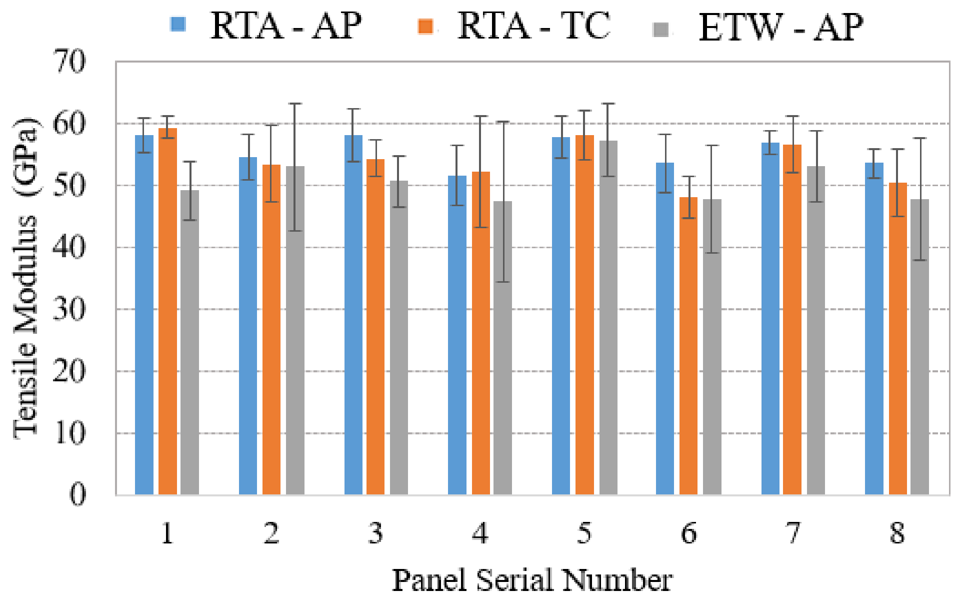
Test Results: Tensile Testing (DIC Data)



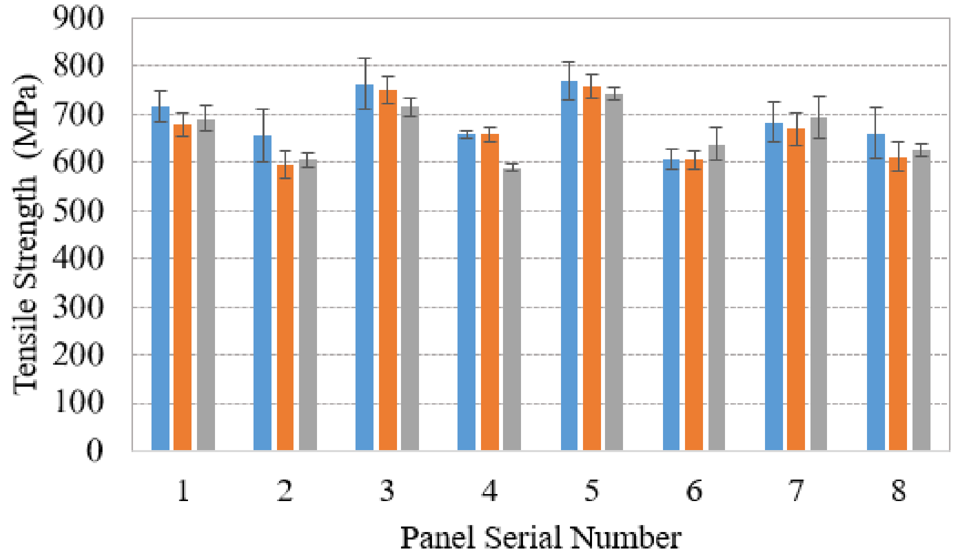


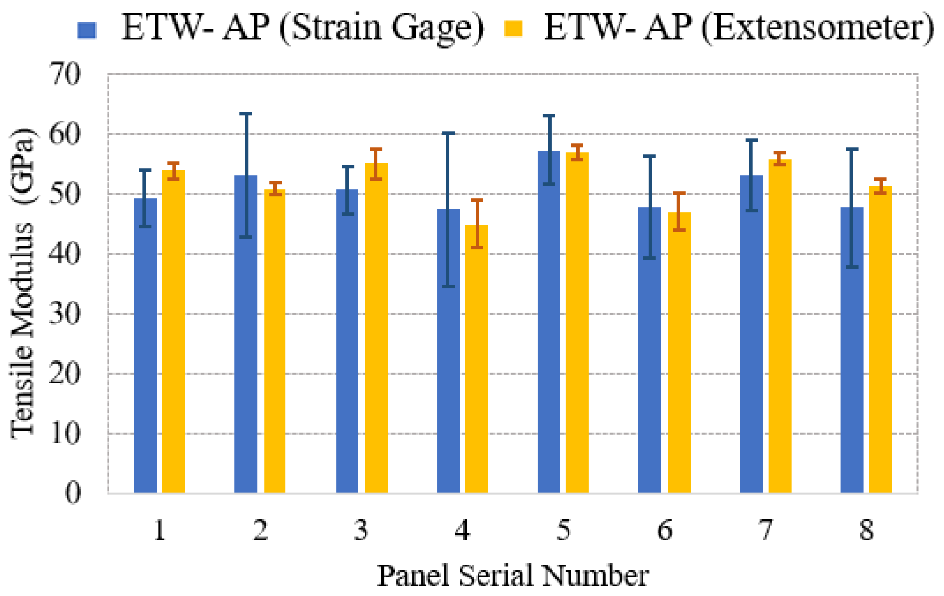
- Slightly higher stiffness and strength for 6K weave configurations (finer and tighter weave structure)
- Slight change (drop) in stiffness and strength as a result of thermal cycling

Test Results: Tensile Testing (Strain Gage)

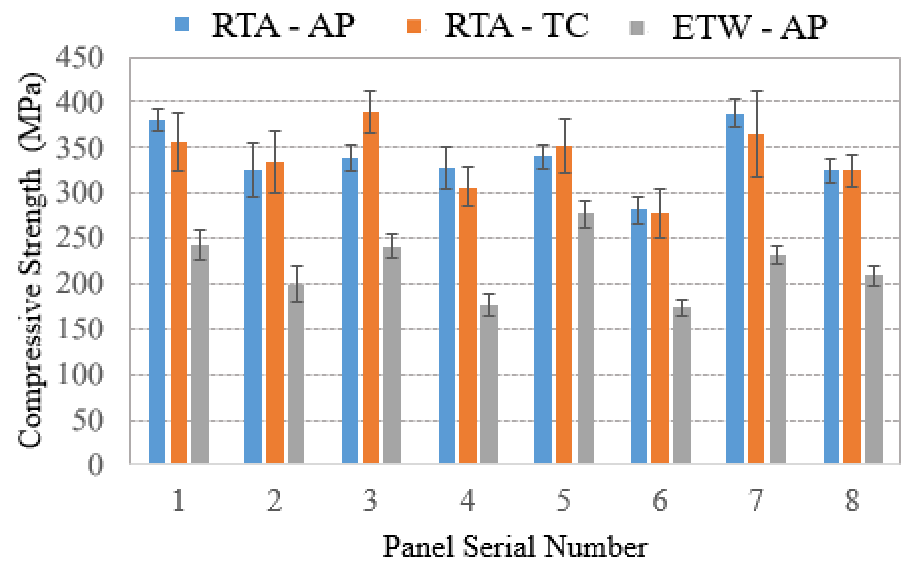


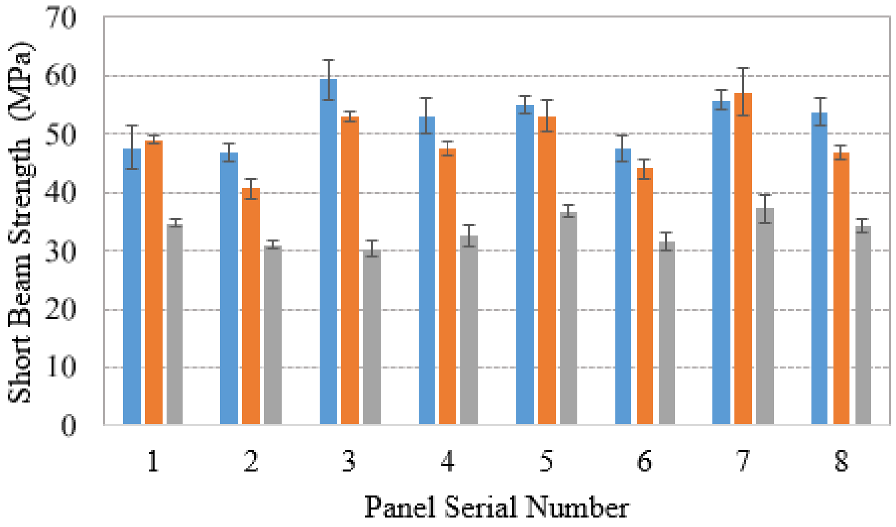
- Higher standard deviation in modulus data attributed to strain measurements using strain gages (~9 mm x ~5 mm) and large RUC (16.8 x 7.6 mm and 19.1 x 8.5 mm) of the materials
- Standard deviations in modulus values using extensometer vs. gage data for ETW tests further support above hypothesis

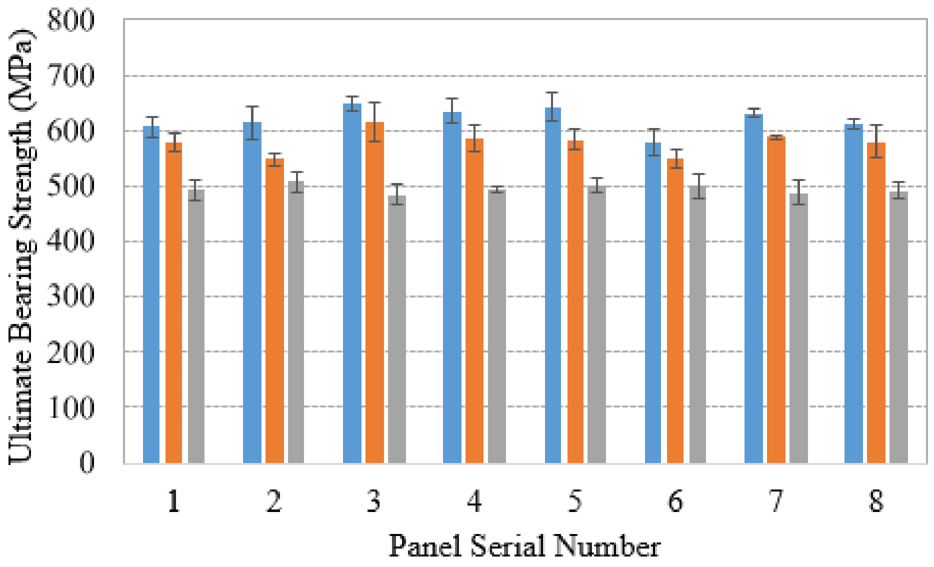




Test Results: Compressive, SBS, and Bearing Strength



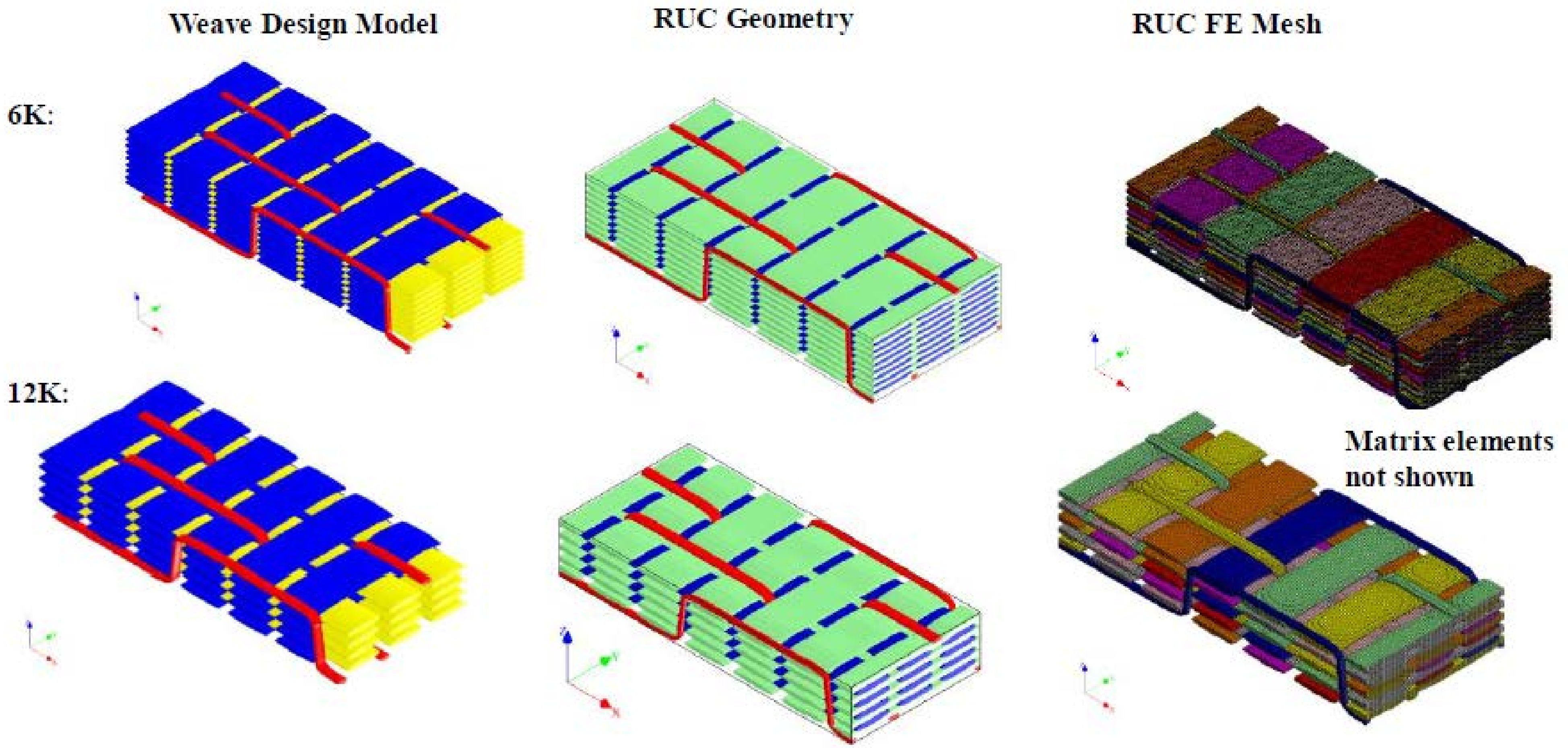




- 6K weave configuration consistently performed better
- ~50% reduction in strength (compression vs. tension)
- Higher standard deviation in compression anticipated to raise from narrower and shorter coupon geometry in ASTM 6641 vs. ASTM 3039

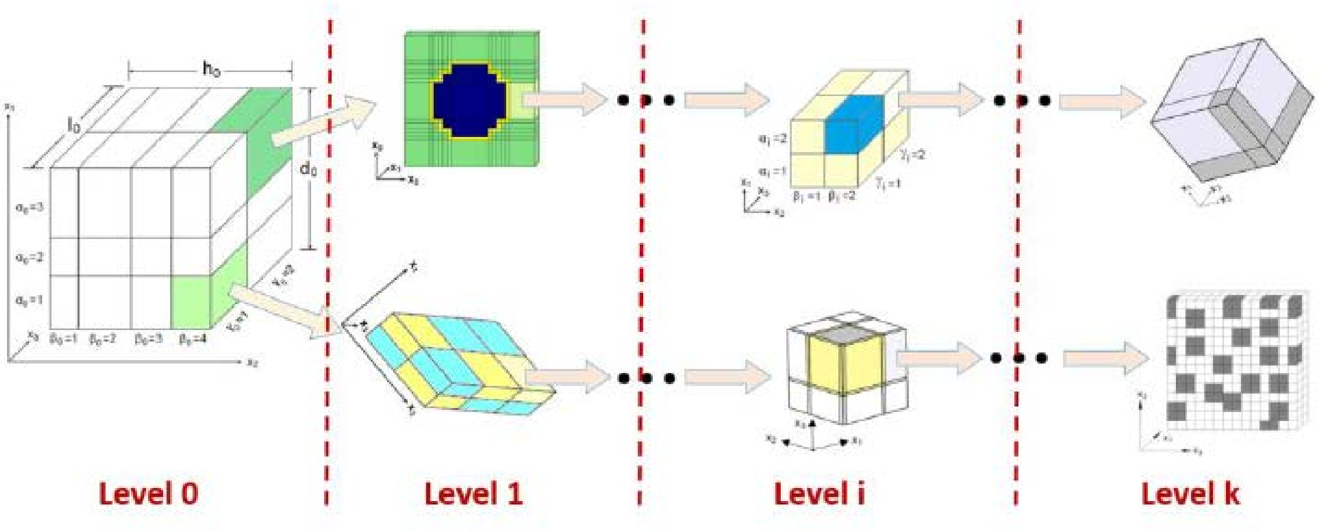
Material Modeling Approaches: FE Based

- **Finite element (FE) based approach**
  - Digimat FE

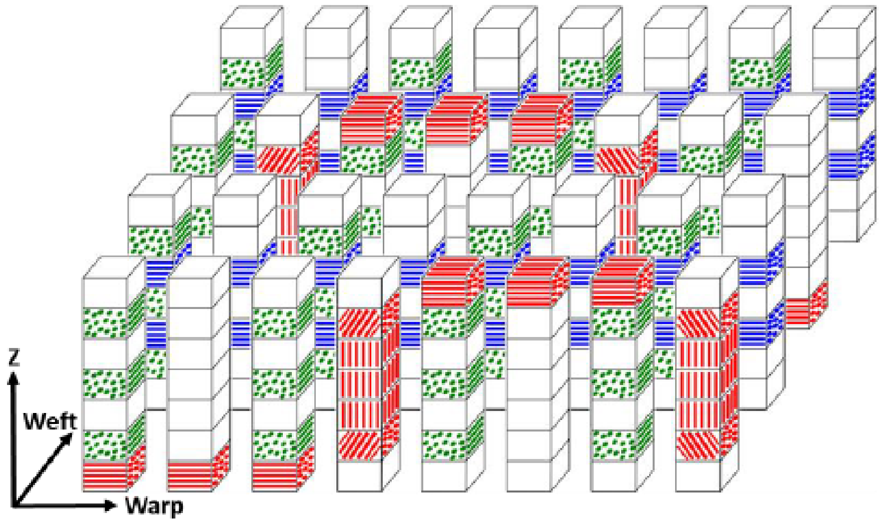


Material Modeling Approaches: MSGMC

- **Multiscale Generalized Method of Cells (MSGMC)**
  - **Developed by NASA GRC**
  - **Semi-analytical (efficient)**
  - **Provides homogenized, nonlinear constitutive response of composites**



MSGMC RUCs and sub-cells across an arbitrary number of length scales

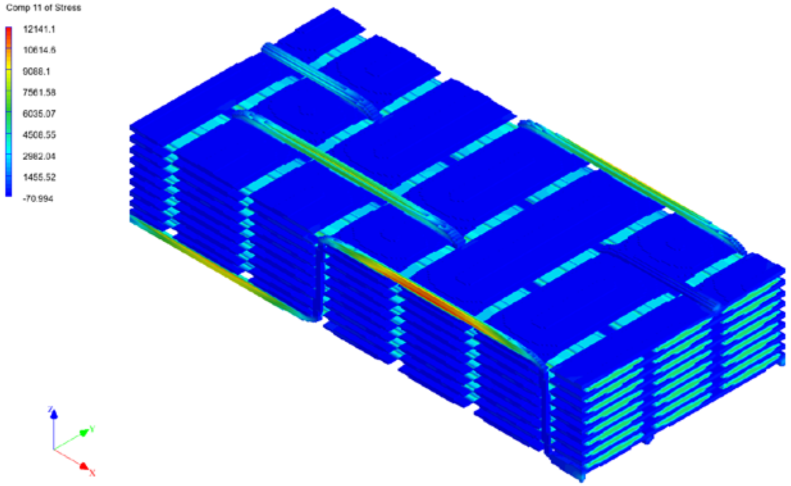


MSGMC 3D orthogonal woven representation

Property Computations

- **AS4/RTM6 material system was selected for modeling and analysis**
  - Both 6K and 12K
  - RTA

Configuration	Method	Material Parameter/Property								
		E_{11} (MPa)	E_{22} (MPa)	E_{33} (MPa)	v_{12}	v_{13}	v_{23}	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
AS4 6K/ RTM6 (SN005)	MSGMC	**61,977**	60,096	9,257	0.059	0.444	0.446	3,385	2,253	2,261
	Digimat-FE	**61,833**	59,907	9,691	0.056	0.443	0.429	3,283	2,450	2,471
	%Δ	-0.2	-0.3	4.7	-5.1	-0.2	-3.8	-3.0	8.7	9.3
AS4 12K/ RTM6 (SN006)	MSGMC	**56,803**	57,018	8,885	0.059	0.444	0.449	3,207	2,136	2,180
	Digimat-FE	**56,400**	57,500	9,308	0.052	0.448	0.425	3,029	2,369	2,420
	%Δ	-0.7	0.8	4.8	-11.9	0.9	-5.3	-5.6	10.9	11.0

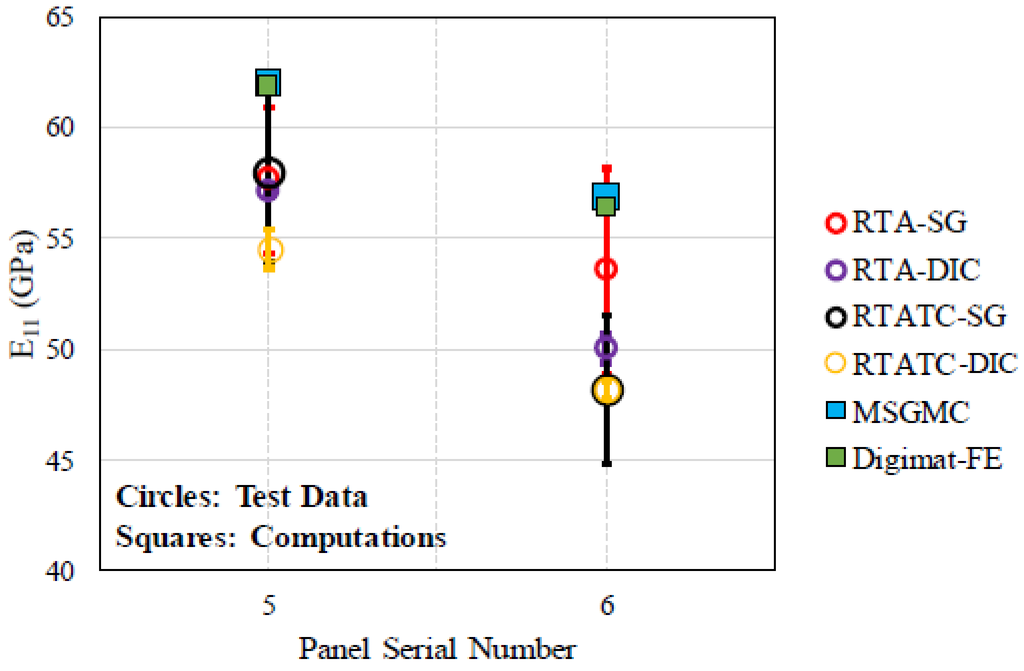


- Good agreement between Digimat-FE and MSGMC
- Largest difference of 12% for v12

Computed Properties vs. Test Data

- **Only test data available: Warp (E_{11})**
- **Models and analysis did not include (effect of) micro-cracks**

Condition	Panel#	Strain Gage (from 5 Tests)				DIC (from 2 Tests)			
		E_{11} (GPa)	SD	% Δ to MSGMC	% Δ to Digimat-FE	E_{11} (GPa)	SD	% Δ to MSGMC	% Δ to Digimat-FE
RTA (AP)	SN005	57.6	3.3	7.5	7.3	57.1	0.2	8.6	8.4
	SN006	53.5	4.7	6.2	5.4	50	0.6	13.7	12.9
RTA (TC)	SN005	57.9	4	7	6.8	54.5	0.9	13.7	13.4
	SN006	48.1	3.4	18	17.2	48.2	0.4	17.9	17.1



- Analysis over-predicted (averaged) test values
(Strain measurement technique (strain gage vs. DIC) made a difference)
- Possible sources for the differences:
  - Ignoring micro-cracks
  - Not accounting for irregularities in weave pattern (idealized modeling)

Summary

- **Eight 3D woven composite panels were fabricated and subjected to material characterizations and testing**
  - **The 3D orthogonal weave included 6K and 12K yarn configurations and four different resin systems**
- **Optical microscopy and X-Ray CT revealed the presence of micro-cracks in the as-processed materials**
  - **Thermal cycling increased micro-crack density in all eight panels**
- **No significant change in tensile performance of the materials as a result of thermal cycling or ETW environment (Fiber dominated, warp direction)**
- **Analysis over-predicted the test results by ~5% to ~13% for the AP materials and the difference increased as the material underwent thermal cycling**

Acknowledgements

- X-Ray CT support by Grace Fischetti and Dr. Justin Jones from Materials Branch at NASA Goddard Space Flight Center

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