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475 Bridge Street, Suite 100, Groton, CT 06340
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Dynamic Shock Response of an S2 Glass/SC15 Epoxy Woven Fabric Composite Material System

Christopher T. Key
Applied Physical Sciences

C. Scott Alexander, Eric N. Harstad, Shane C. Schumacher
Sandia National Laboratories

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Engineering Solutions Through Science

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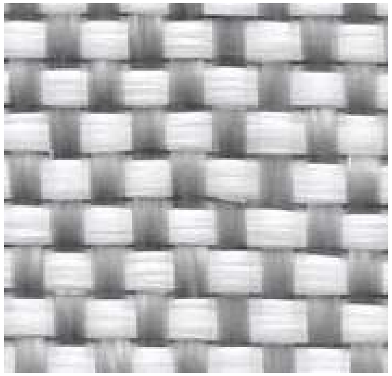
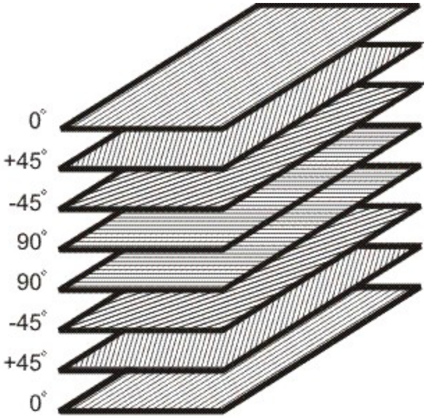
Introduction

- Motivation
    - Work is driven by a need to understand the shock response of (S2-Glass/Epoxy) woven composites for various applications.

- Outline
    - Why composites, applications, anisotropy considerations
    - Experimental testing
        - Experimental testing setup
        - Experimental testing results
    - Micromechanics modeling overview and approach
    - Multiple Constituent Model (MCM) overview
        - Composite constitutive model within the CTH hydrocode
    - Micromechanics simulation results
        - Comparison to experimental results
        - Future modifications
    - MCM simulation results
        - Comparison to experimental results
    - Conclusions and path forward
    - Questions



Plain Weave Fabric Preform



Stacking of plies into a composite laminate with different angles of the fibre reinforcement

Why Composites?

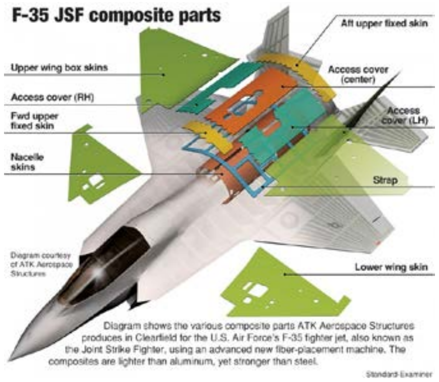
- Composites are widely used in various commercial and military applications:
  - Automotive
    - High performance sports cars
    - Military ground vehicles
  - Aerospace
    - Commercial and military aircraft
    - Satellite launch vehicles
  - Marine
    - Small recreational craft
    - Surface combatants and submarines
  - Protective gear
    - Recreational helmets to body armor

- Composites offer various design benefits over conventional materials
  - Reduced weight (density)
  - High strength
  - Directionally tailorable material properties
  - Large deflections under shock loading (netting)
  - Formability
  - Environmental resistance

Taurus Launch Vehicle

Carbon Fiber Body Armor Panel

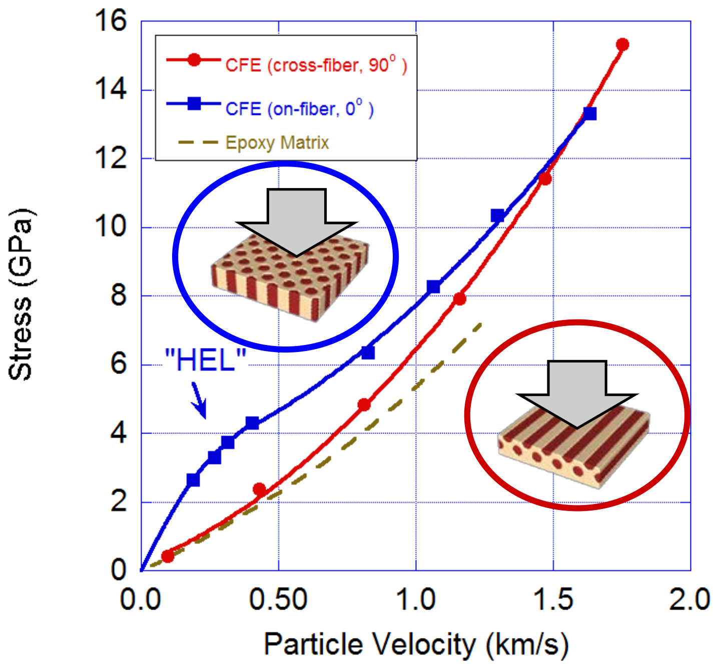
Kali Protective Prana Helmet



F-35 JSF Composite Usage

Anisotropic Dynamic Response of Composites

- Most material shock models in the dynamic regime assume isotropic behavior.
- Composite materials are anisotropic in nature
  - Directionally dependent shock responses.
    - The equation of state (EOS) for the on-fiber and through-thickness directions are different.
  - The EOS is dependent upon the deviatoric strain tensor
    - Deviatoric (strength) and spherical (EOS) responses are coupled.
    - Conventional isotropic materials are uncoupled.
- Methods derived to account for anisotropic coupling:
    - C.E. Anderson, et al. "*A Constitutive Formulation for Anisotropic Materials Suitable for Wave Propagation Computer Programs – II*," Computational Mechanics, 1994
    - A. Lukyanov, "*A Constitutive Behavior of Anisotropic Materials under Shock Loading*," International Journal of Plasticity, 2008



- Test Material:
  - Plain Weave (5x5 tows/inch)
  - S-2 Glass Fibers
  - SC15 Epoxy
  - 50% and 60% FVF

$$\sigma_{ij} = P\delta_{ij} + P(S_{ij}) + S_{ij}$$

Coupling Terms

Experimental Testing to Determine EOS

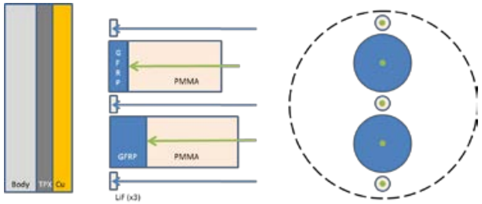
- EOS testing on GFRP composite system
  - 89 mm bore powder driven gas gun at Sandia National Labs STAR Facility
  - Copper impactors at 0.5-2.0 km/s impact velocity produce 2-15 GPa stress in composite targets
- To reduce sample variation, all test samples (for each FV and fiber orientation) were cut from a single composite panel

89 mm bore gun

Panel ID	V_{fiber}	V_{resin}	V_{void}	layup	orientation
5138	50.6	49.1	0.3	40x(0/90)	Longitudinal
4089	49.0	50.7	0.4	8x(0/90)	Transverse
5137	59.6	39.5	0.9	40x(0/90)	Longitudinal
4075	61.1	38.5	0.4	5x(0/90)	Transverse

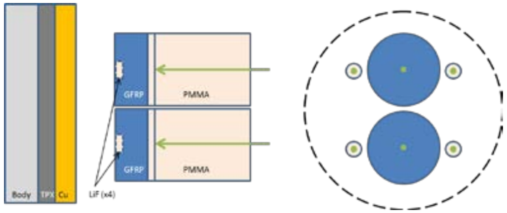
Experimental Target Setup

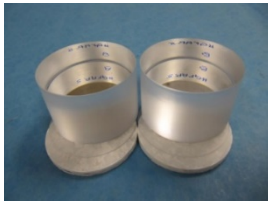
- Multiple targets used to determine sample-to-sample variability
- Longitudinal orientation samples smaller due to manufacturing process limitations
- Buffered windows (transverse orientation only) provide long read time but at a cost of some local response averaging
  - Buffers not used on longitudinal samples due to previously observed wave structure in carbon fiber composites



Longitudinal Orientation

(3 and/or 6 mm thick samples; 25 mm diameter)

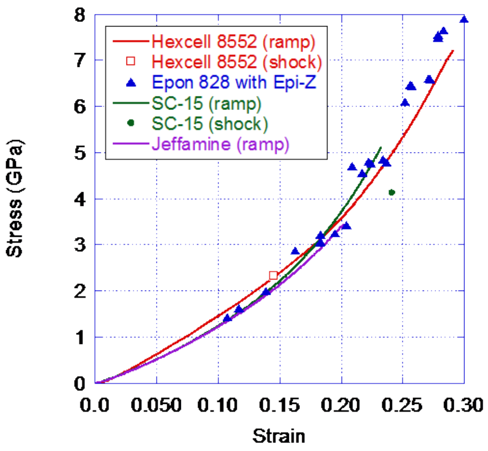




Transverse Orientation

(3 and/or 6 mm thick samples; 36 mm diameter)

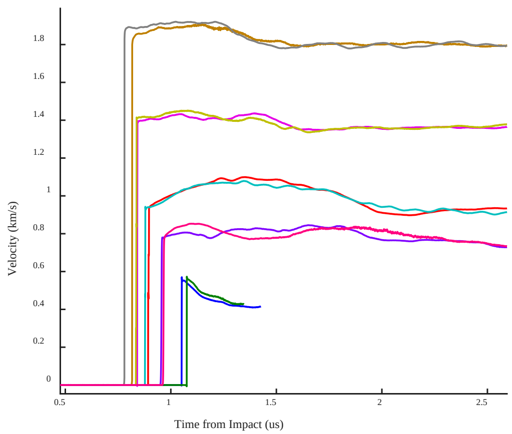
- Neat epoxy resin is tested to provide the constitutive properties
  - Ramp loading provides full quasi-isentrope
  - Shock loading provides Hugoniot states
- Samples must be free from defects

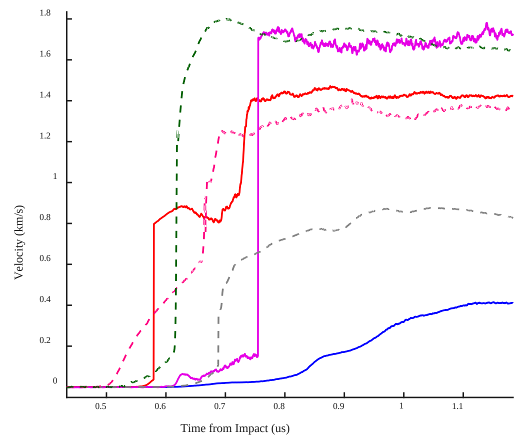


Epoxy Test Data

All tested epoxies have very similar constitutive response

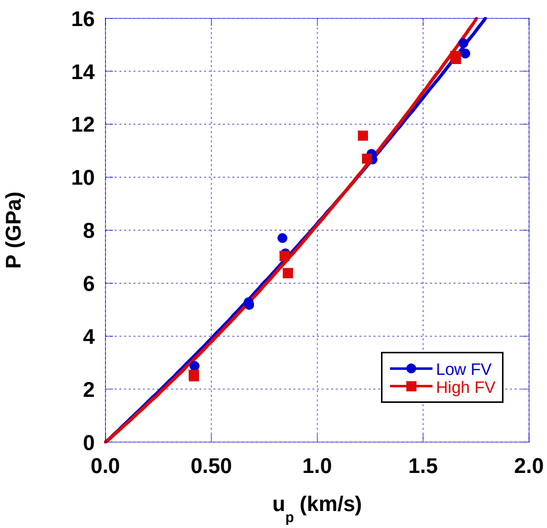
Experimental Testing Results

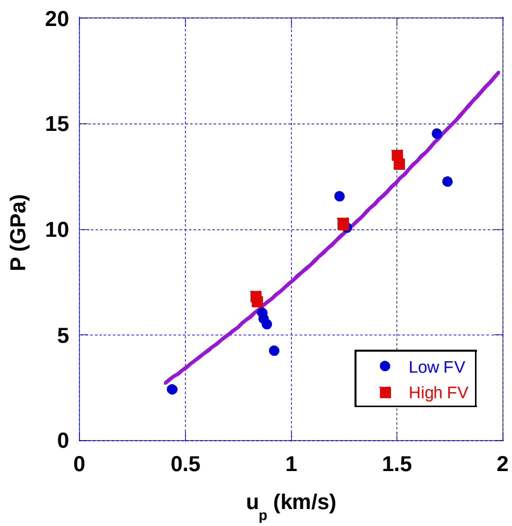




Transverse

Longitudinal





- Data quality is outstanding considering heterogeneous nature of the sample material.
- Impact velocities shown are nominally 0.5, 0.8 (tr), 1.0, 1.5, 2.0 *km/s*.
- More variability observed in longitudinal targets likely due to sample variations
- Similar plateau velocities indicate similar EOS response
  - Differences attributed to slight variations in thickness and impact velocity, and heterogeneity of the composite
- Fiber fill volume has little effect on shock response

Micromechanics Modeling

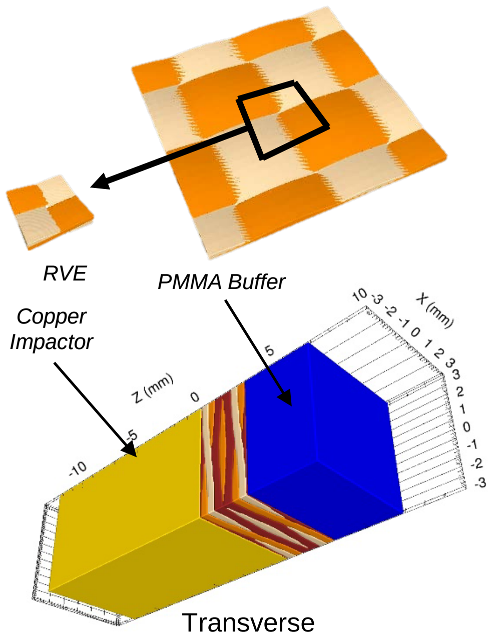
- Transverse Micromechanics Model:
  - Unit cell representative volume element (RVE) constructed
  - Three (3) RVE’s staggered and layered
    - Actual specimen ~5 layers thick with considerable nesting of the plies (see micrograph image).
- Longitudinal Micromechanics Model:
  - Single RVE used to provide an estimate of the experimental test specimen
    - The actual specimen was not a full RVE in thickness
    - 3mm or 6mm thick test specimens vs. the 10mm unit cell
- Fiber bundles were ”homogenized”
  - Individual fibers were not modeled.
- Constituent properties:
  - Density (ρ) = 2.48 *g/cc*
  - S2 Fiber EOS -- Us = 5.244 – 0.1054*u_p
  - Epoxy EOS -- Us = 2.35 + 1.604*u_p

Warp Bundle:

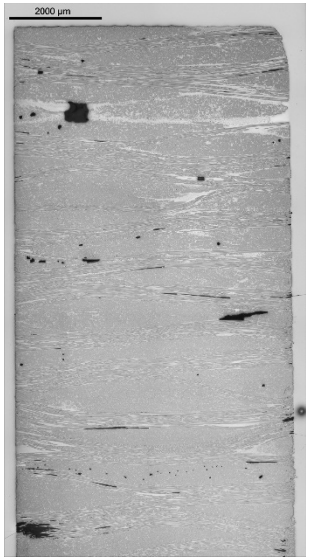
- Cs = (0.7)(5.244)+(0.3)*(2.35) = 4.3728 *km/s*
- S = (0.7)(-0.1054)+(0.3)*(1.604) = 0.40742 *km/s*
- Poisons ratio = 0.22

Fill Bundle:

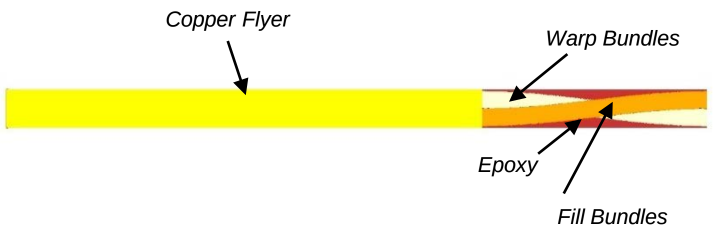
- Cs = 5.244 *km/s*
- S = – 0.1054 *km/s*
- Poisons ratio = 0.22



Transverse Micromechanics Model



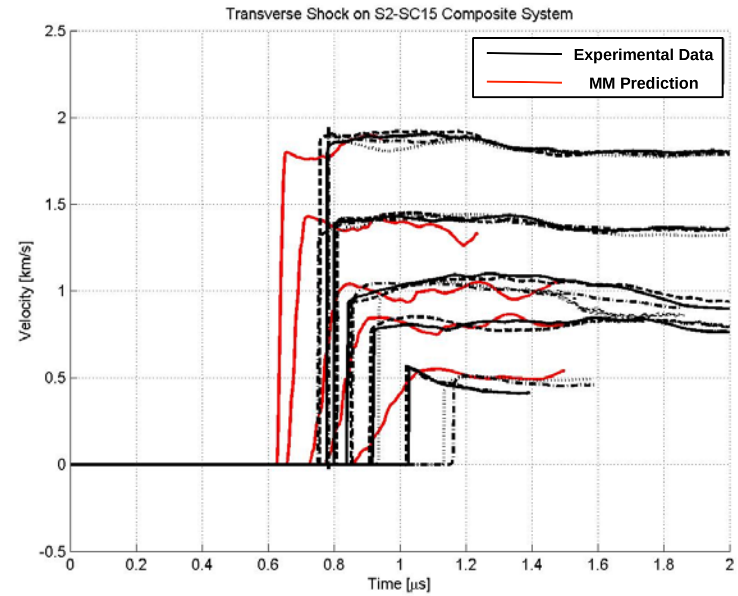
Experimental Specimen Micrograph



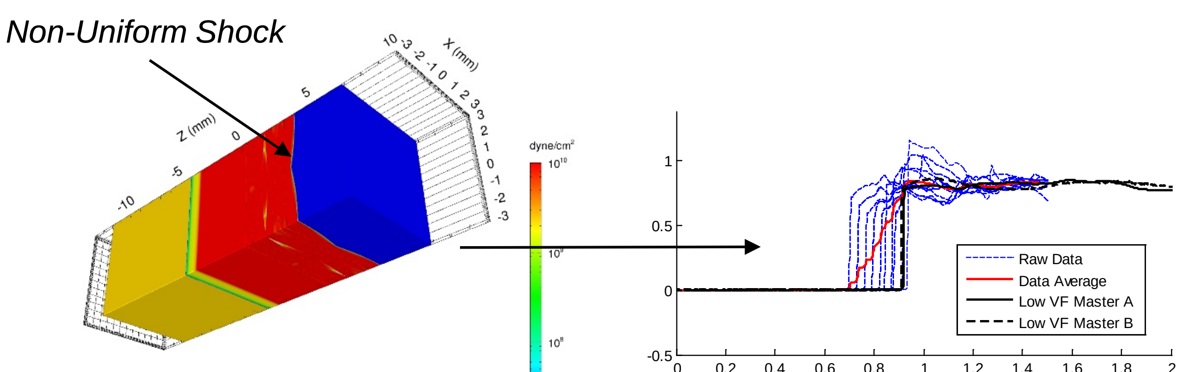
Longitudinal Micromechanics Model

Micromechanics Model Results: Transverse

- Transverse micromechanics results in particle velocities that agree well with the experimentally measured levels.
- Shock velocity is faster than the experimental results.
  - EOS of the S-2 fibers may need altered.
- Strongly ramped behavior observed in the micromechanics simulations.
  - Result of averaging the tracer grid to estimate VISAR response.
  - Simplistic approximation of bundle “nesting” results in non-uniform averaged wave.



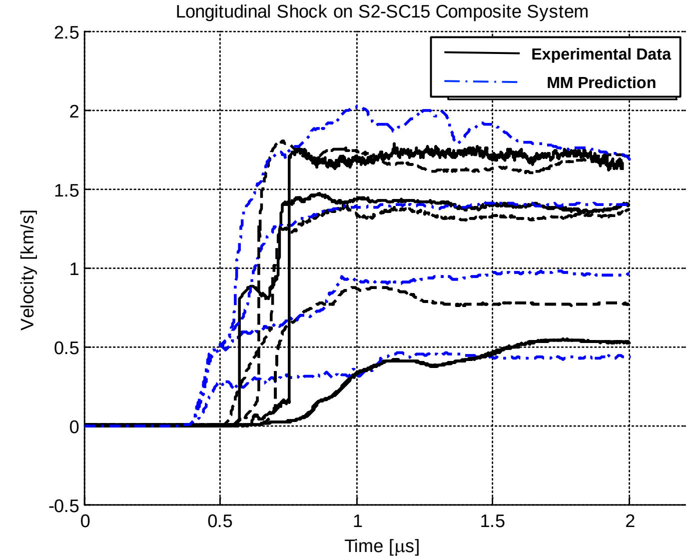
Comparison of transverse micromechanics simulations with experimental test data



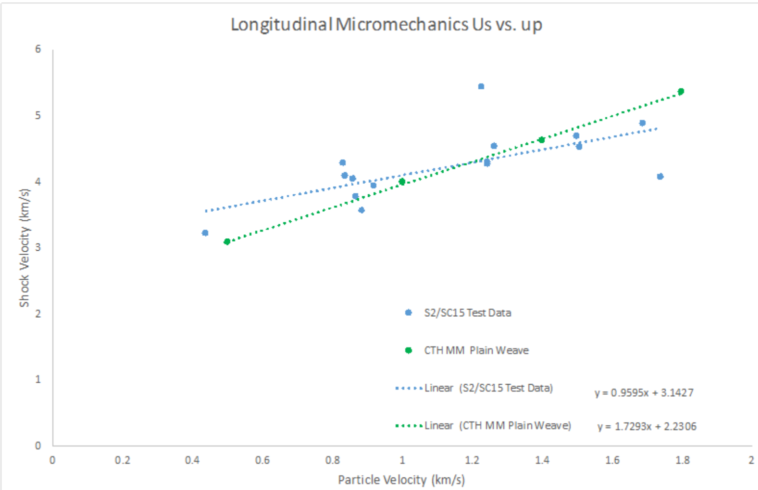
Tracer averaging

Micromechanics Model Results: Longitudinal

- Longitudinal micromechanics results in particle velocities that agree fairly well with the experimentally measured levels.
- Shock velocity is faster than the experimental results.
    - EOS of the S-2 fibers may need altered.
    - Similar conclusion for the transverse micromechanics.
- Micromechanics show the expected two-wave structure for each shock level.
    - Experimental results only show this at the 1.5 km/s impact level.
    - Additional testing planned to better understanding the longitudinal shock.



Comparison of longitudinal micromechanics simulations with experimental test data



Video: Shock wave propagation in longitudinal micromechanics model

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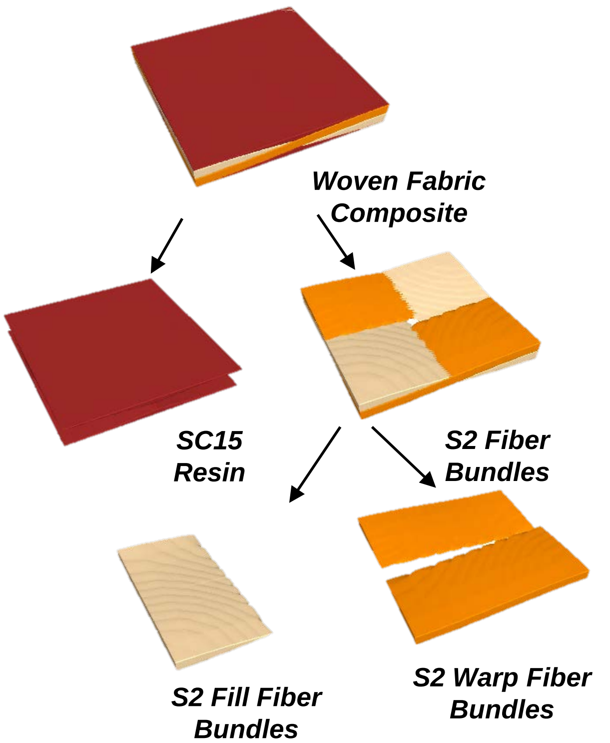
Overview: MCM Model

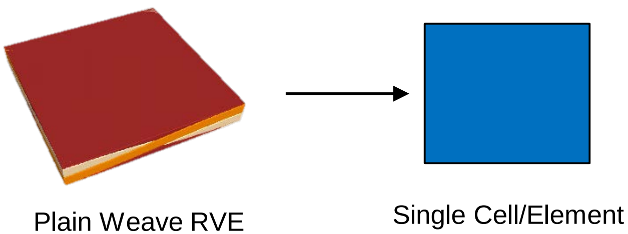
- *The Multiconstituent Model (MCM) extracts* ***constituent*** (fiber and matrix) stress and strain fields From the composite or "homogenized" response.

$$\{\varepsilon_{Matrix}\} = \left(\phi_{Matrix}[I] + \phi_{Fiber}[A]\right)^{-1}\left(\{\varepsilon\} - \theta\{a\}\right)$$

- Through the knowledge of constituent level stress and strain fields, constituent level damage/failure criteria can be applied.
- Nonlinearity introduced through material stiffness changes according to damage/failure level.
- An entire RVE can mathematically be represented as a single cell or element.
  - Greatly increases computational efficiency, while still allowing access to constituent level stress and strain information.
- Strength model within the CTH hydrocode.



MCM microstructural decomposition



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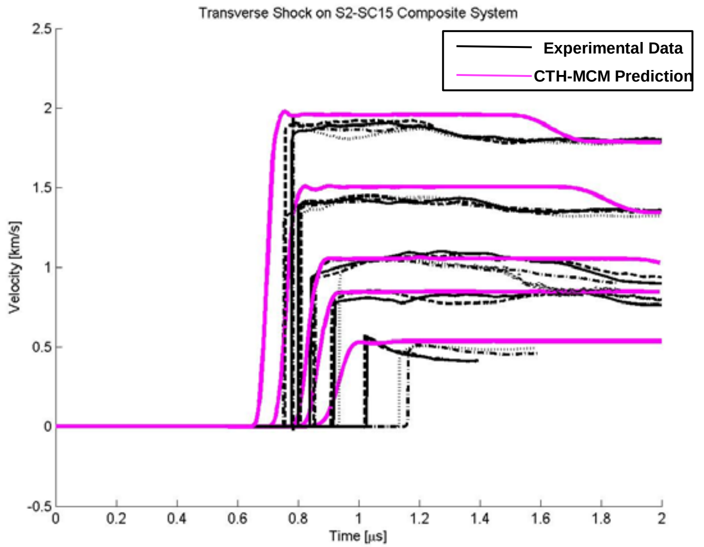
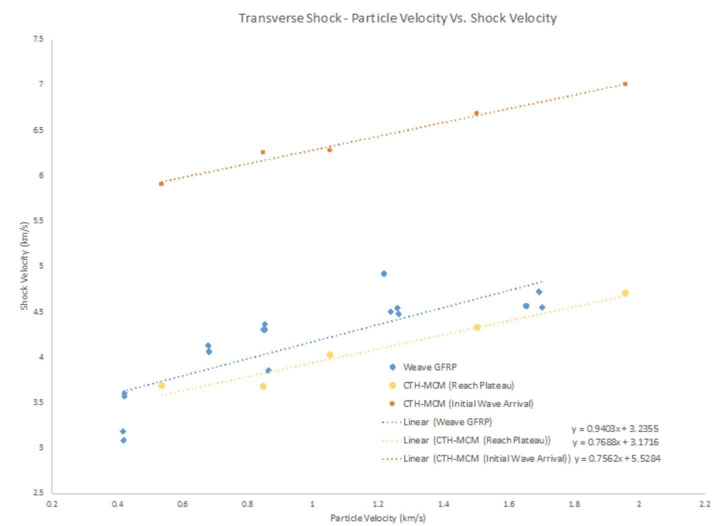
MCM Model Results: Transverse

- MCM transverse shock predictions are in good agreement with the experimental data.
- Both the analytical and experimental responses show a single “bulk” shock.
    - Similar to what has been observed for transverse shocks in previous efforts.
- Two different points used to estimate the Hugoniot shock velocity.
    - (foot and peak of shock ramp) bound the experimental Us vs. u_p data.
- The MCM predictions show more of a ramp than true “shock” front.
    - Work underway to understand this model response.

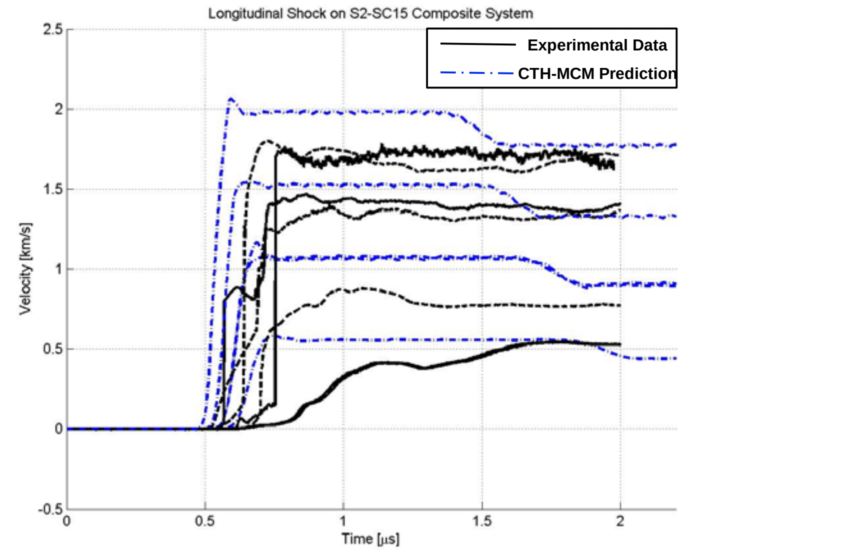


Comparison of CTH-MCM transverse shock simulations with experimental test data

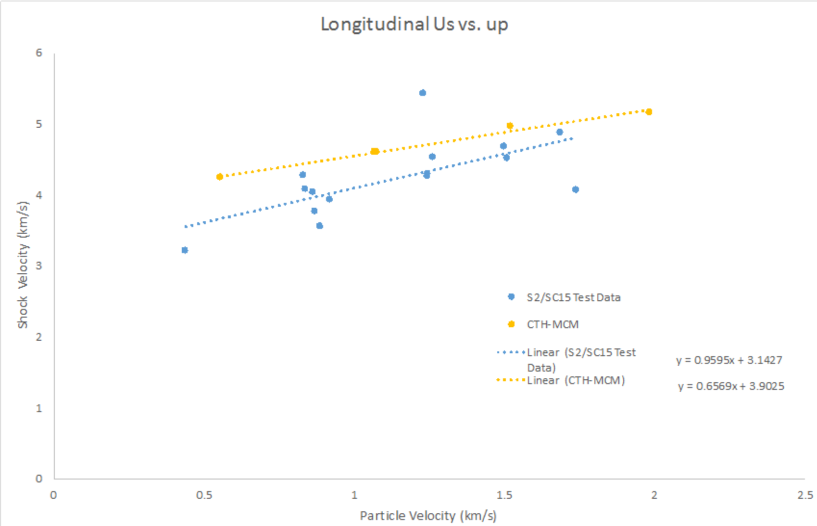


MCM Model Results: Longitudinal

- MCM longitudinal shock predictions are similar to the experimental data.
  - Noticeable discrepancies exist
- Large scatter in the experimental data makes direct comparison difficult.
- Some tests show a distinct precursor wave (1.5 *km/s*) while others do not (0.5, 1.0 and 2.0 *km/s*).
  - In previous unidirectional work the longitudinal response showed a two-wave structure.
    - Initial wave travelling in the fibers followed by a bulk shock in the resin/fibers.
- CTH-MCM Us vs. u_p response in good agreement with the experimental data.
- Additional testing planned to improve experimental data quality and understanding.



Comparison of CTH-MCM longitudinal shock simulations with experimental test data



Conclusions and Path Forward

- Anisotropic behavior for a plain weave fabric S-2/SC15 composite material system explored.
  - Similarities to the response observed in unidirectional composites.
    - Transverse – single "bulk" shock.
    - Longitudinal – two-wave structure (at times).
  - Additional testing to be performed (focused on longitudinal direction) to improve confidence in data and reduce data spread.
- Micromechanics models do a good job of replicating the experimentally measured responses.
  - Provides initial estimate of S-2 glass EOS parameters
    - Future iterations planned to improve correlation.
  - Highlight the effect that the lamina "nesting" has on the observed shock response.
    - Idealized microstructures can lead to erroneous.
- MCM does a good job of replicating the experimental results.
  - Simulations run orders-of-magnitude faster
  - Minimal model efforts in model generation vs. micromechanics models.
  - Current work focused on understanding MCM "ramped" shock response.

Questions ?

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