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Dynamic Characterization of IM7 Composites in Support of M&S Efforts

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Sandia National Laboratories

IM Hazards M&S PA Meeting
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Los Alamos, NM

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Dynamic Behavior of Composite Materials

Goals:

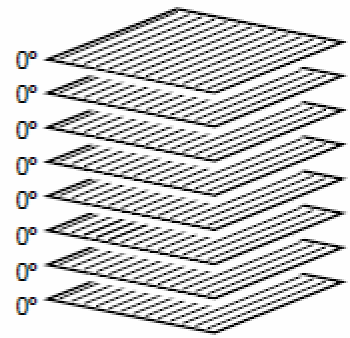
Obtain shock data to characterize the anisotropic response of fiber composite materials for development of advanced EOS and constitutive models

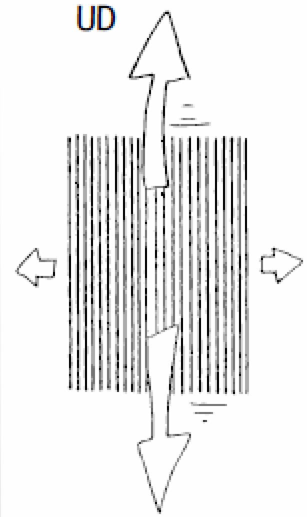
Utilize simulation results to better understand observed response

Test Material:

Hexcel IM7/8552
unidirectional / laminate
vary volume fraction (62, 65, 68%)

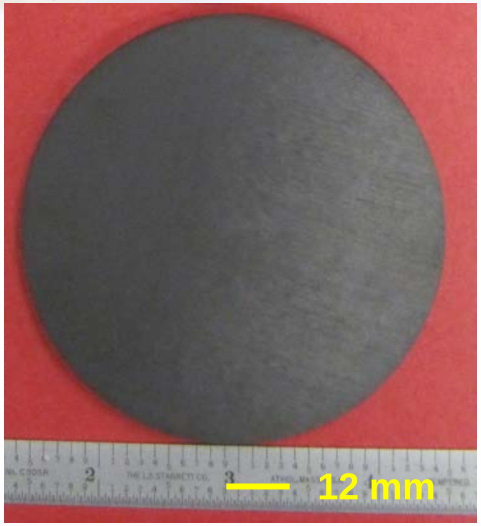
<u>Extremely low porosity material</u>
(ultrasound / x-ray confirmed)

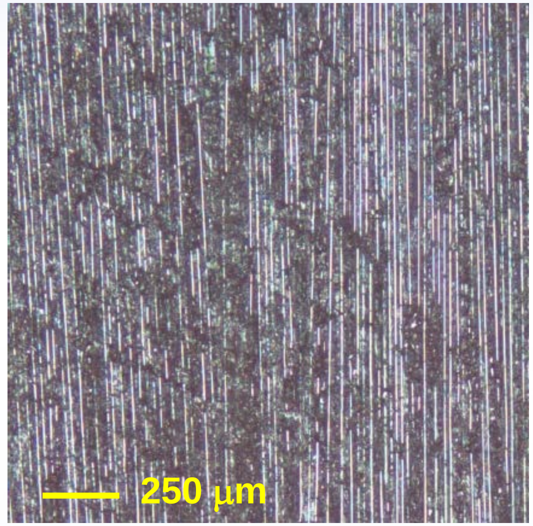


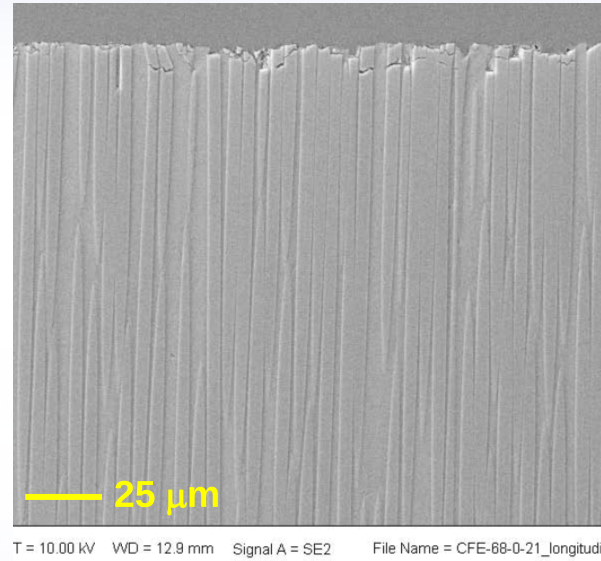


Hexcel Prepreg Technology Guide
Publication No. FGU 017b
March 2005

Material is engineered to exhibit anisotropic response

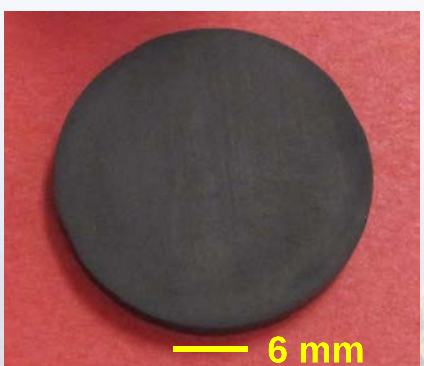




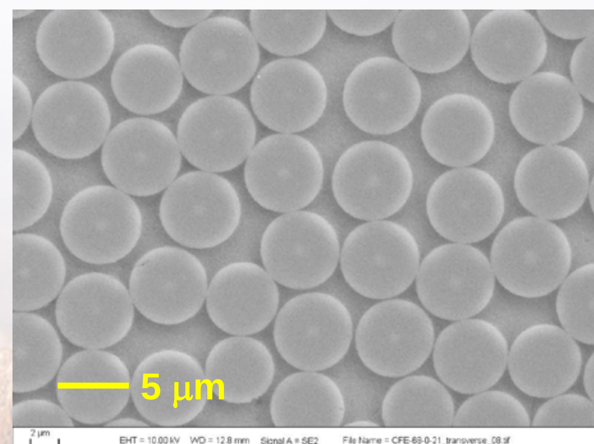


Cross-fiber orientation (90˚)

On-fiber orientation (0˚)

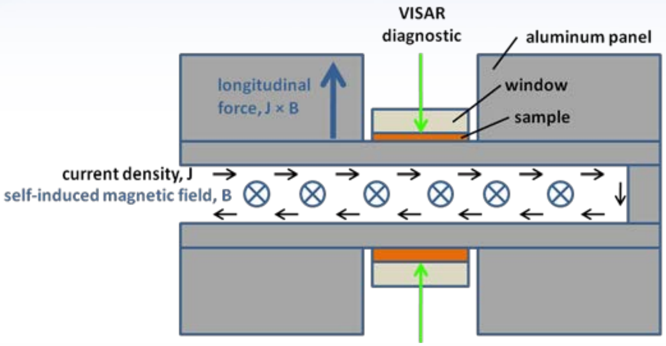


Ultrasonic Wave Speeds	
0°	10.763 km/s
90°	3.042 km/s

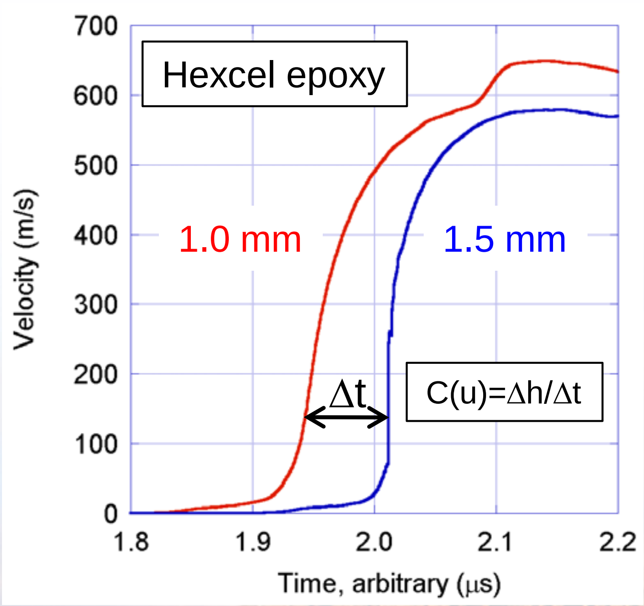


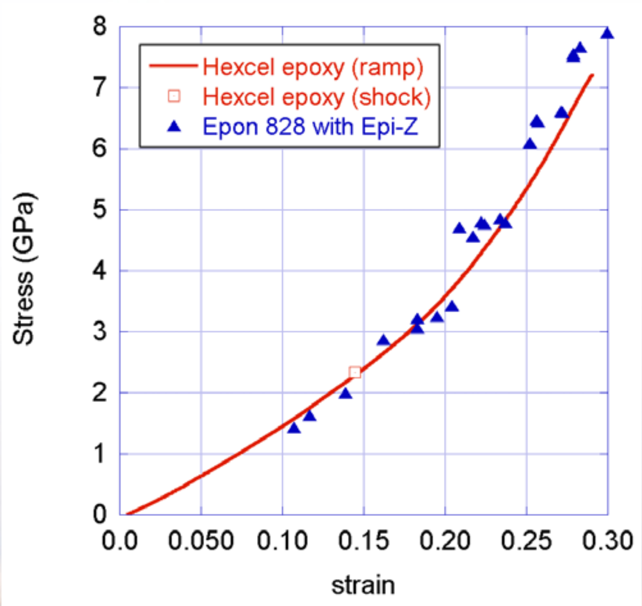
Unreinforced epoxy was characterized using both shock and ramp loading

Hexcel 8552
epoxy test sample

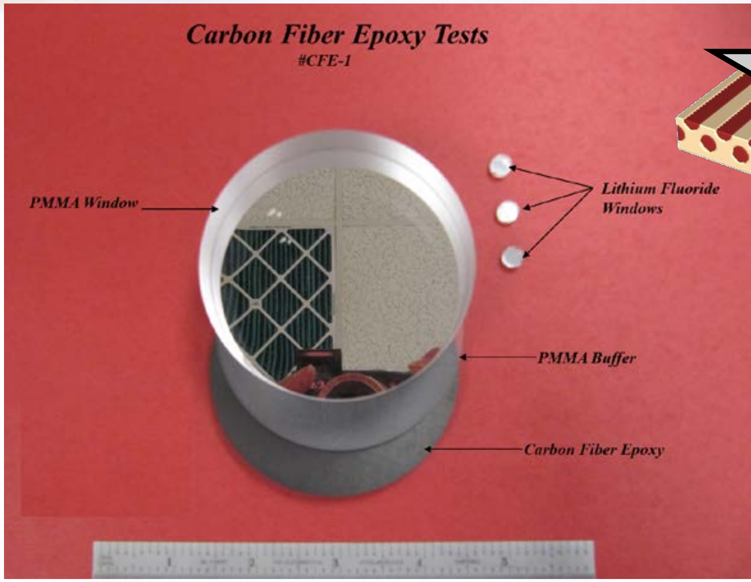


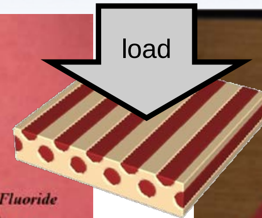
- Epoxy response is needed by model development effort
- Response measured via shock and ramp loading techniques
- Data similar to another common (well characterized) epoxy

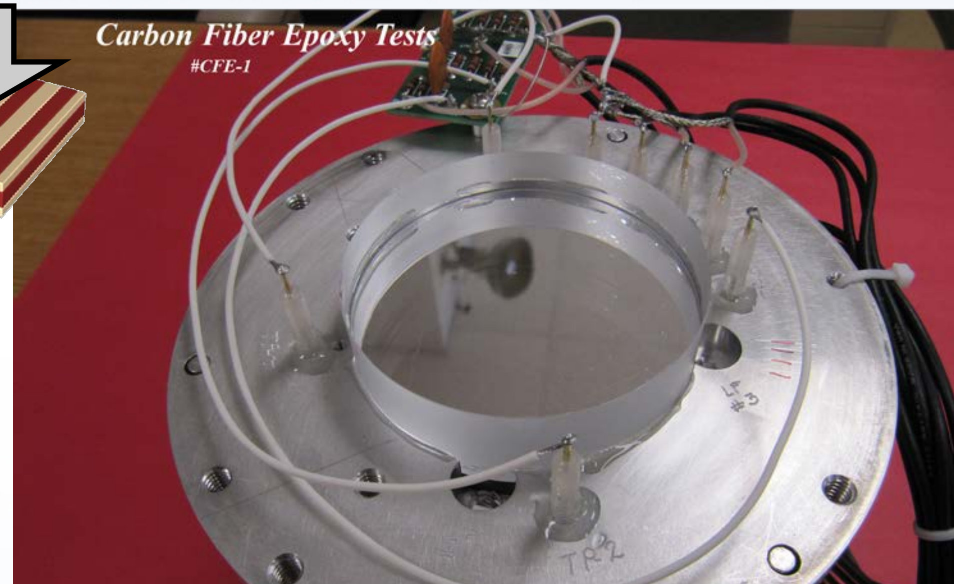


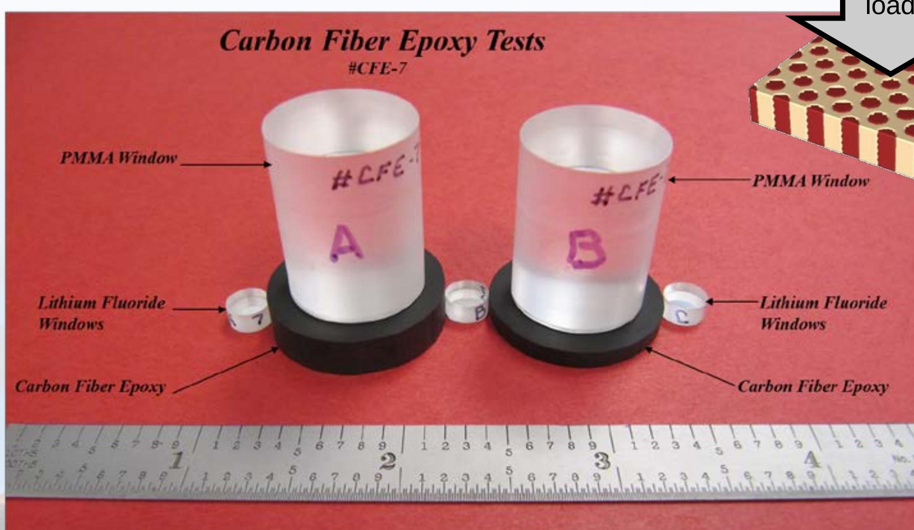


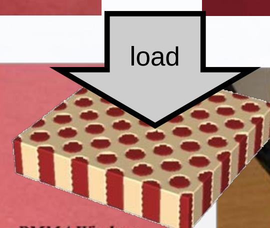
Experimental designs vary slightly depending on fiber orientation

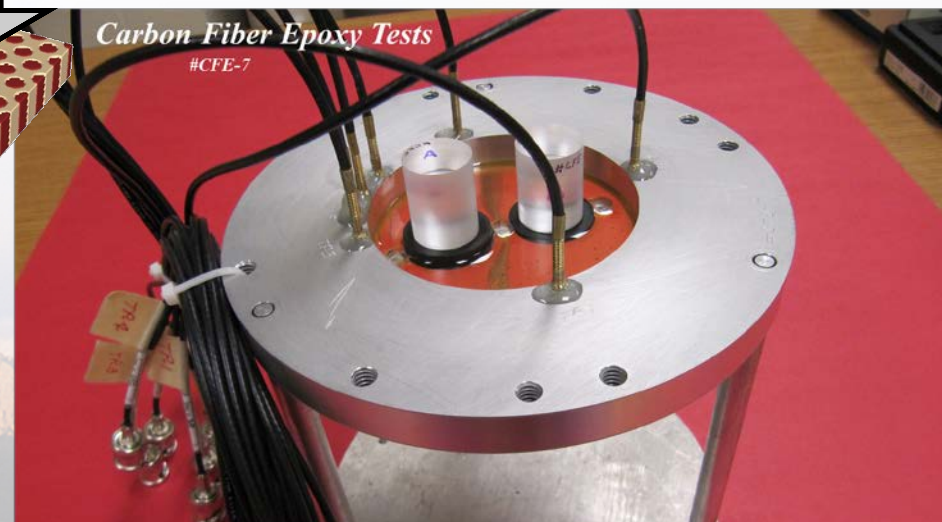




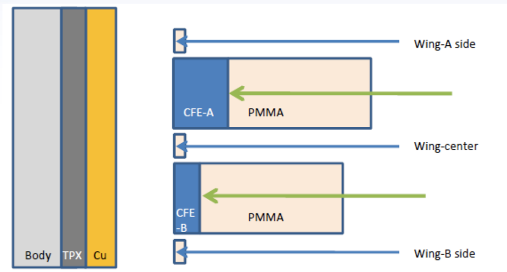


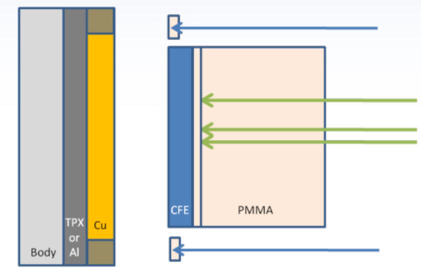




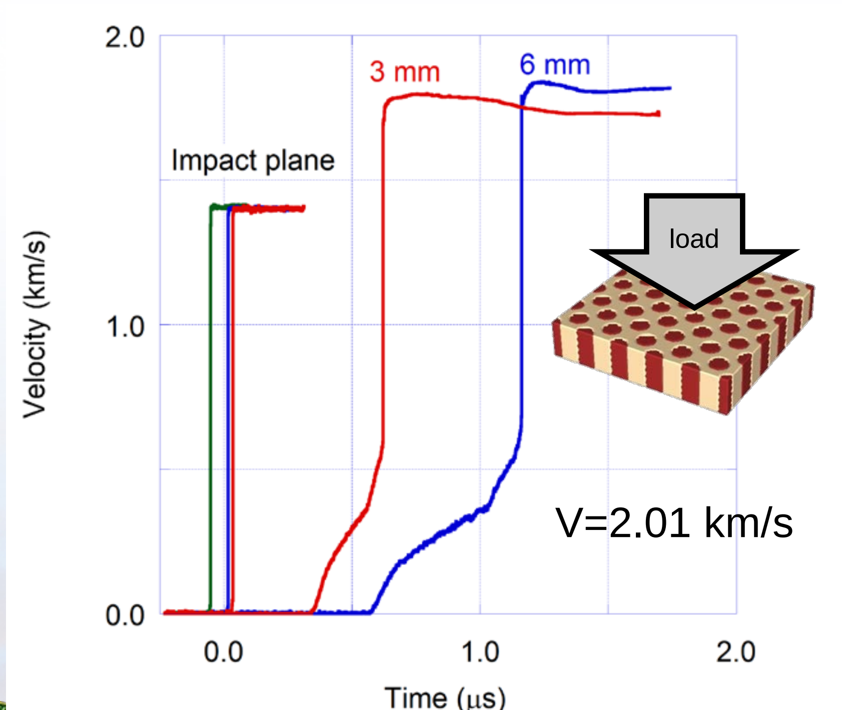


Response depends on fiber orientation

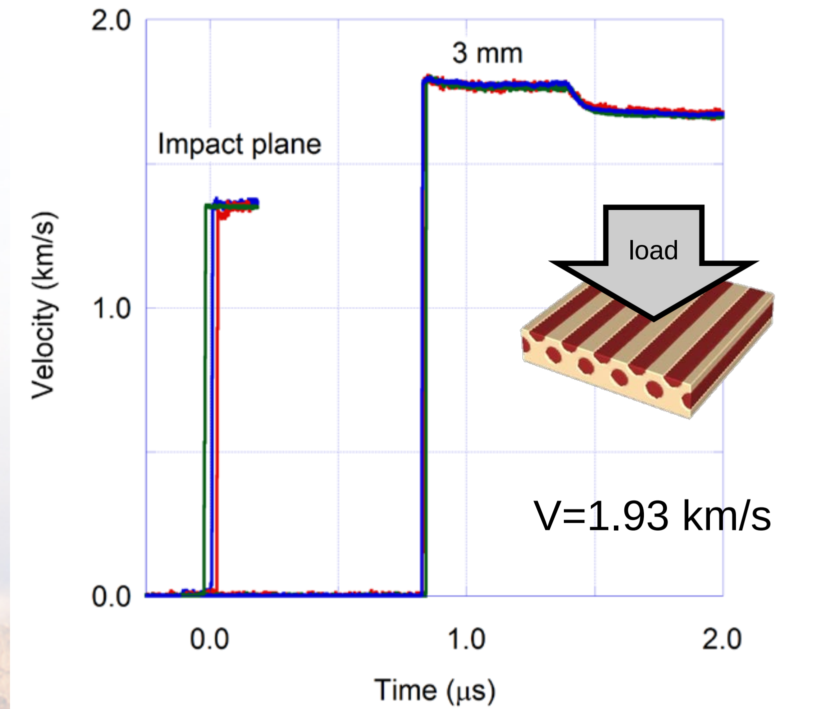




0° (shock along fiber direction)



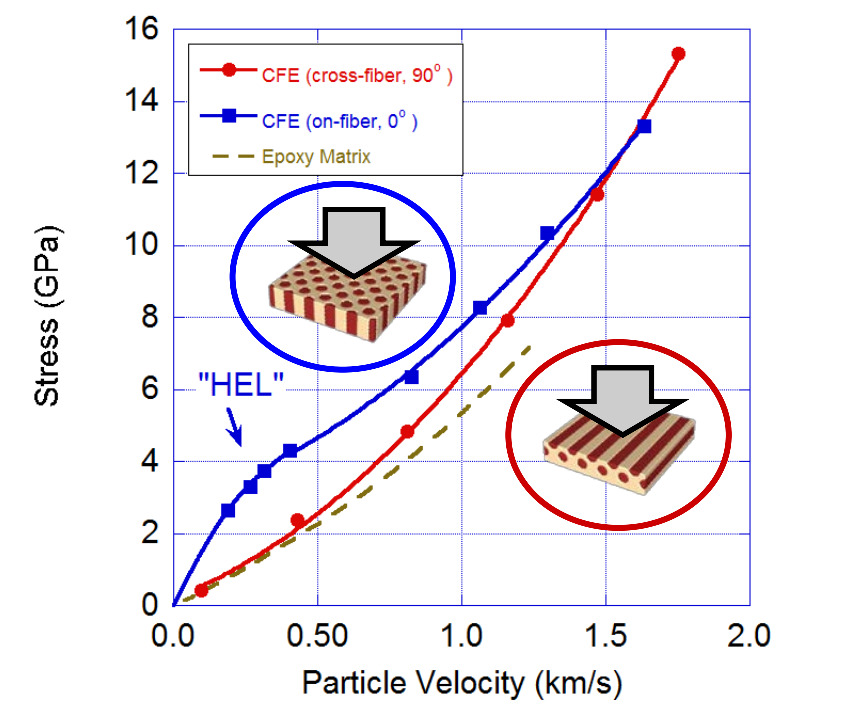
90° (shock normal to fiber direction)



Data for 68% fiber FV

Shock response of CFE is anisotropic up to ~10-12 GPa

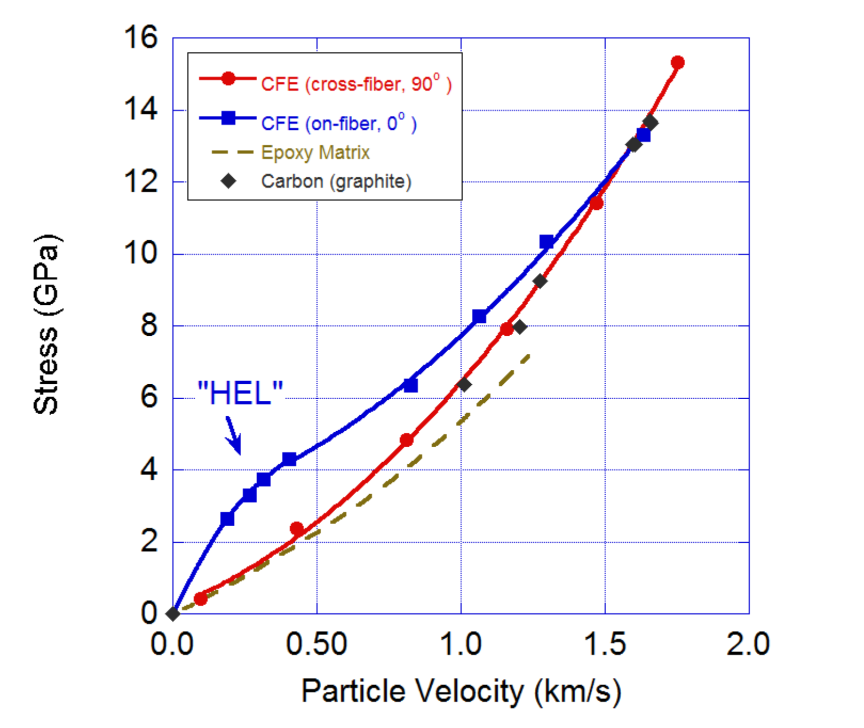
The vast majority of models in the dynamic regime assume **isotropic behavior**, especially for shock response



- Fiber stiffens matrix at low-intermediate pressures (up to ~10-12 GPa)
- Response appears to become isotropic at higher pressures
  - Epoxy disassociates at 10-20 GPa

Cross-fiber material response is similar to pressed graphite

Cross fiber response is similar to carbon, stiffer than epoxy

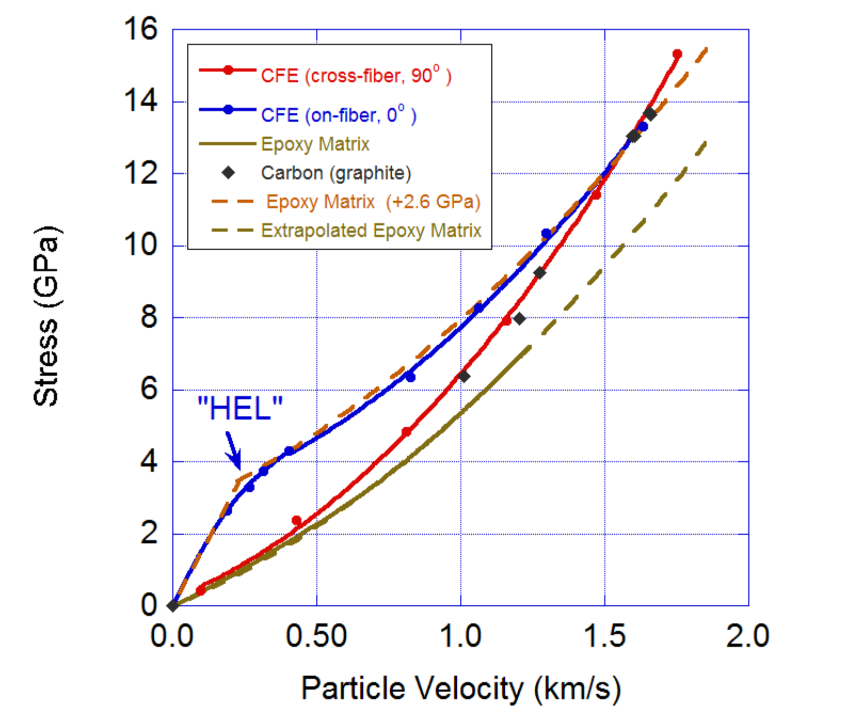


Pressed graphite ρ_o = 1.77 g/cm^3
CFE ρ_o = 1.58 g/cm^3

- Fiber stiffens matrix at low-intermediate pressures (up to ~10-12 GPa)
- Response appears to become isotropic at higher pressures
  - Epoxy disassociates at 10-20 GPa
- Comparison with pressed carbon of similar density shows like response in cross-fiber orientation

Fibers provide an elastic component to the epoxy response (HEL = 3.5 GPa) on-fiber

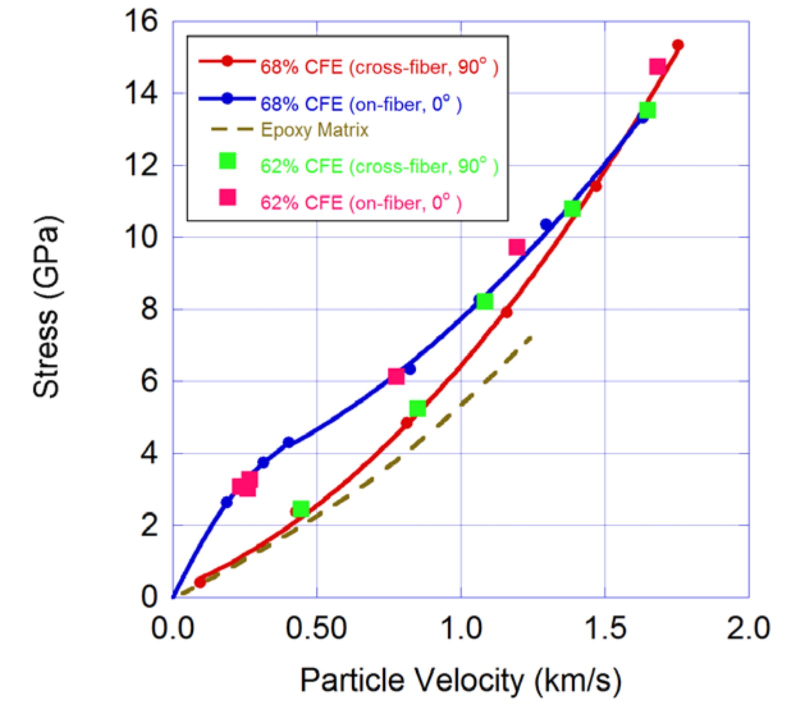
On-fiber bulk response is similar to epoxy but with an HEL of 3.5 GPa



- Fiber stiffens matrix at low-intermediate pressures (up to ~10-12 GPa)
- Response appears to become isotropic at higher pressures
  - Epoxy disassociates at 10-20 GPa
- Comparison with pressed carbon of similar density shows like response in cross-fiber orientation
- On-fiber response shows a stiffening of the epoxy matrix with an HEL of 3.5 GPa
- Different fundamental mechanisms in play for different orientations

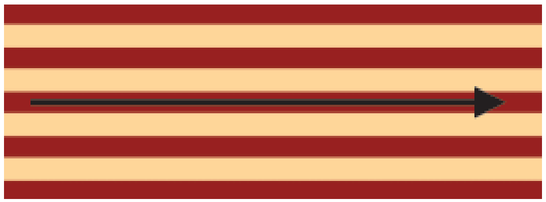
Dynamic response is not sensitive to exact fiber fill volume

No observed difference in response of 62 – 68 % fiber fill volumes

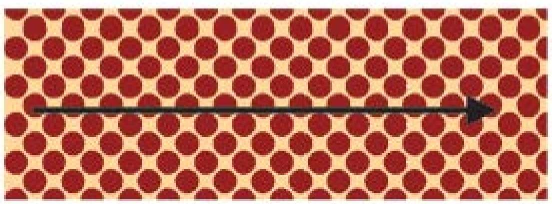


- 62% fill material (large squares) shows similar dynamic response to 68% fill
- Samples tested are maximum and minimum possible fill volumes for this composite

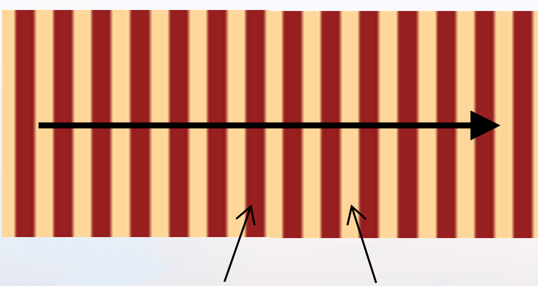
Understanding complex material response is improved through numeric simulation



Longitudinal Shock



Transverse Shock

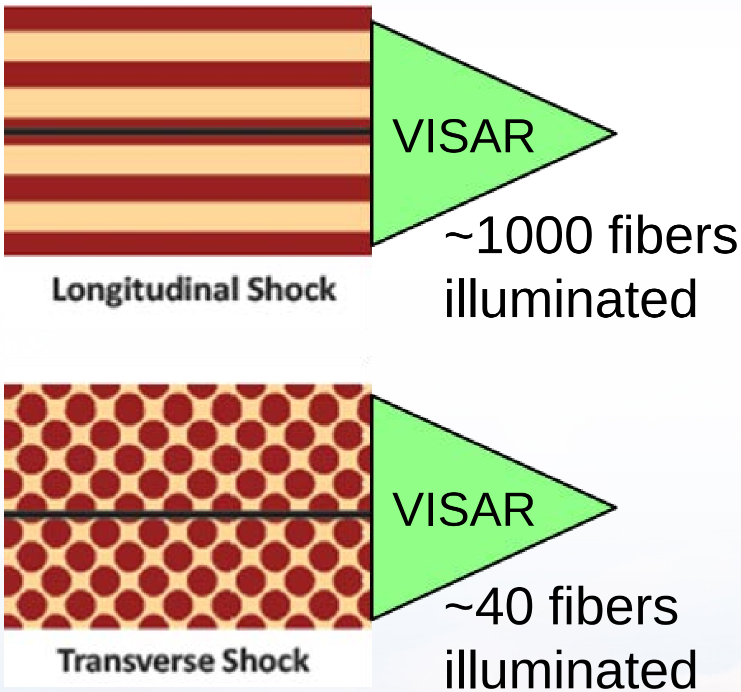


carbon fiber   epoxy

- Hydrocode simulations of multiple shock-fiber orientations
- Explicit modeling of all constituents
  - Small mesh to resolve fibers
    - ≥10 cells/fiber ($\Delta x \leq 500$ nm)
  - Limited domain sufficient to achieve stable waves

	Fiber Longitudinal	**Fiber** Transverse	**Matrix**
Mie-Gruneisen EOS	ρ_o=1.694 g/cc C_o=4.50 km/s S=1.478	ρ_o=1.694 g/cc C_o=2.35 km/s S=1.478	ρ_o=1.305g/cc C_o=2.35 km/s S=1.604
Elastic-Perfectly Plastic Strength	ν=0.050 Y_o=3.5 GPa	ν=0.352 Y_o=3.5 GPa	ν=0.393 Y_o=0.1 GPa

Simulation data is interpreted consistent with VISAR diagnostic averaging



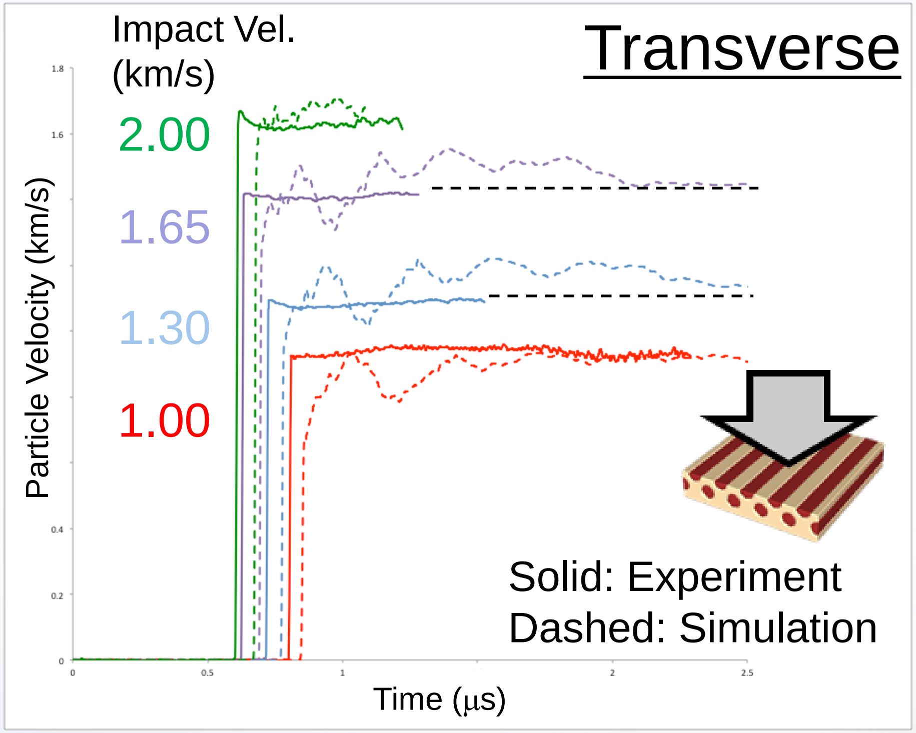
- VISAR diagnostics use ~200μm spot size
- Multiple fibers and surrounding matrix are illuminated
- Volume fraction weighting used to mimic VISAR detection

$$Vel_{composite} = \emptyset_{fiber} Vel_{fiber} + \emptyset_{matrix} Vel_{matrix}$$

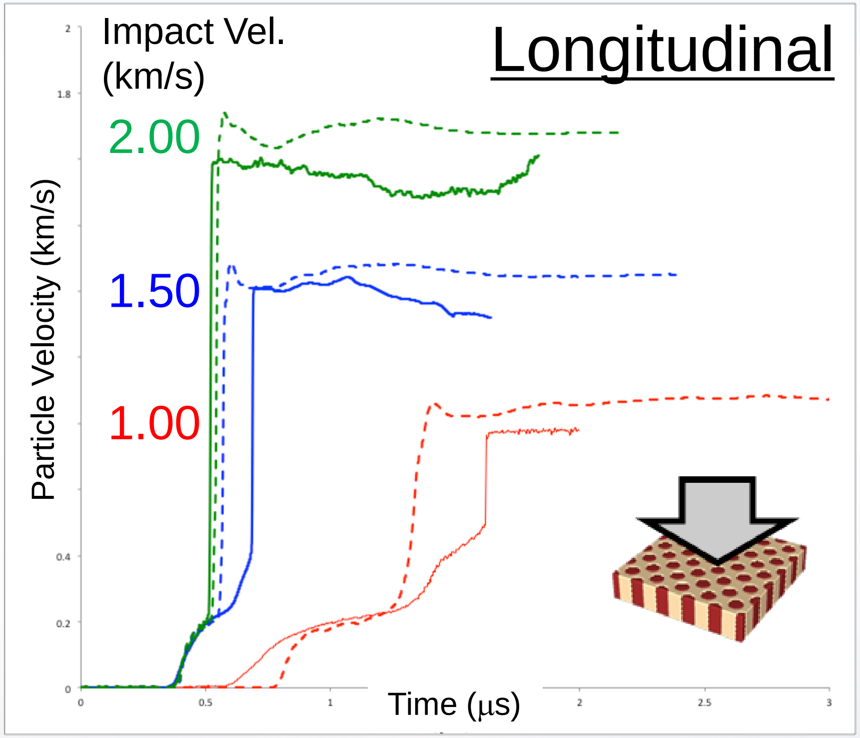
- Periodicity of fibers in simulation domain is known to result in oscillatory response*

*T.J. Vogler, J.P. Borg and D.E. Grady, JAP **112** 123507-1 (2012)

Simulation results are in good agreement with experiments



- Shock velocities agree within 10%
- Particle velocities agree within ≤ 5% (generally better)



- Shock velocities agree within 10% of linear ramp arrival
- Particle velocities agree within ≤ 10% (generally better)

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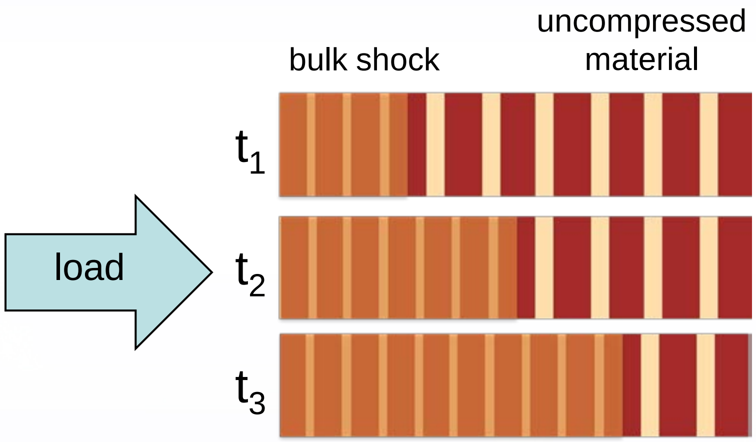
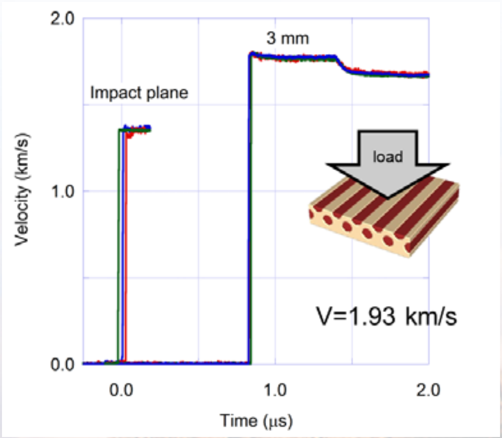
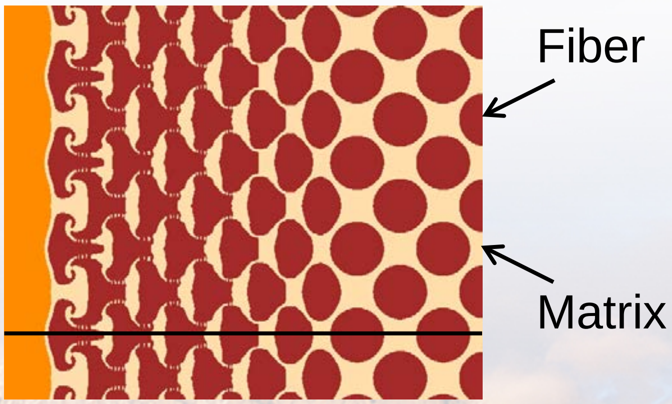
Simulation results help to visualize and understand observed shock response

Cross-fiber orientation (90˚)



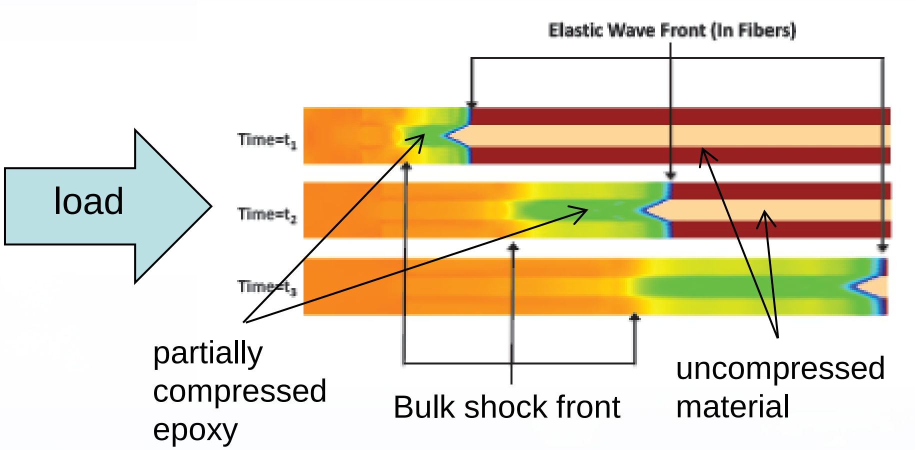
- Epoxy is compressed
  - Jet formation due to wave speed differences
- Fiber-on-fiber contact may occur
- Shock wave moves comparable to bulk carbon response at a similar density

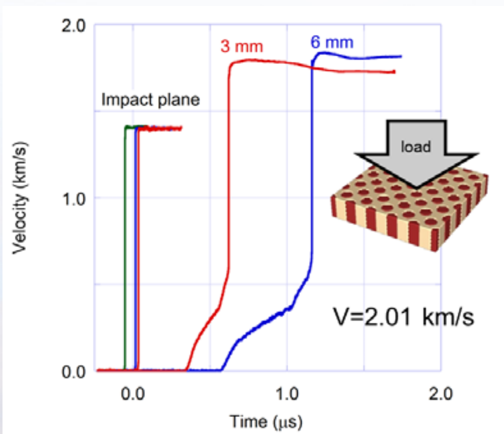




Simulation results help to visualize and understand observed shock response

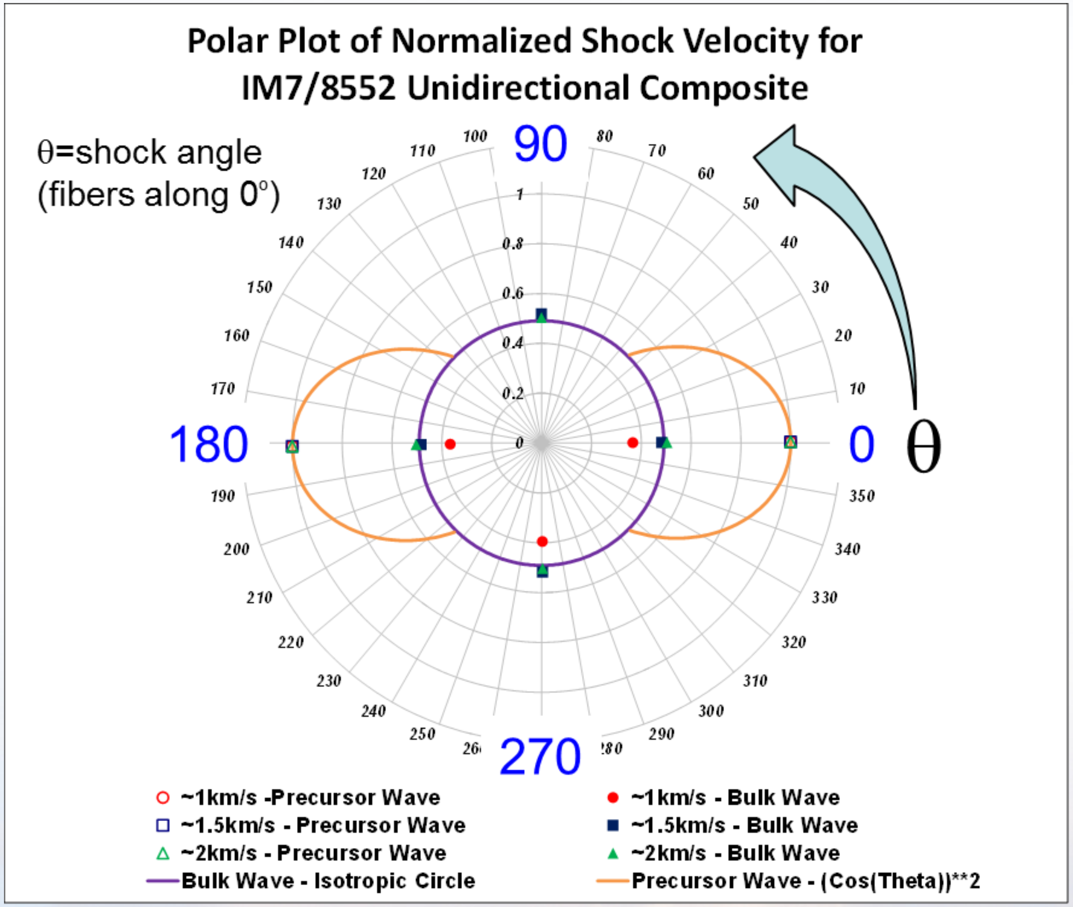
On-fiber orientation (0°)





- Elastic waves travel along fibers
  - Observed elastic response entirely in fibers
- Mach wave features observed in epoxy behind elastic waves
- Bulk shock travels at slower epoxy velocity
- Results in observed complex loading structure

Shocks in real world applications rarely travel only along principal axes



- Wave speeds best observed in polar space
  - Measurements made in 0-90°
  - Symmetry used to complete plot
- Velocities are normalized based on 0° precursor velocity
- Theory (solid curves) predicts
  - Elastic waves speeds will follow a $\cos^2(\theta)$ relation
  - Bulk shock will be isotropic
  - Elastic wave overdriven at 45°
- Experiments are required to verify these predictions

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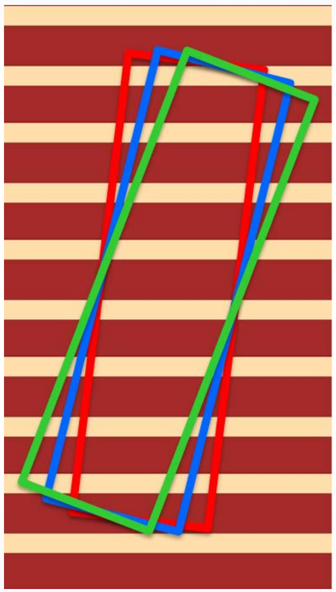
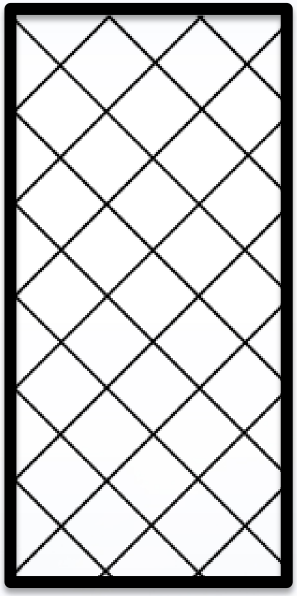
Off-principle-axis testing



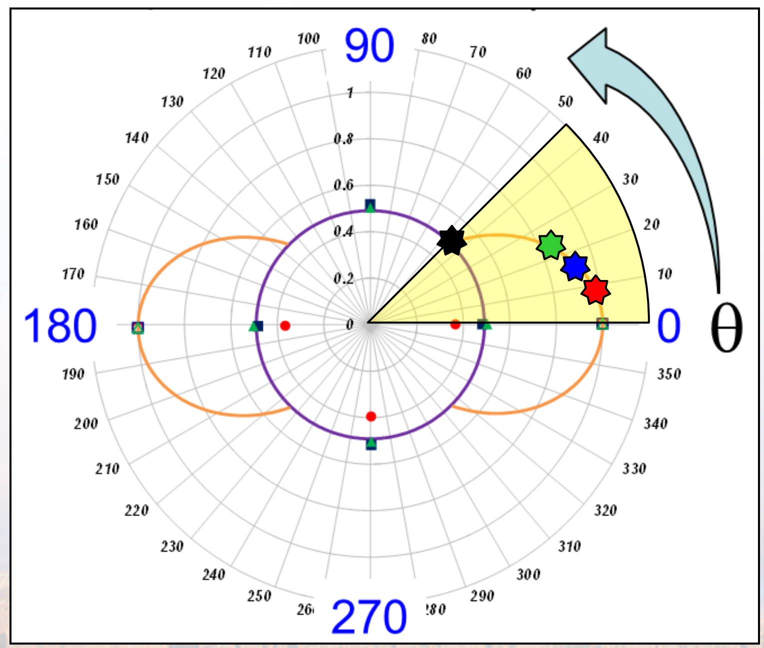
7, 14, 21° samples



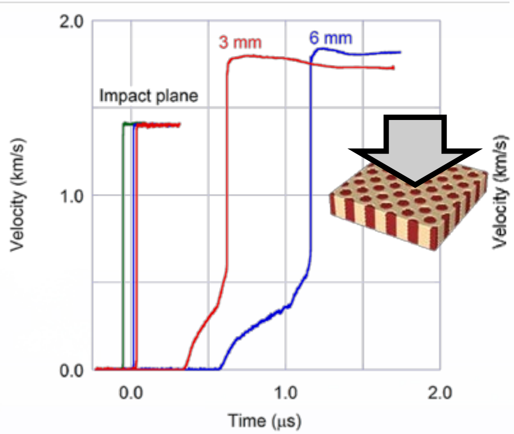
± 45° samples

Example 21° sample

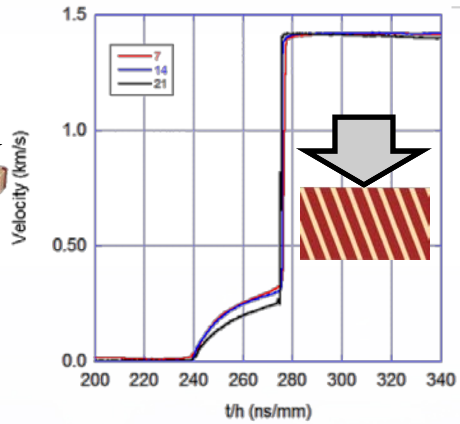
- Material manufactured as previously
- Samples cut from oversized parts at fixed angles (7, 14, 21 degrees)
- ±45 degree samples cut from 0-90 cross-ply material



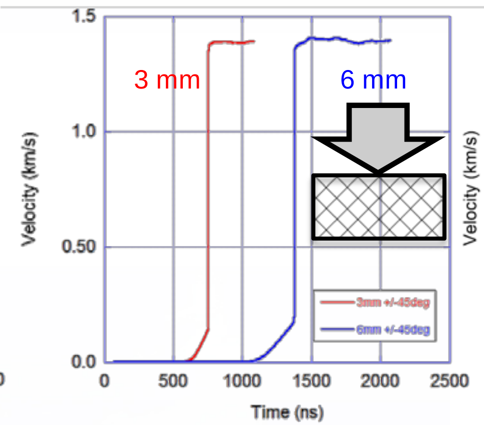
Off-principle-axis testing reveals trends



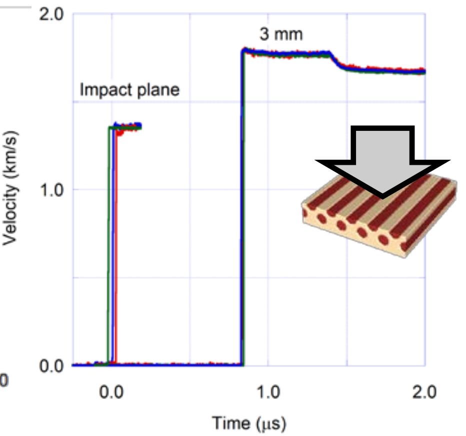
0°



7, 14, 21°



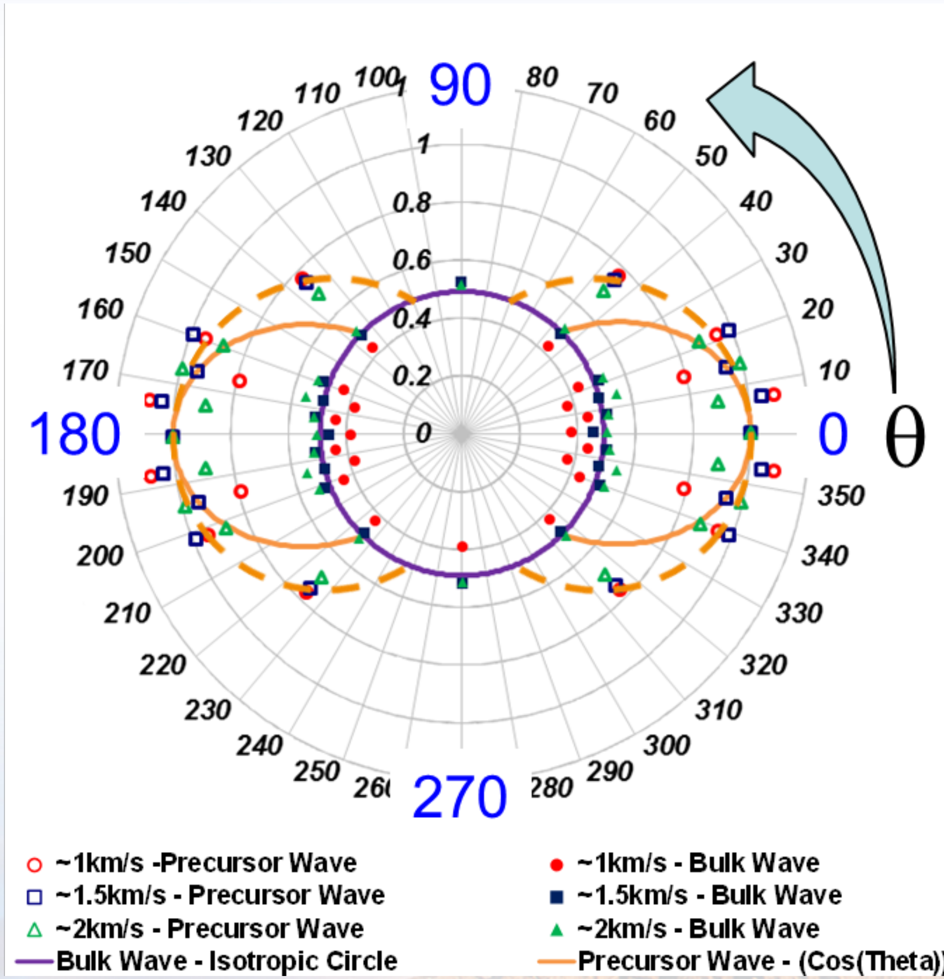
±45°



90°

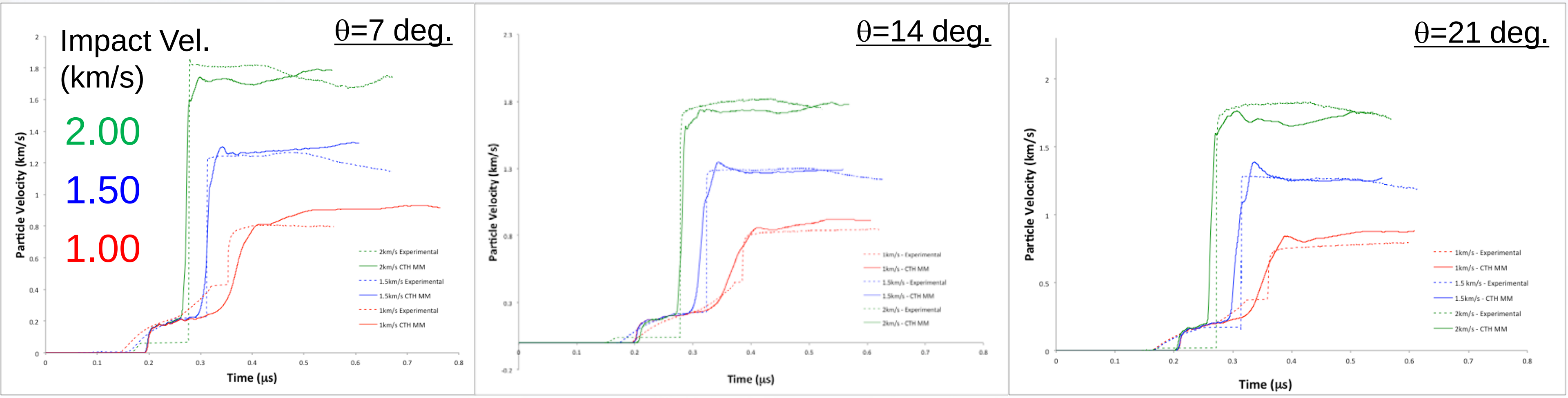
- Wave profiles show systematic trends
- Less pronounced precursor with increasing angle

Off-principle-axis testing verifies premise of predictions, suggests revision



- Solid curves represent isotropic (circle) response and predicted $\cos^2(\theta)$ response for precursor
- Isotropic bulk wave was observed
- Results suggest revised (dashed) precursor velocity curve matching bulk velocity at around 70°

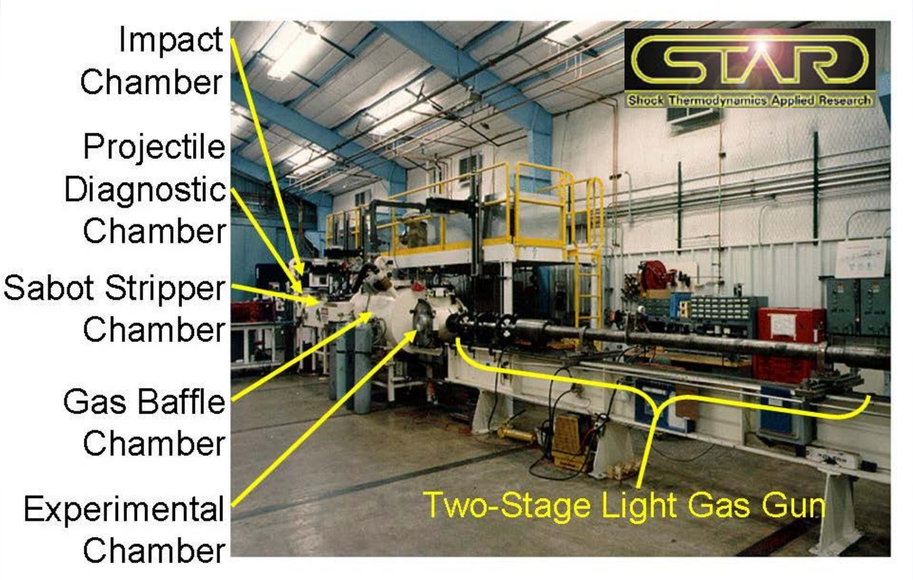
Model predictions (explicit) agree well with off-axis test results



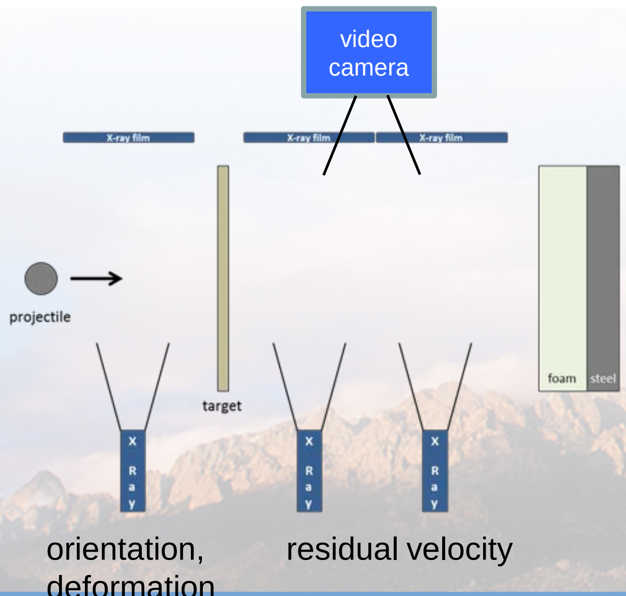
Solid: Simulation
Dashed: Experiment

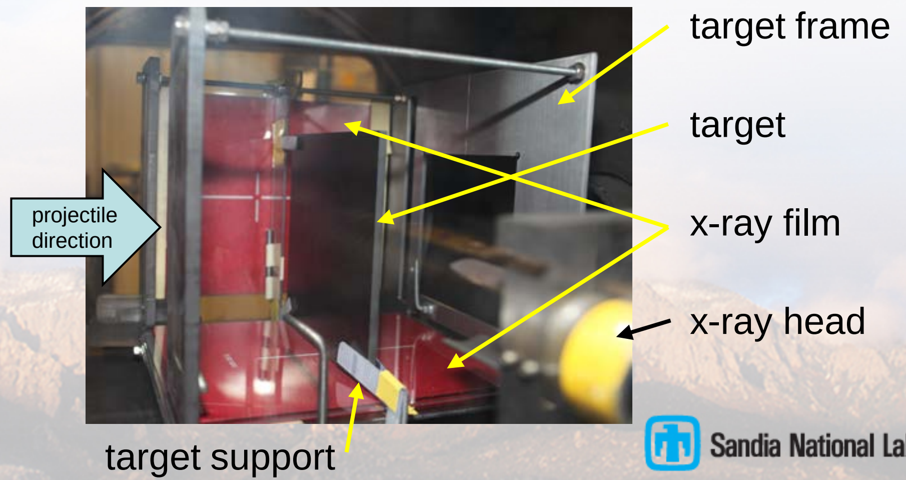
- Shock velocities agree within 10% (generally better)
- Particle velocities agree within ≤ 10% (generally better)
- Consistent with on-axis results, discrepancies exist in detailed wave structure of precursor

Testing was performed to support validation of advanced composite models

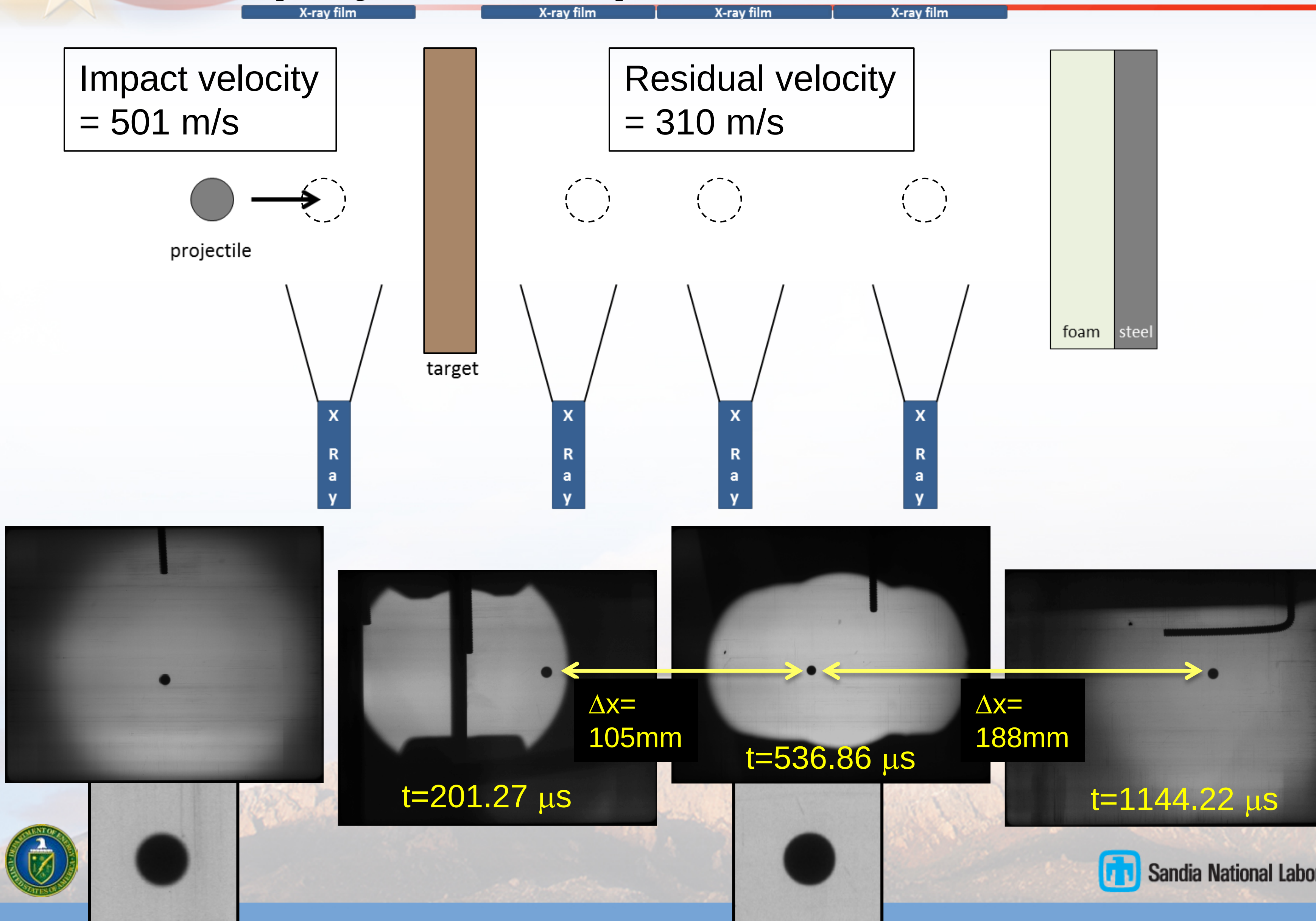


- Impact 0, 90, +45, -45 layup composite with standard projectiles
  - Hard (440C) steel ¼" sphere
  - Soft (1018) steel ¼" sphere
  - Sourced from Bal-tec
  - Previously characterized by Tom Mason
- Impact velocities similar to typical threats
  - 250, 500, 1000 m/s
- Vary composite thickness
  - 0.25, 0.50, 1.00 inch
- Measure impact and residual velocities
- Post shot damage characterization via ultrasound and/or x-ray CT

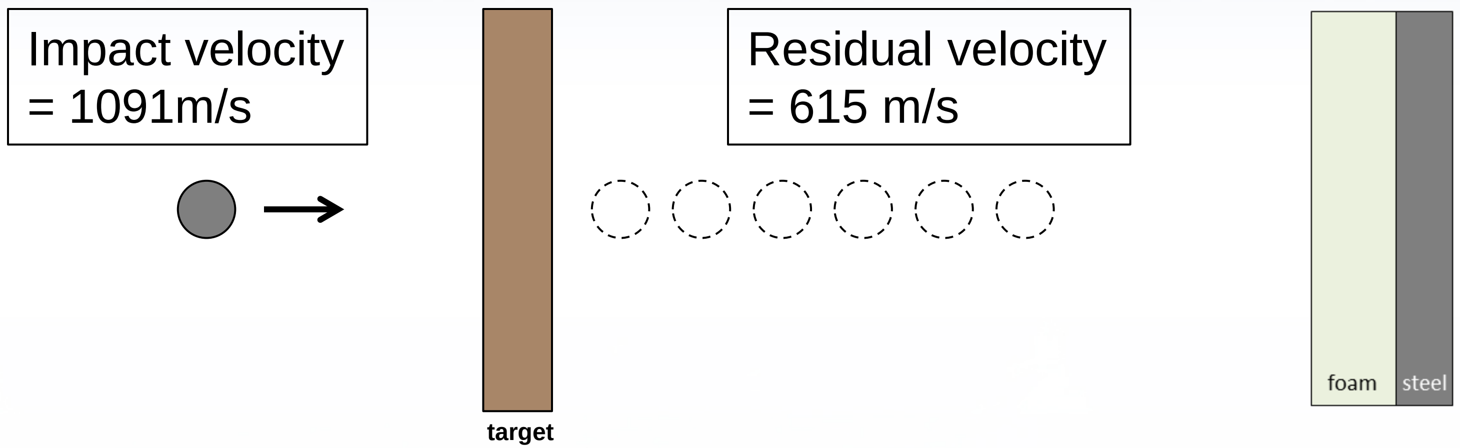


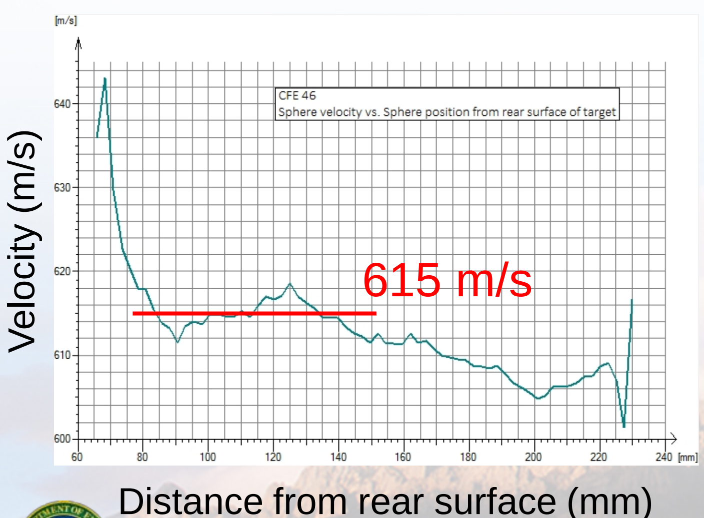


X-ray images provide residual velocity and projectile shape information



High speed video used in place of x-ray diagnostics on some shots





Test matrix includes range of impact conditions resulting in varying damage

Target Thickness (in)	Impactor	Impact Velocity (m/s)	Residual Velocity (m/s)	Diagnostics
¼	soft	282	0	x-ray
¼	soft	320	0	x-ray
¼	soft	501	310	x-ray
¼	hard	263	0	x-ray
¼	hard	309	0	x-ray
¼	hard	503	unknown*	x-ray
½	soft	507	0	x-ray
½	soft	517	0	x-ray
½	soft	1073	562	video
½	hard	502	0	x-ray
½	hard	520	0	x-ray
½	hard	1091	615	video
1	soft	1073	0	video
1	hard	1072	0	video

* Trigger failure on x-ray diagnostic system

Penetration?

velocity / thick	300 m/s	500 m/s	1000 m/s
¼”	no	yes	
½”		no	yes
1”			no

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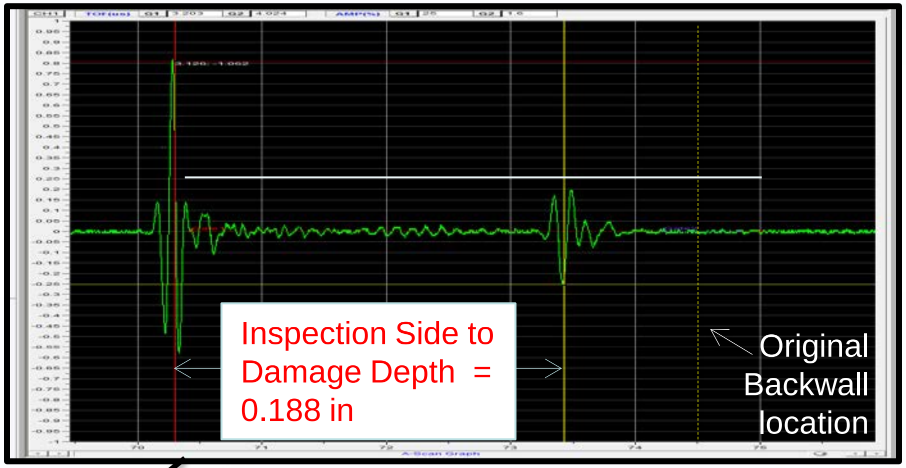
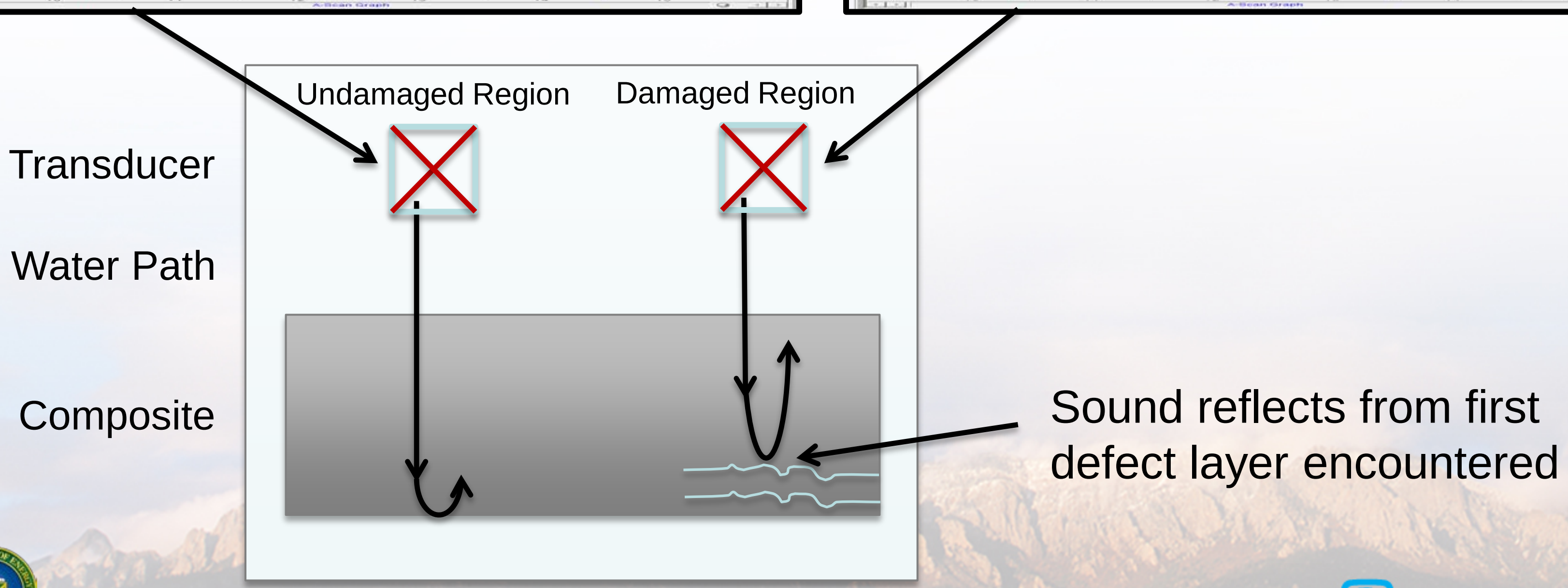
Ultrasound utilizes sound waves to characterize internal damage

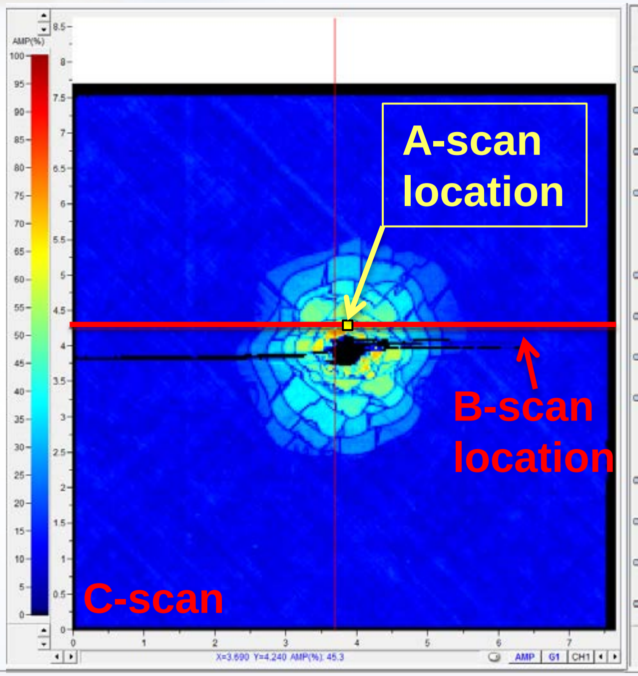
Undamaged ¼" Panel A-Scan Signal

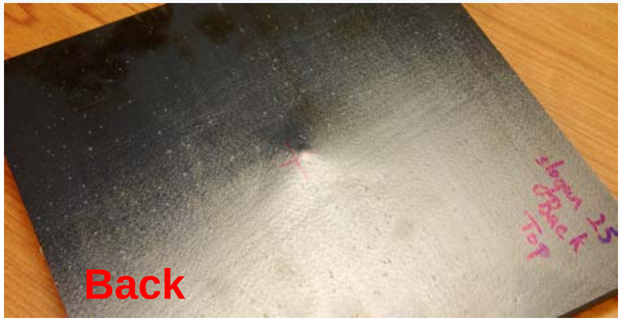
Damaged ¼" Panel A-Scan Signal

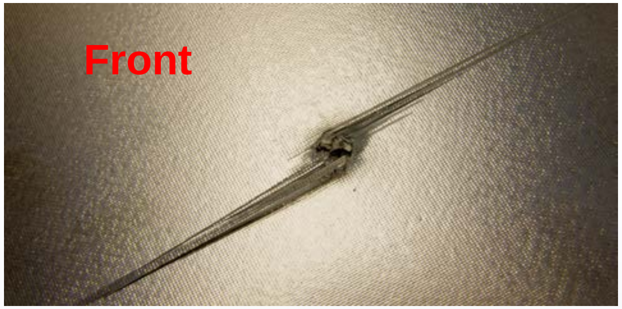


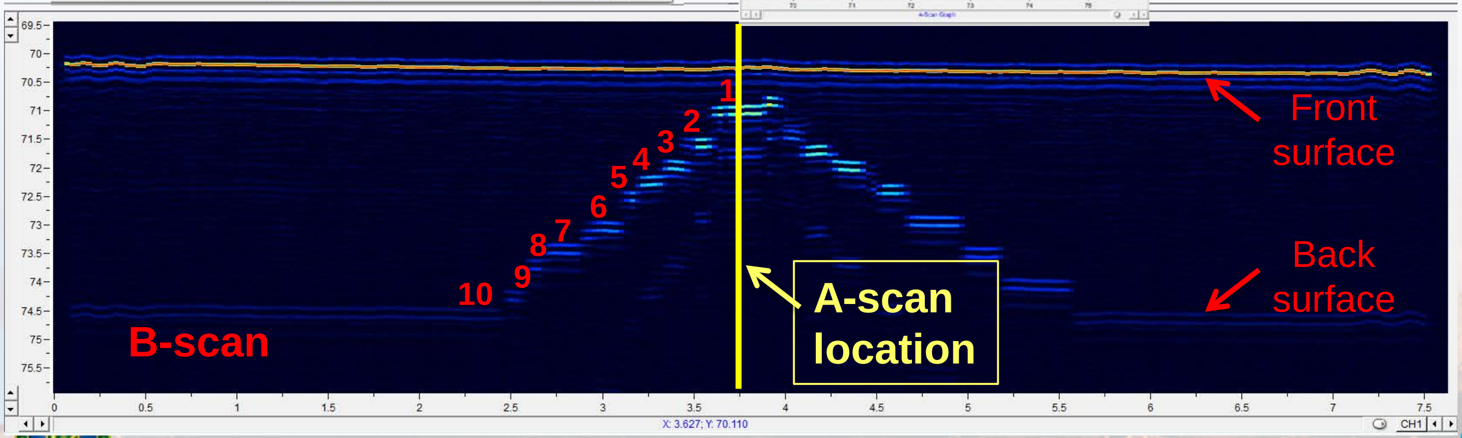


Ultrasound data used to determine depth of leading edge damage in target





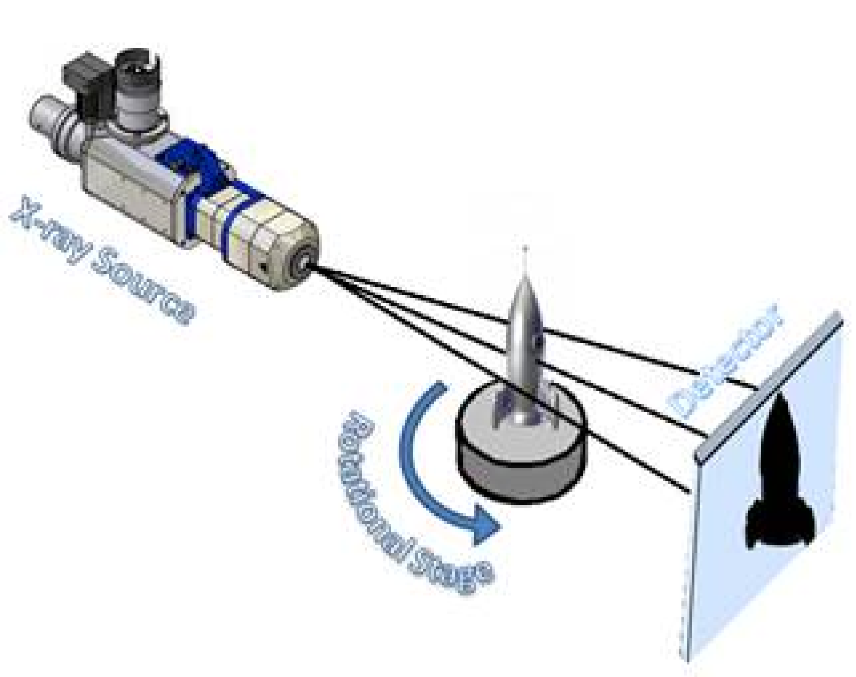




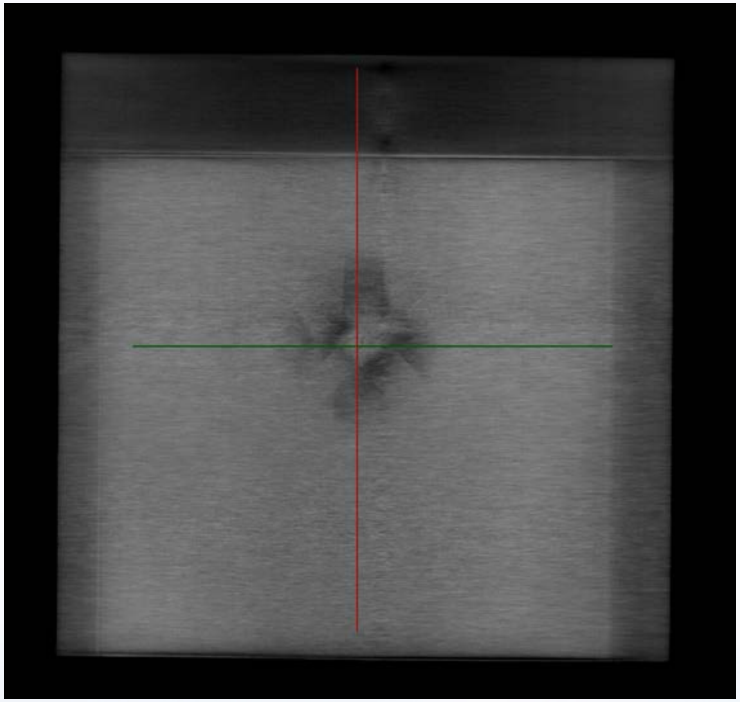
Point	Depth into Part (in)
1	0.049
2	0.079
3	0.101
4	0.118
5	0.132
6	0.163
7	0.188
8	0.204
9	0.236
10	0.255

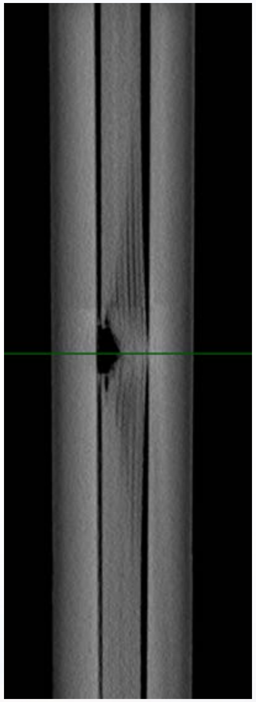
X-ray computed tomography (CT) provides 3D view of damage patterns

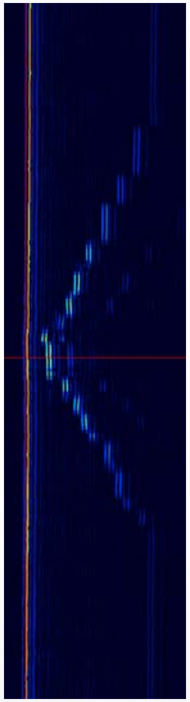
- Penetrating radiation (X-Ray) attenuated by composite material
- Digital sampling of the radiation
- Multiple images taken at different angles while spinning 360 degrees.
- Images mapped into a three dimensional data set
- Data shown as single “slice” or rendered

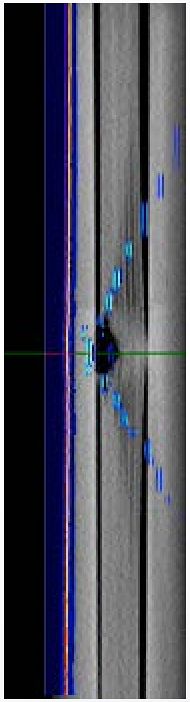


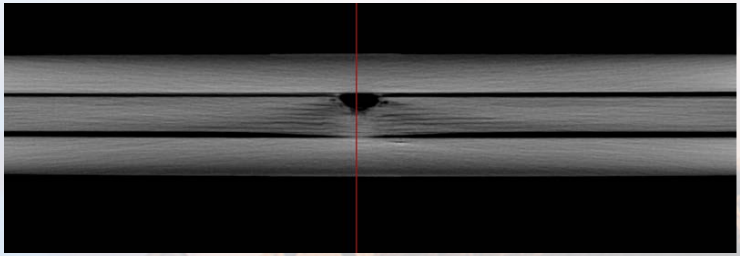
Combination of x-ray CT and ultrasound data will be compared to simulated damage











- Non-penetrating shot showing characteristic damage pattern
- ¼” panel, 309 m/s impact, hard sphere

Summary of results

- **Dynamic response of composite is anisotropic**
  - highlights need for advanced models
- **Compression across fibers shows:**
  - no elastic precursor
  - bulk response similar to pressed carbon
- **Compression along fibers shows:**
  - an elastic precursor traveling along fibers
  - a bulk response similar to the epoxy binder
- **Explicit numeric simulations confirm experimental observations and offer new insight**
  - transverse simulations in excellent agreement with data
  - longitudinal simulations match all but fine detail in precursor wave
- **Off-axis response consistent with predictions**
  - require minor alterations to form of $f(\theta)$
  - simulations in good agreement with data
- **Testing has been performed to provide a basis for advanced model validation**
  - Impact and residual velocities known
  - Damage characterized with x-ray CT and ultrasound