SAND2011-0150P

DuPont, Richmond, VA, 1/18/2011

Transverse Impact Response of DuPont Kevlar® KM2 Fiber Yarn

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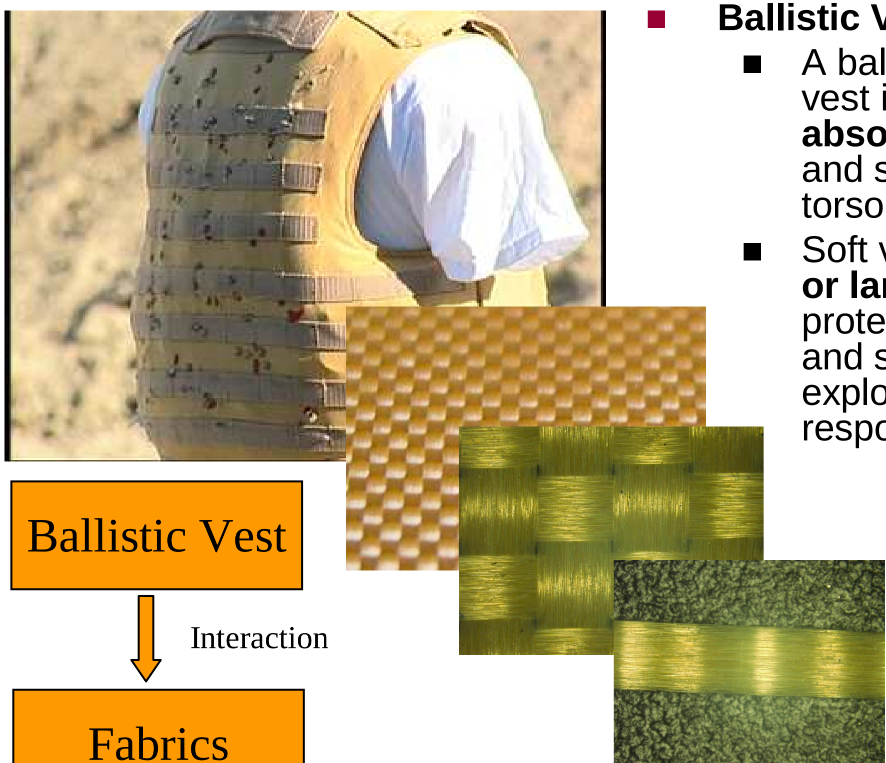
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND -2005-6648P

Soft Body Armor



- **Ballistic Vest**
  - A ballistic vest, bulletproof vest or bullet-resistant vest is an item of personal armor that helps **absorb the impact** from firearm-fired projectiles and shrapnel from explosions, and is worn on the torso (*www.wikipedia.org*).
  - Soft vests are made from many layers of **woven or laminated fibers** and can be capable of protecting the wearer from small-caliber handgun and shotgun projectiles, and small fragments from explosives such as hand grenades. Impact response of ballistic fabrics (*www.wikipedia.org*)

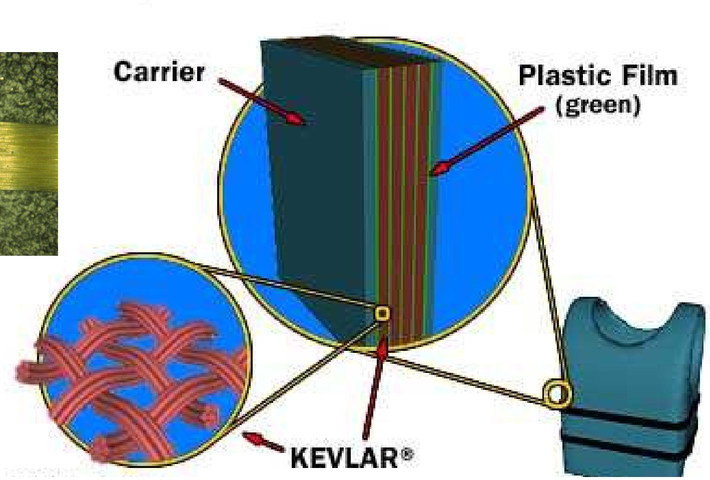
Ballistic Vest

↓ Interaction

Fabrics

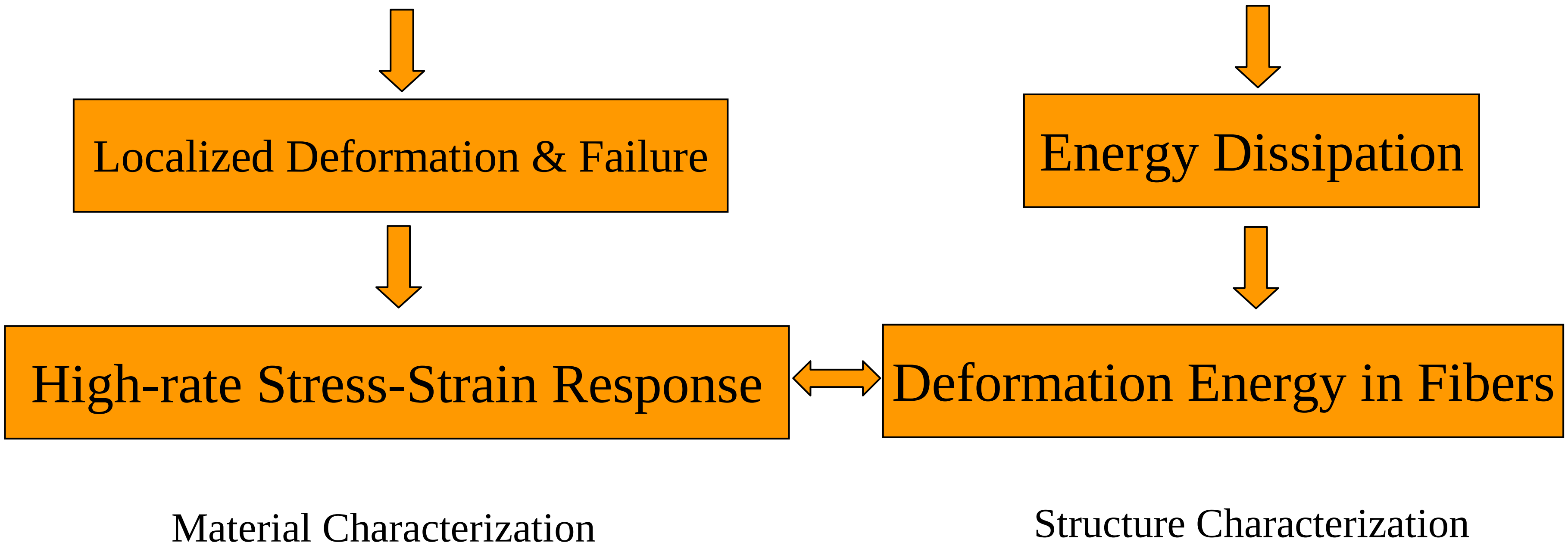
↓ Interaction

Fiber Yarns → Interaction → Single Fibers



Ballistic Performance

- Bullet/projectile should be stopped before the soft body armor is penetrated;
- The maximum displacement of the back surface of the soft body armor should not exceed 44 mm (NIJ Standard)

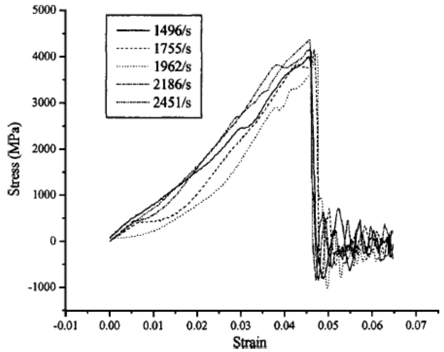


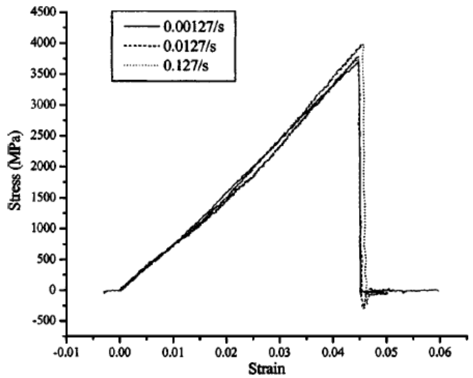
Tensile Stress-Strain Response of Fibers

- Experimental Techniques
  - Quasi-static Testing: Commercial Load Frames (MTS, Instron, etc)
    - ASTM Standards
  - Dynamic Testing: Kolsky Tension Bar (or Split Hopkinson Tension Bar)
    - No Standard Available

- Challenges in Dynamic Experiments
  - Stress wave propagation/Inertia effect
    - Non-uniform stress and strain along the fiber gage length
    - Size effect
  - More challenging in dynamic testing of single fibers
    - Specimen gripping
    - Small force measurement
    - Non-uniformity in stress and strain

- Inaccurate Strain Measurement
  - Failure strain ?
  - Modulus of Elasticity ?
  - Stress-strain curve ?
  - Strain-rate effect ?

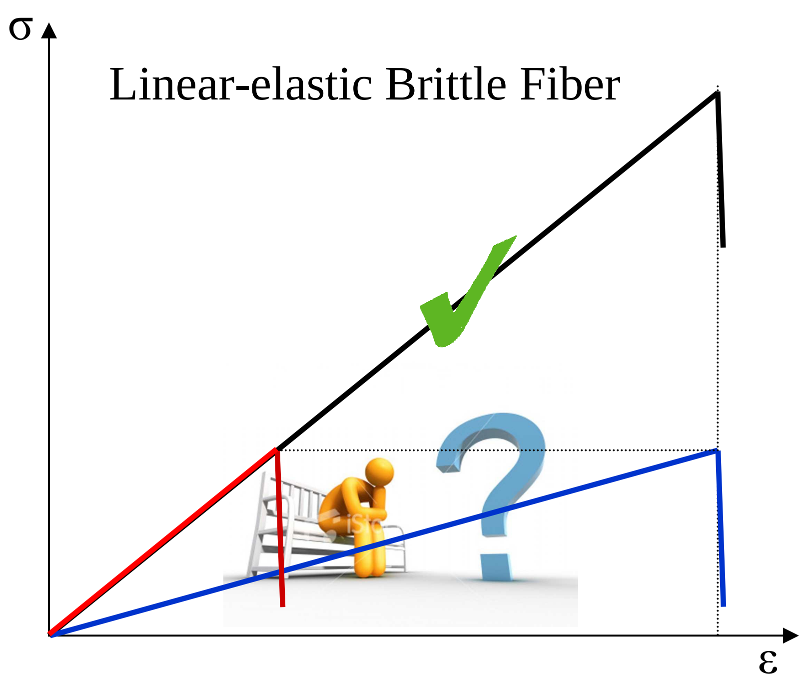




(Cheng et al. 2005)

Mechanical Properties & Ballistic Performance

- **Higher Failure Strength**
- **Higher Modulus of Elasticity**
- **Larger Failure Strain**



Theoretical Ballistic Performance of Common Fibers *(Kim et al. 2008)*

Fiber	Density (Calc.) (ρ) (g/cm^3)	Strength (σ) (GPa)	Failure strain (ε) (%)	Modulus (E) (GPa)	$(U^*)^{1/3}$ (m/s)
PBO (as spun)	(1.56)	5.20	3.10	169	813
Spectra 1000	(0.97)	2.57	3.50	120	801
600 den. Kevlar KM2	(1.44)	3.40	3.55	82.6	682
850 den. Kevlar KM2	(1.44)	3.34	3.80	73.7	681
840 den. Kevlar 129	(1.44)	3.24	3.25	99.1	672
1,500 den. Kevlar 29	(1.44)	2.90	3.38	74.4	625
200 den. Kevlar 29	(1.44)	2.97	2.95	91.1	624
1,000 den. Kevlar 29	(1.44)	2.87	3.25	78.8	621
1,140 den. Kevlar 49	(1.41)	3.04	2.30	120	612
Carbon fiber	(1.80)	3.80	1.76	227	593
E-glass fiber	(2.89)	3500	4.70	74	559
M5 (2001 sample)	(1.74)	3.96	1.40	271	583
M5 Conservative	(1.70)	8.50	2.50	300	940
M5 Goal	(1.70)	9.50	2.50	450	1043

It is difficult to directly correlate the tensile properties of the fibers to their ballistic performance.

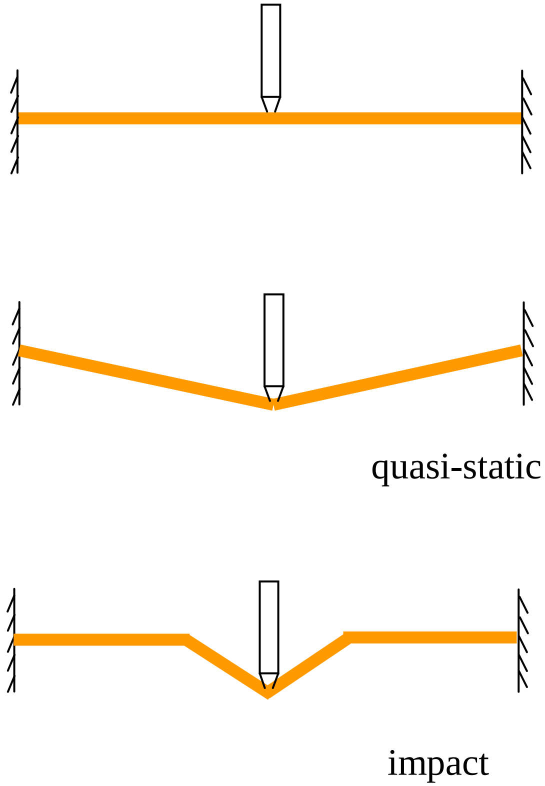
What properties are critical to the ballistic performance?

Fundamental research that has direct relation to ballistic performance is desired.

Transverse Impact Response of Fiber Yarns

Characteristics

- High Rate
- Wave Propagation
  - Longitudinal Wave
    - Tension in the fiber yarn
  - Transverse Wave
    - Shape change of the fiber yarn



Faster Transverse Wave Speed

↓

More Fibers Involved

↓

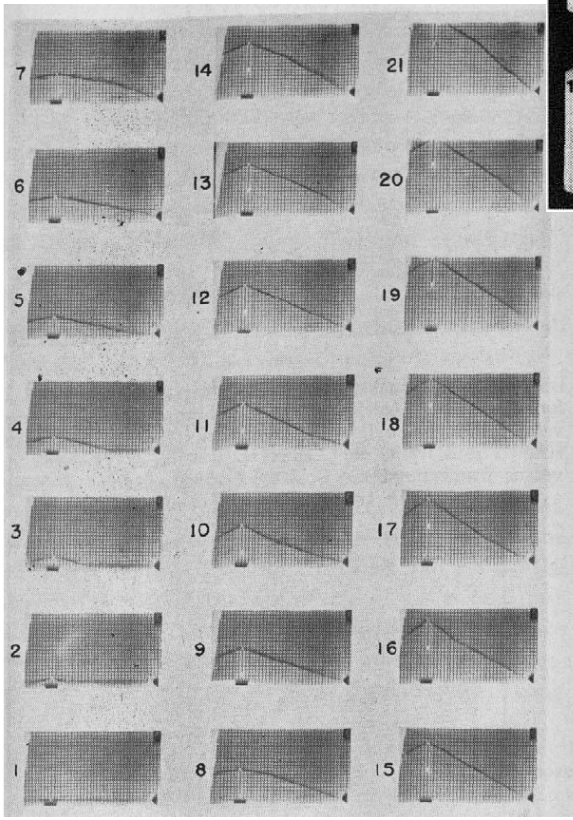
More Impact Energy Dissipated
&
Less Strain Localization

→

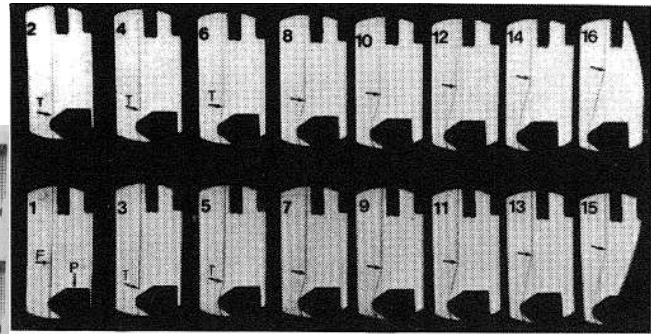
Better Ballistic Performance

Early Research: Transverse Impact Response of Fiber Yarns

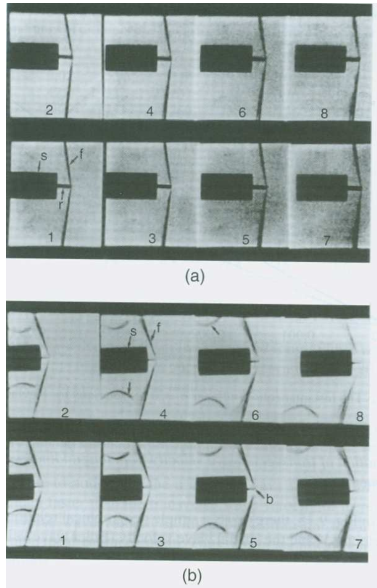
- Research started from 1950s
  - J. D. Cole et al.; 1953
    - Analysis, modeling
  - J. C. Smith et al.; 1950s-1960s
    - Analysis, modeling, experiments
- Diagnostic techniques
  - High-speed Photography
    - Speed
    - Resolution



Smith et al. (1956) 6984 FPS



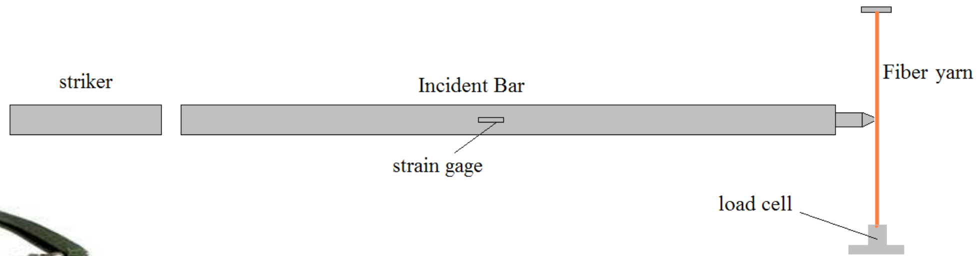
J. E. Field and Q. Sun (1990) 50000 FPS



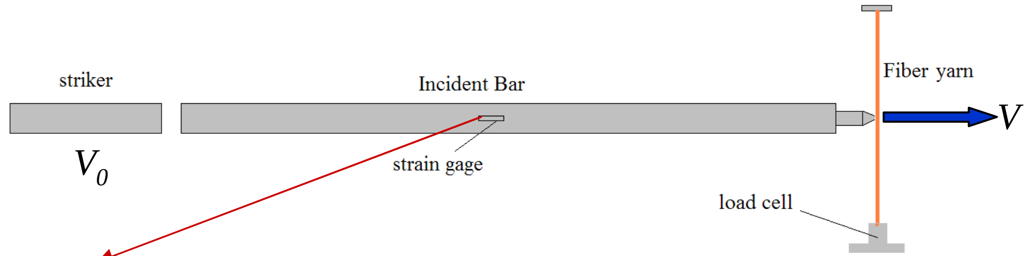
L. Wang et al. (1992)

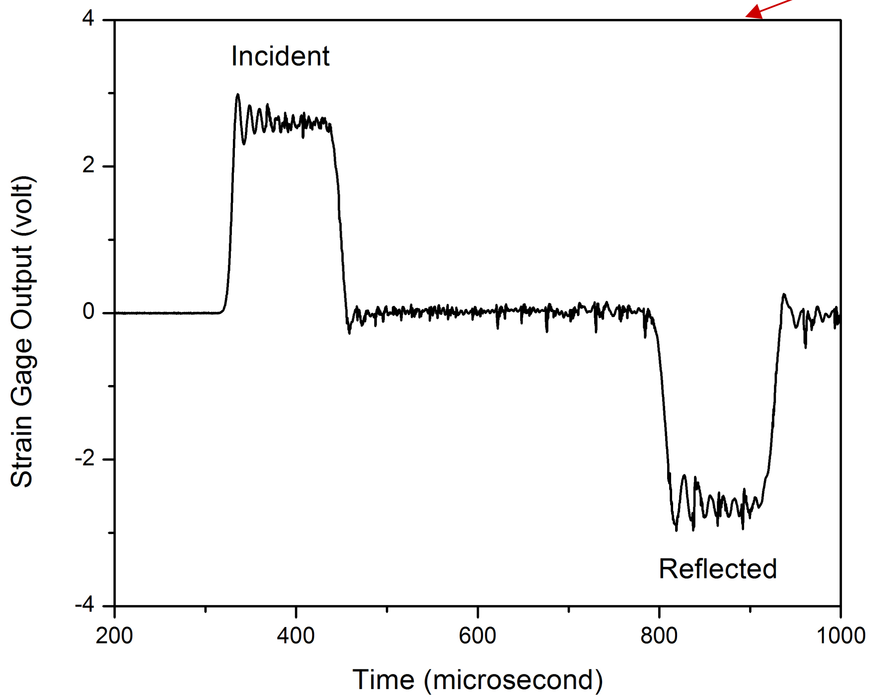
Transverse Impact Techniques of Fiber Yarns

- **Split Hopkinson Pressure Bar (SHPB)/Kolsky Bar**
  - **¾" diameter aluminum bar**
  - **High-speed digital cameras**
    - **Cordin 550**
    - **Phantom V12.1**



Kolsky Bar for Transverse Impact Testing





Impact Speed V

$$V = C_0(\varepsilon_i(t) - \varepsilon_r(t)) = 2C_0\varepsilon_i(t) = V_0$$

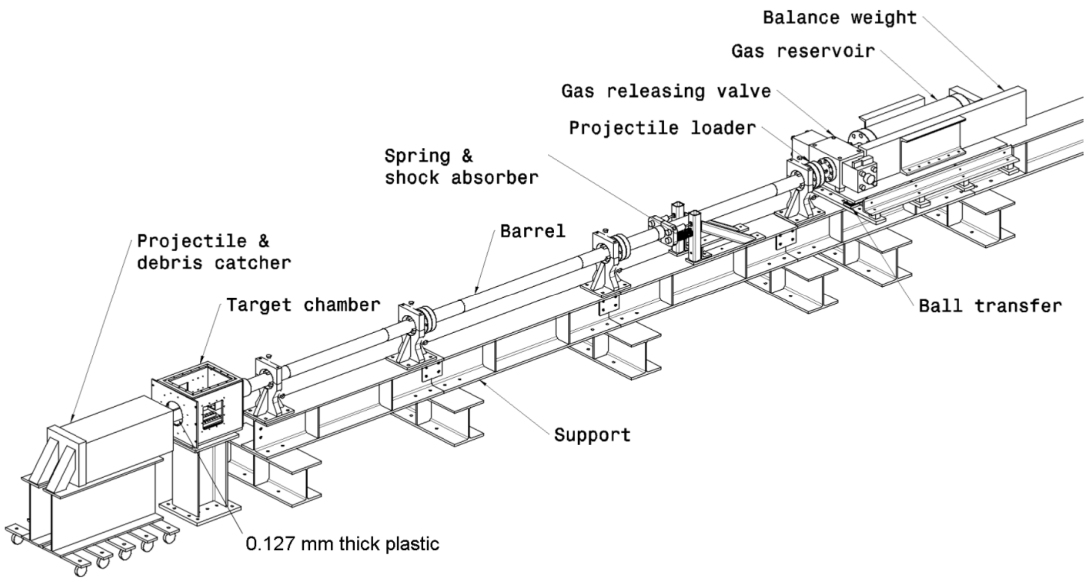
C_0: elastic wave speed in the bar material

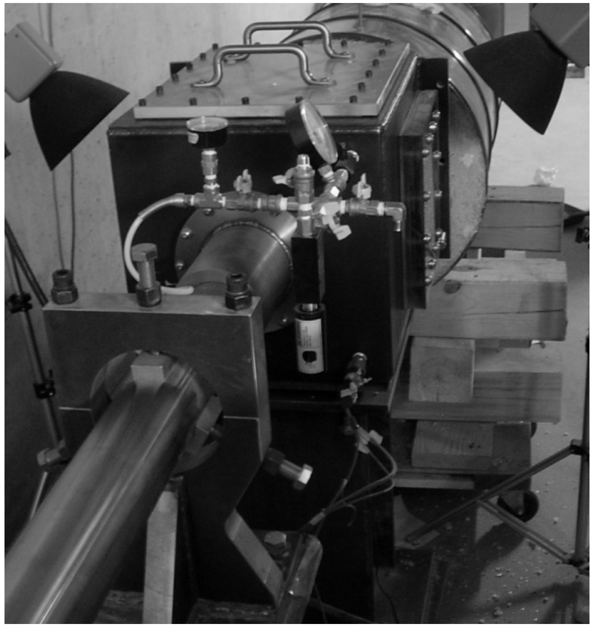
V_0: striker velocity

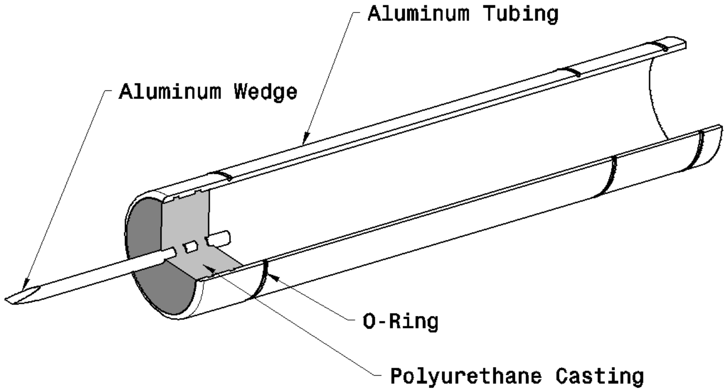
For Aluminum 7075-T651:

$$V_0 < 70 \text{ m/s}$$

Gas Gun for Transverse Impact Testing at Purdue University

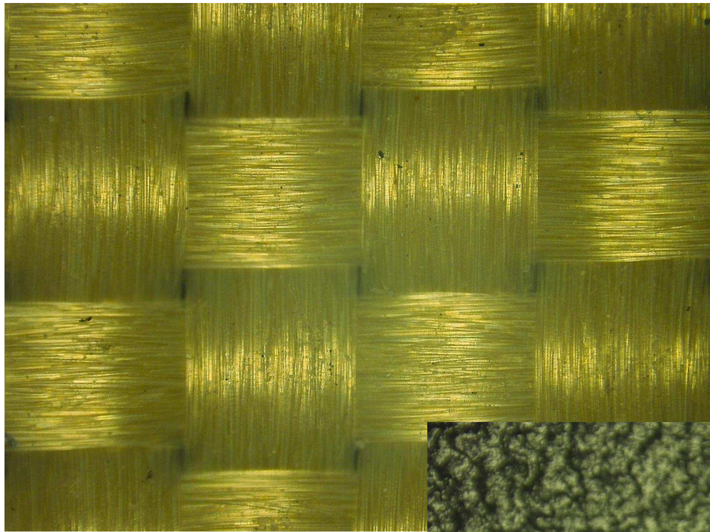


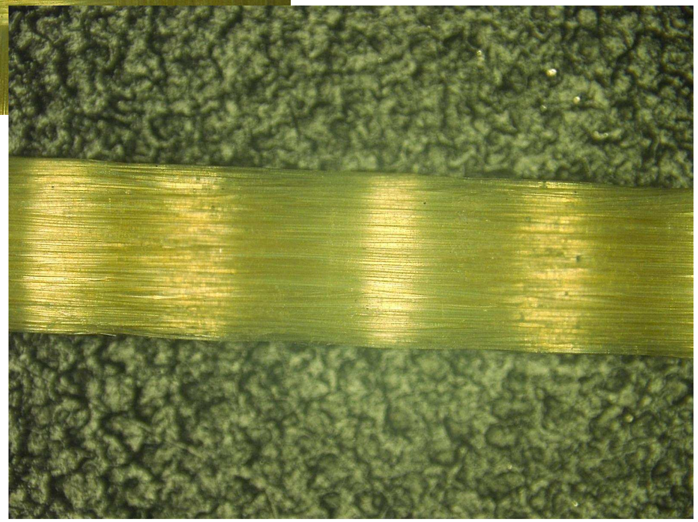




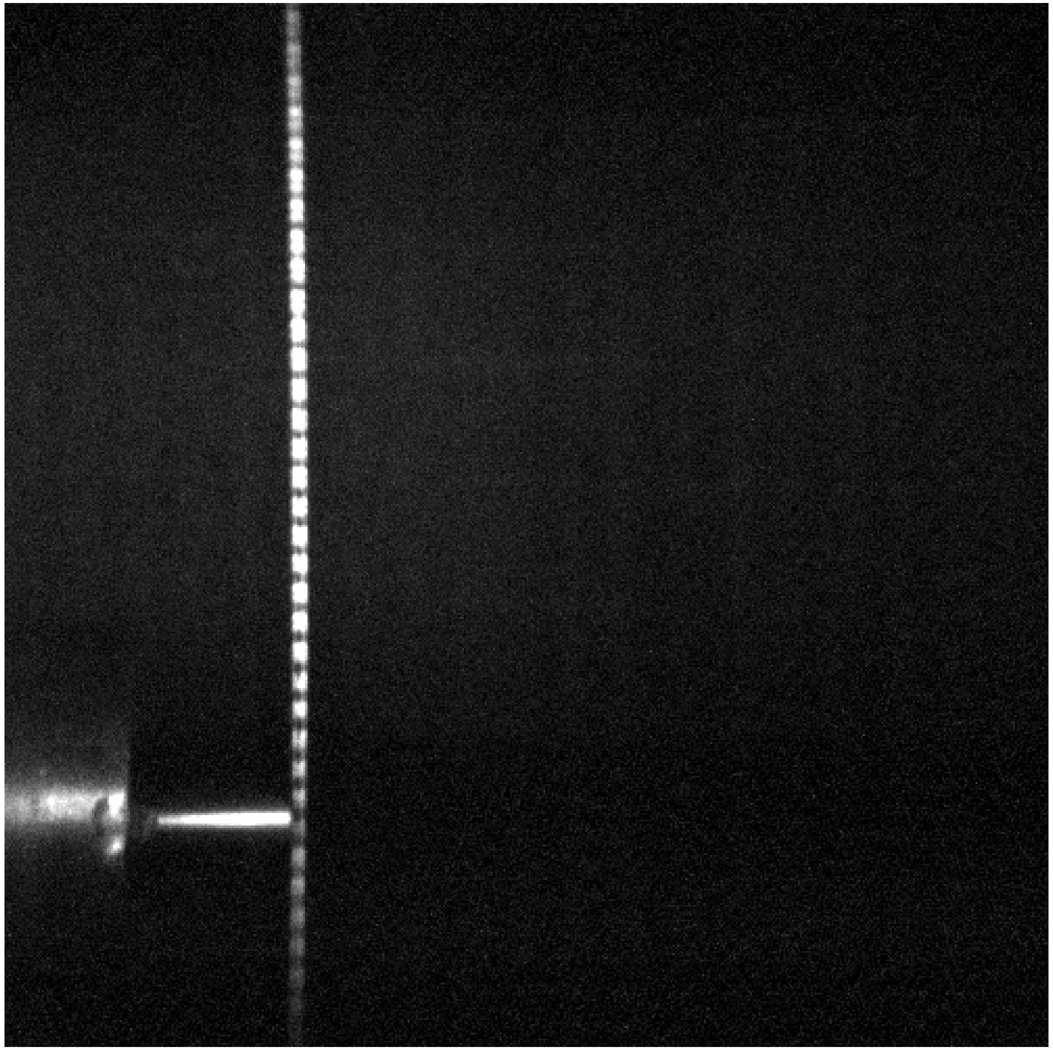
Transverse Impact Response of Kevlar® KM2 Fiber Yarn Taken from a Fabric

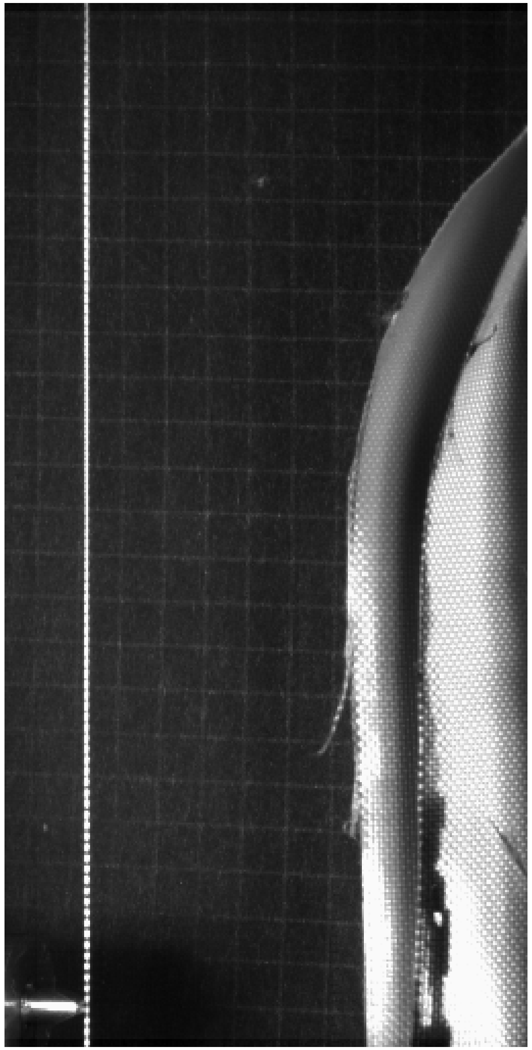
- **400 den. Kevlar® KM2**
  - **Taken from a plain woven fabric**
  - **10-15'' long aligned fiber yarn**
- **Impact Speed**
  - **8 – 53 m/s (Hopkinson bar)**
  - **150-320 m/s (Gas gun)**
- **Pre-loading Condition**
  - **Pre-tension: <0.5 N**





Kolsky Bar Testing of Kevlar® KM2 Fiber Yarn Taken from a Fabric

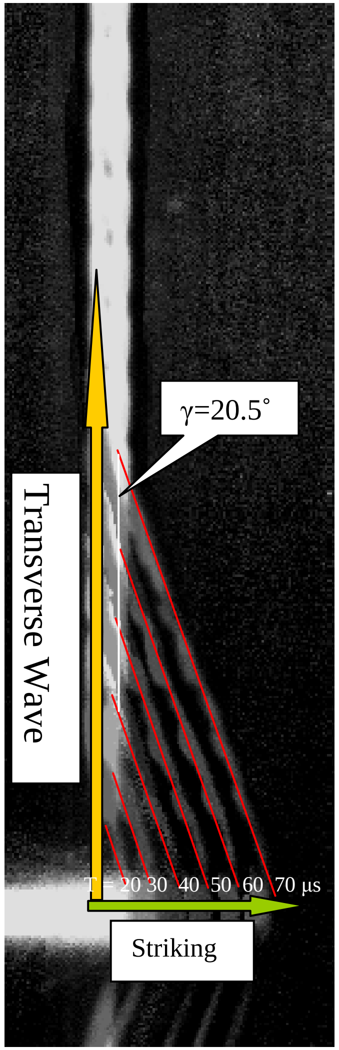


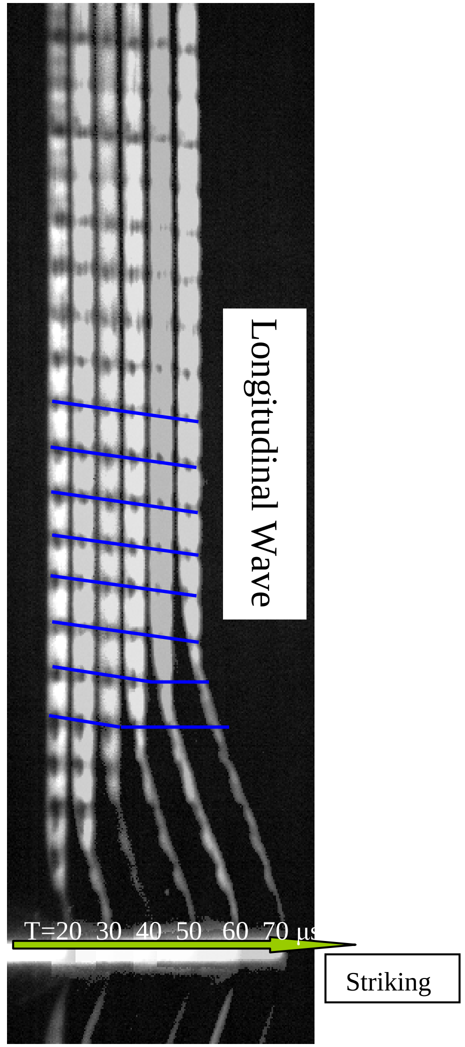


V=53 m/s

Wave Propagation in the Fiber Yarn

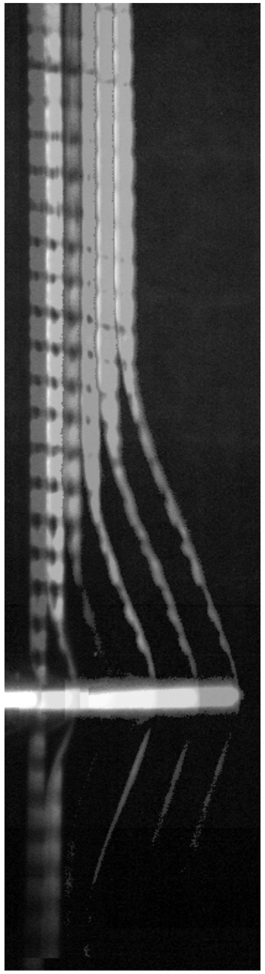
- **Transverse wave**
  - **Changes the shape of fiber yarn**
  - **Produces a kink with triangle shape**
  - **Produces a constant angle for a constant-speed impact**
- **Longitudinal Wave**
  - **Produces tension in the fiber yarn**
  - **Propagates much faster than transverse wave**

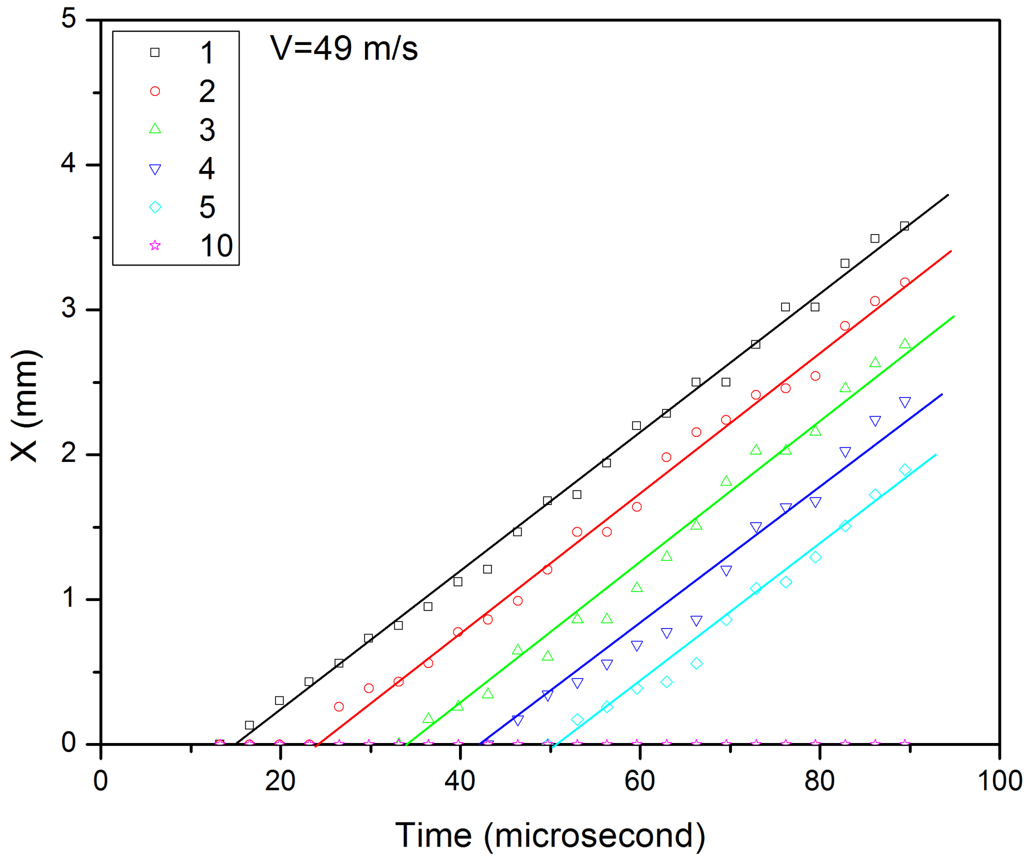




V=53 m/s

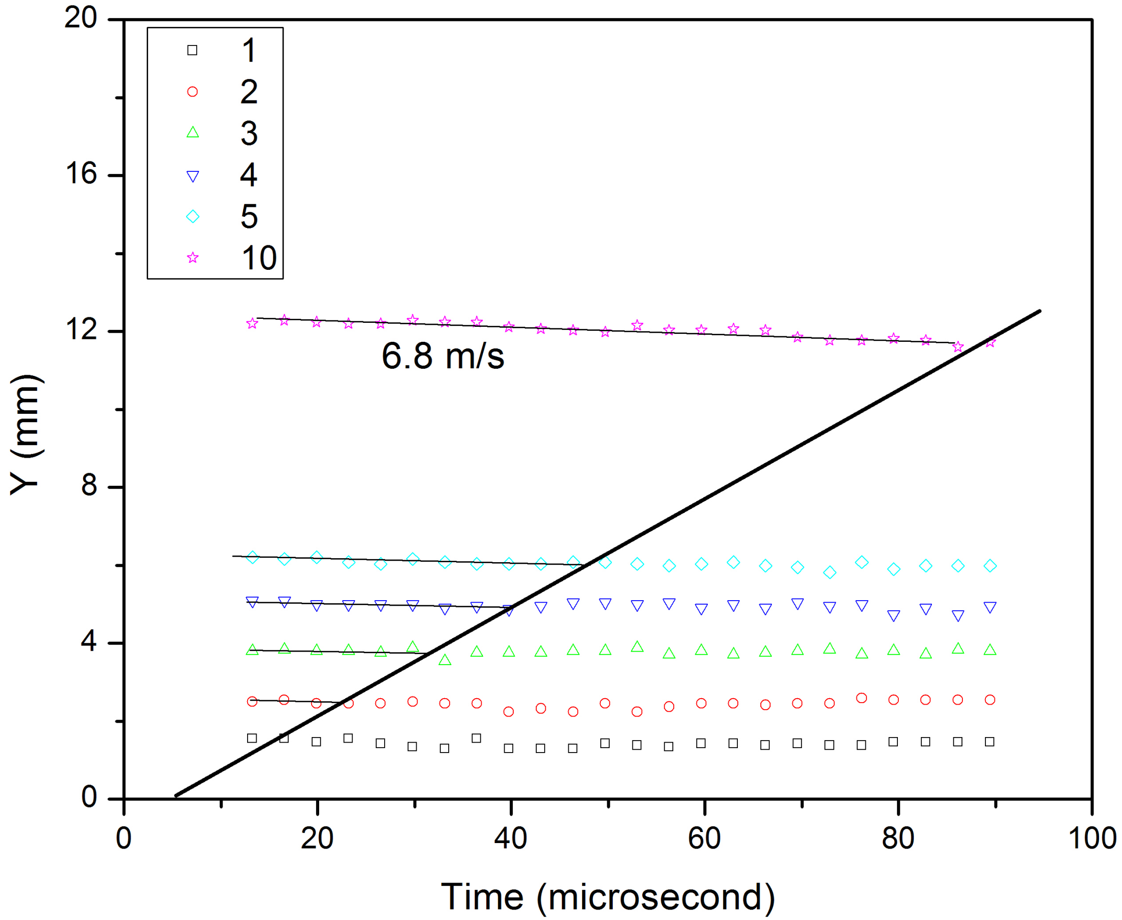
Displacement of Particles on the Fiber Yarn

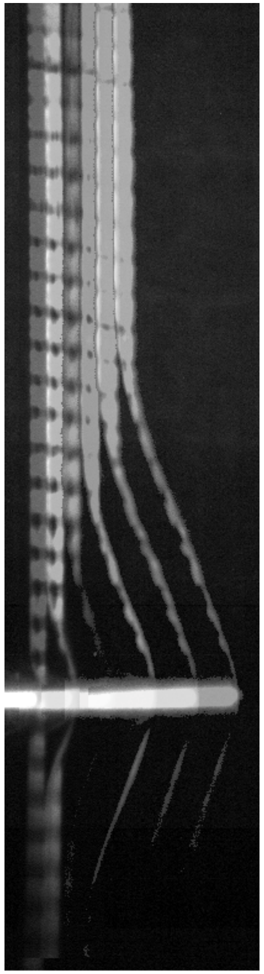




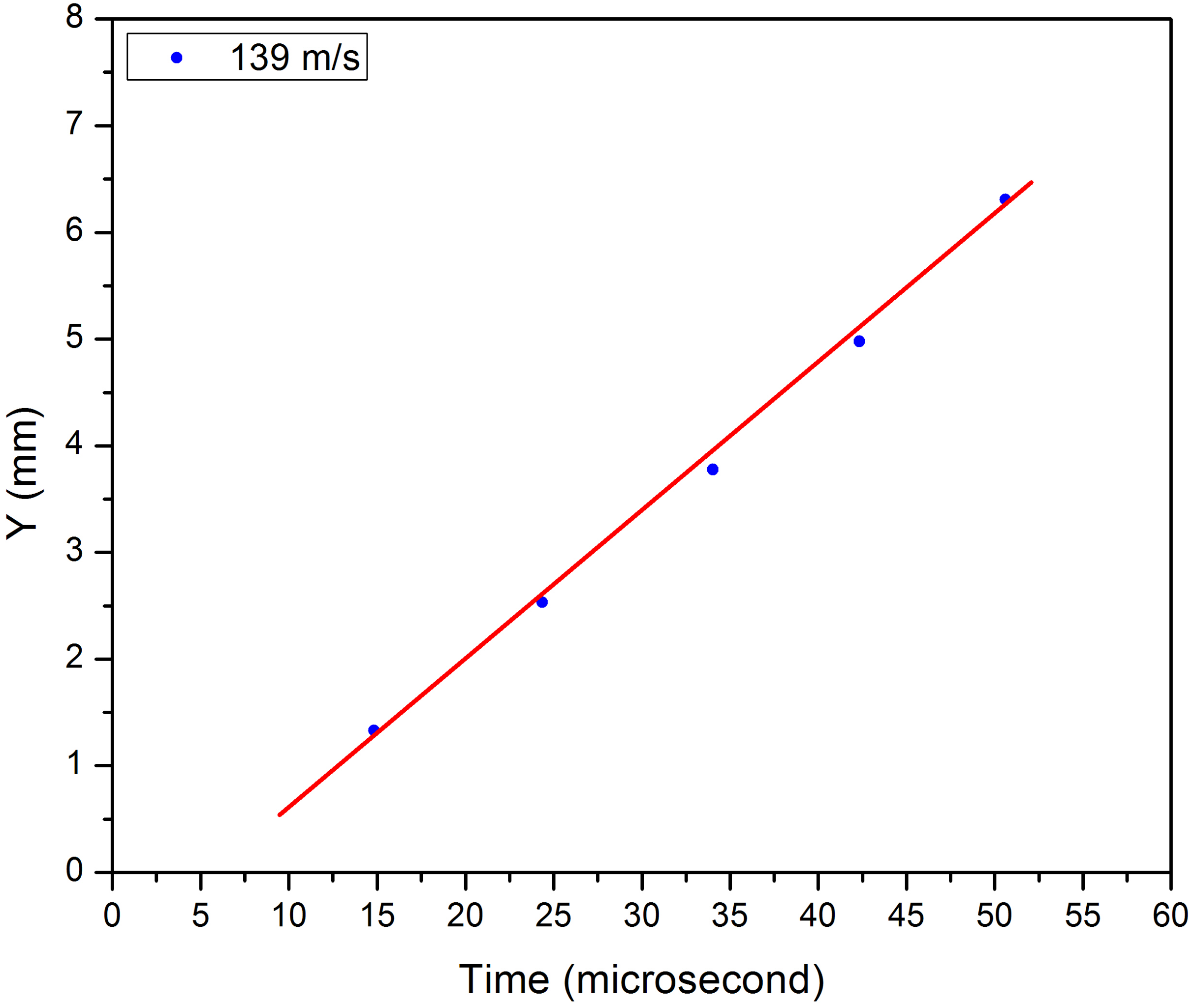
V=53 m/s

Particle Velocity in Y-Direction

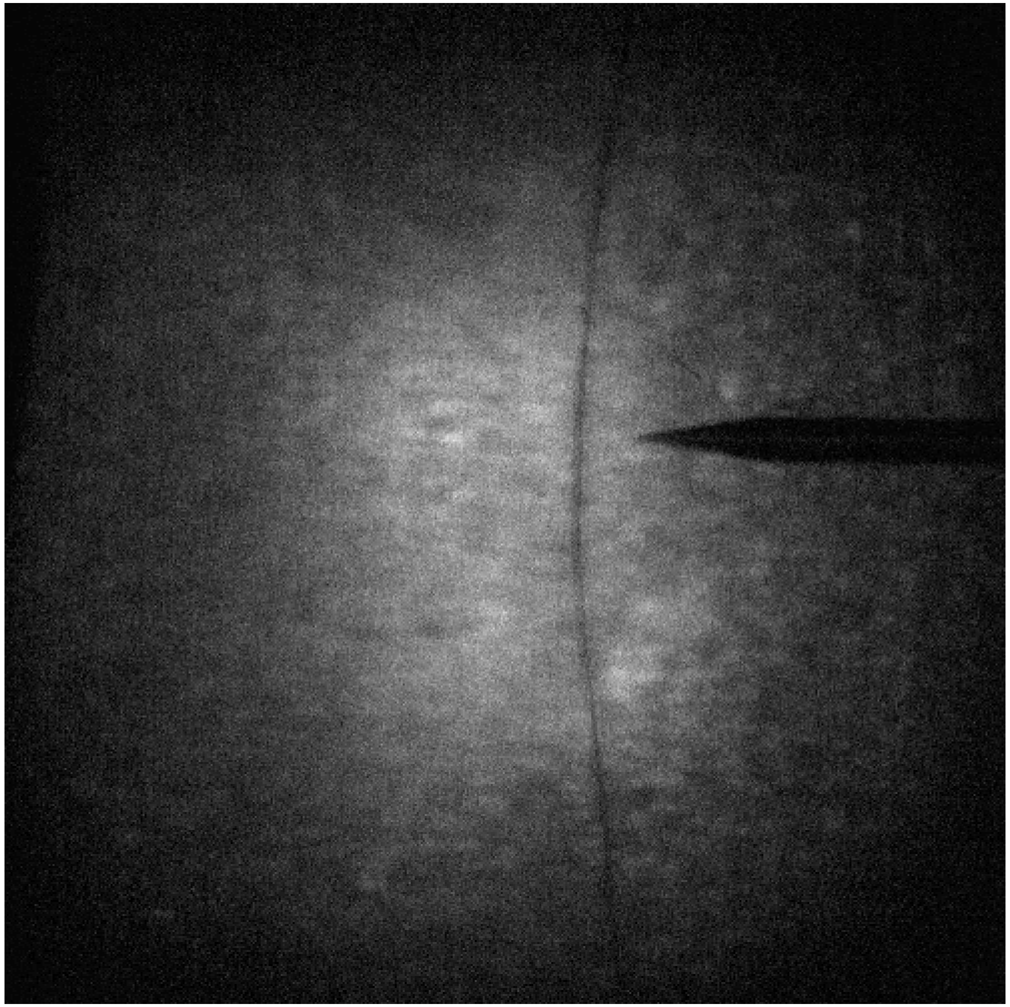




Euler Transverse Wave Speed

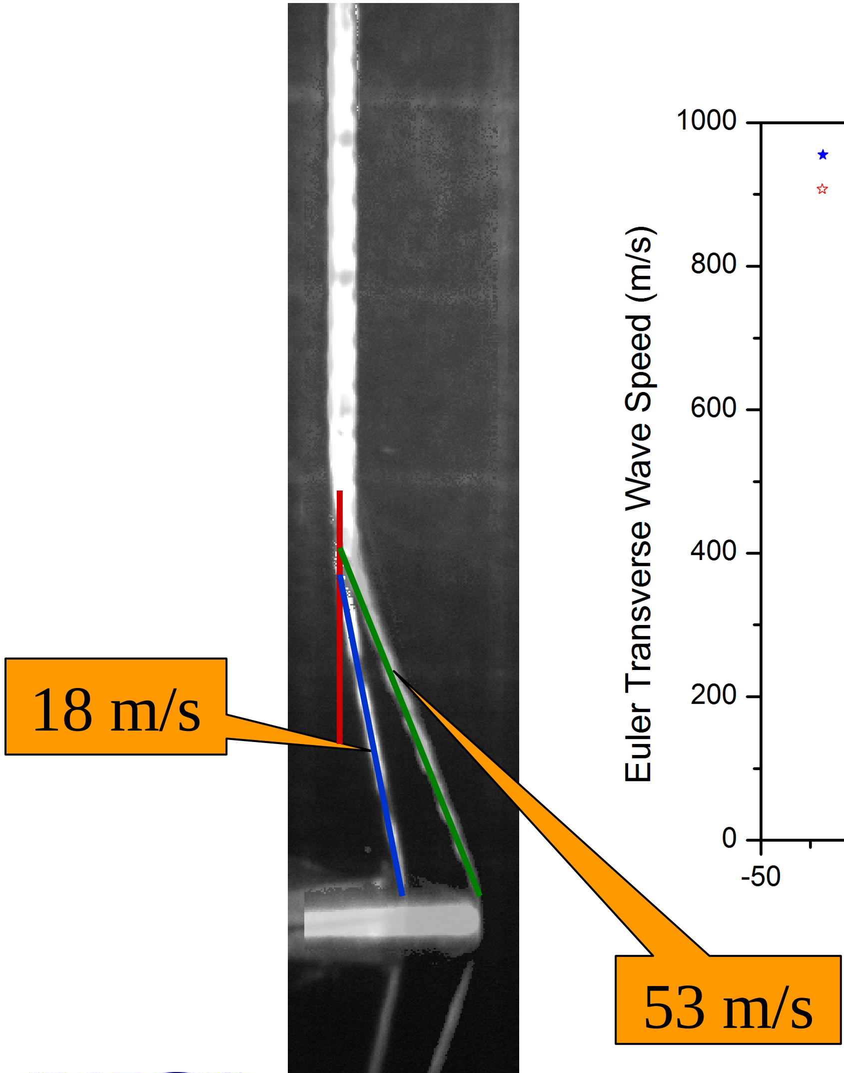


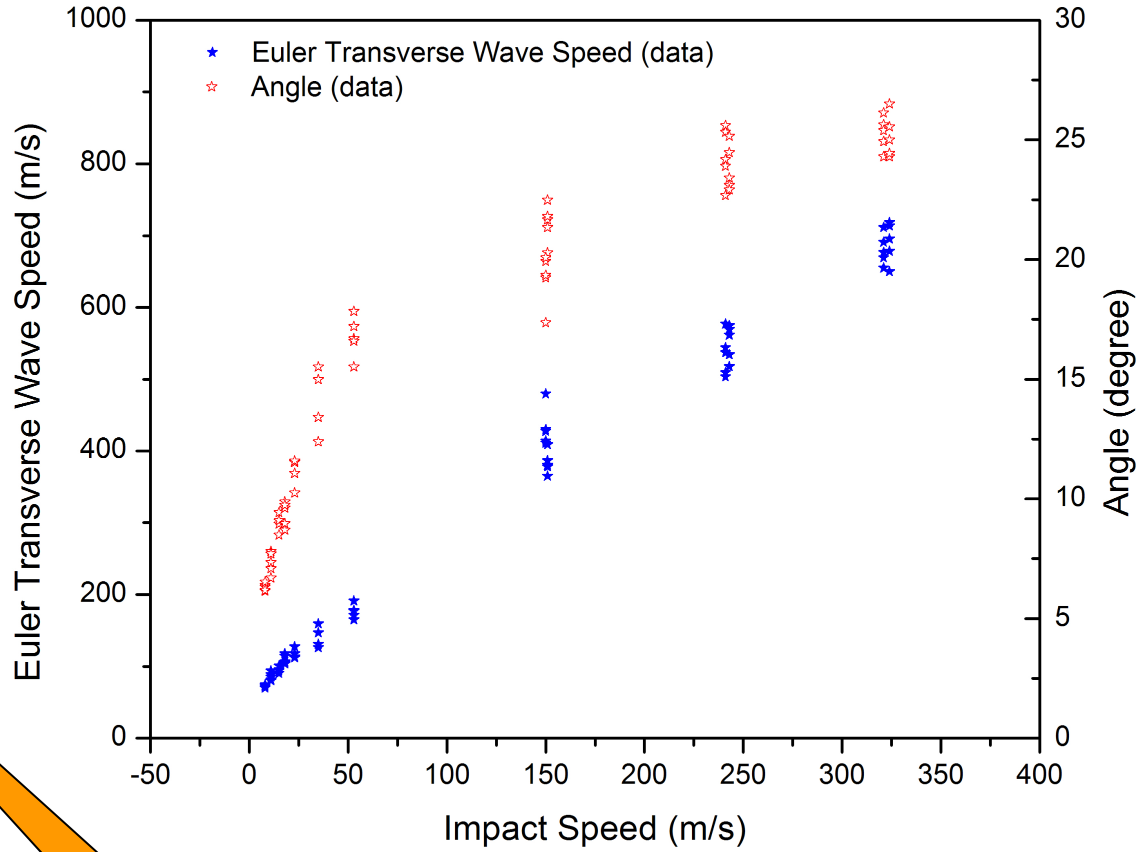
Gas Gun Testing of Kevlar® KM2 Fiber Yarn Taken from a Fabric



V=241 m/s

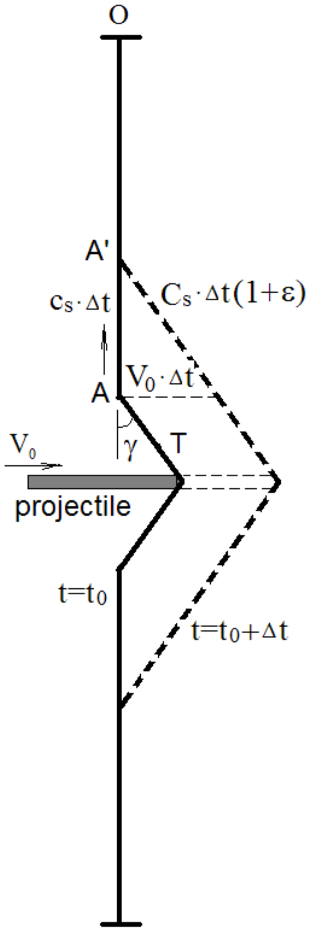
Kevlar® KM2 Fiber Yarn Taken from a Fabric: Effect of Impact Speed





Modeling of Transverse Impact Response of a Fiber Yarn

Assumption: fiber yarn is linear elastic & $T_0 = 0$

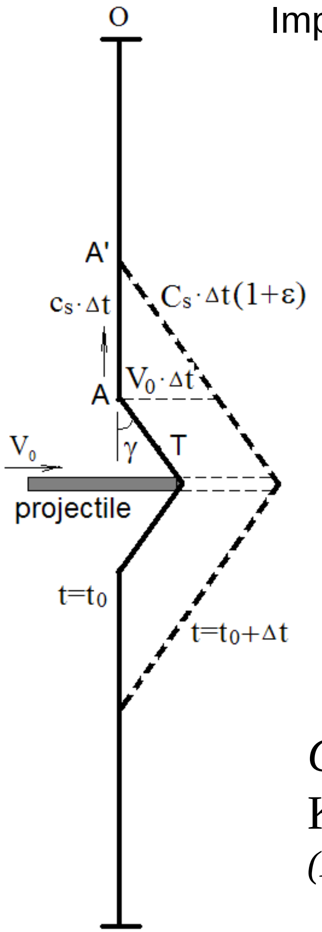


$$
\begin{cases}
c_s = \dfrac{V_0}{\tan\gamma} \\
T = \rho_0 C_l U \\
U = C_l \varepsilon \\
T \sin\gamma = \rho_0 C_s V_0 \\
c_s = C_s(1+\varepsilon) - U \\
V_0 = C_s(1+\varepsilon)\sin\gamma
\end{cases}
$$

- ✓ ρ_0 Line density of fiber yarn
- ? T Tensile load
- ? ε Yarn strain
- ✓ C_l Lagrangian longitudinal wave speed
- ? c_s Euler transverse wave speed
- ? C_s Lagrangian transverse wave speed
- ? U Particle velocity
- ✓ V_0 Striking speed
- ? γ Angle

$$
C_l = \sqrt{\frac{E}{\rho_0}} = \sqrt{\frac{1}{\rho_0}\frac{d\sigma}{d\varepsilon}}
$$

Analytical Solutions



Implicit solution for c_s

$$V_0 = \frac{c_s}{C_l - 2c_s}\sqrt{c_s\left(2C_l - 3c_s\right)}$$

$$\varepsilon = \frac{1}{2}\left(\sqrt{1+4\frac{{c_s}^2}{{C_l}^2}\cdot\frac{(C_l - c_s)^2}{(C_l - 2c_s)^2}} - 1\right)$$

In the case of

$$c_s << C_l$$

$$c_s = \left(\frac{C_l}{2}\right)^{1/3} \cdot V_0^{2/3}$$

Consistent with Cole et al. (1953)

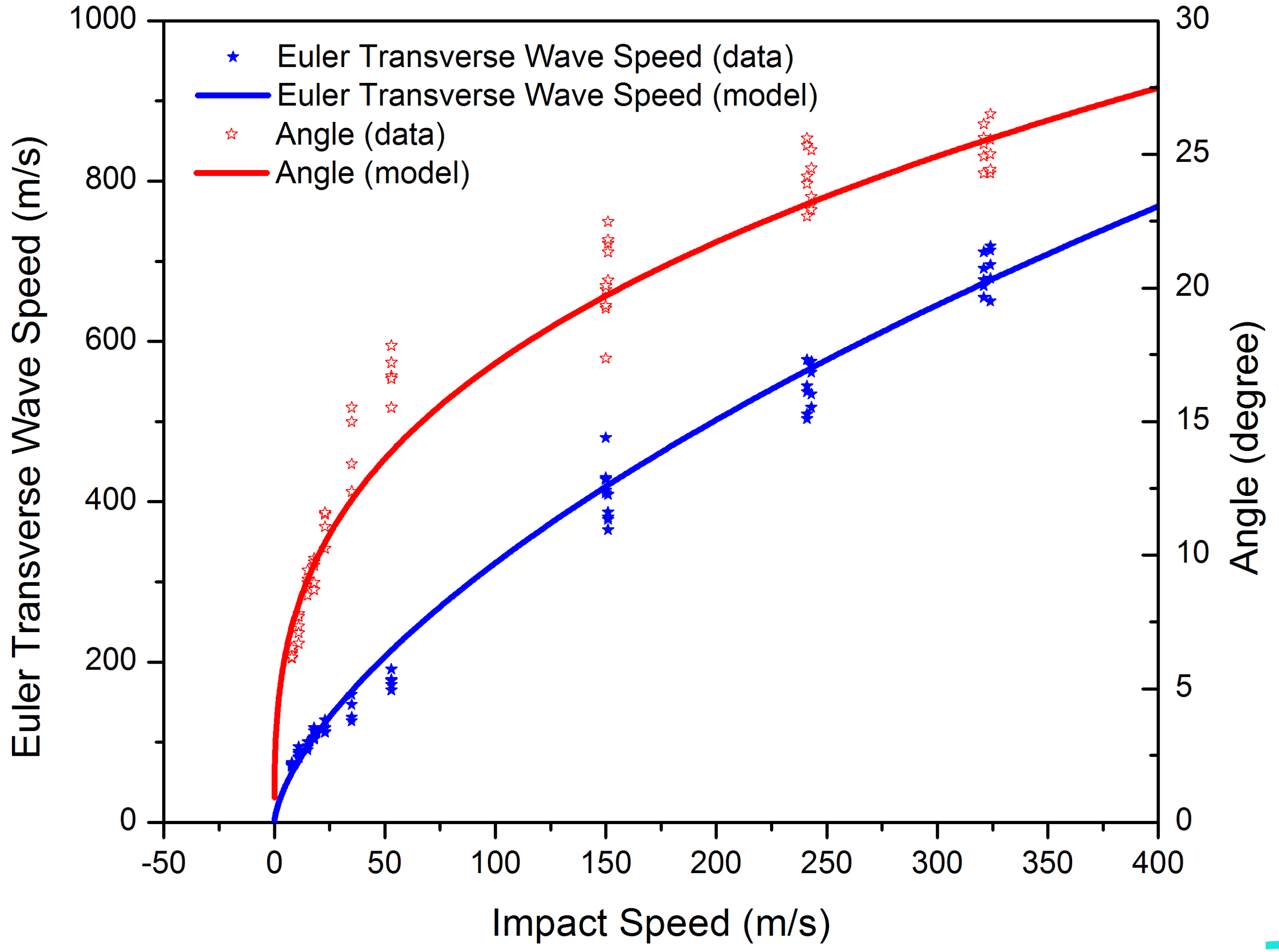
$$\gamma = \tan^{-1}\left(\frac{2V_0}{C_l}\right)^{1/3}$$

C_l = 7574 m/s for 600D Kevlar KM2 fiber
(Kim et al. 2008)

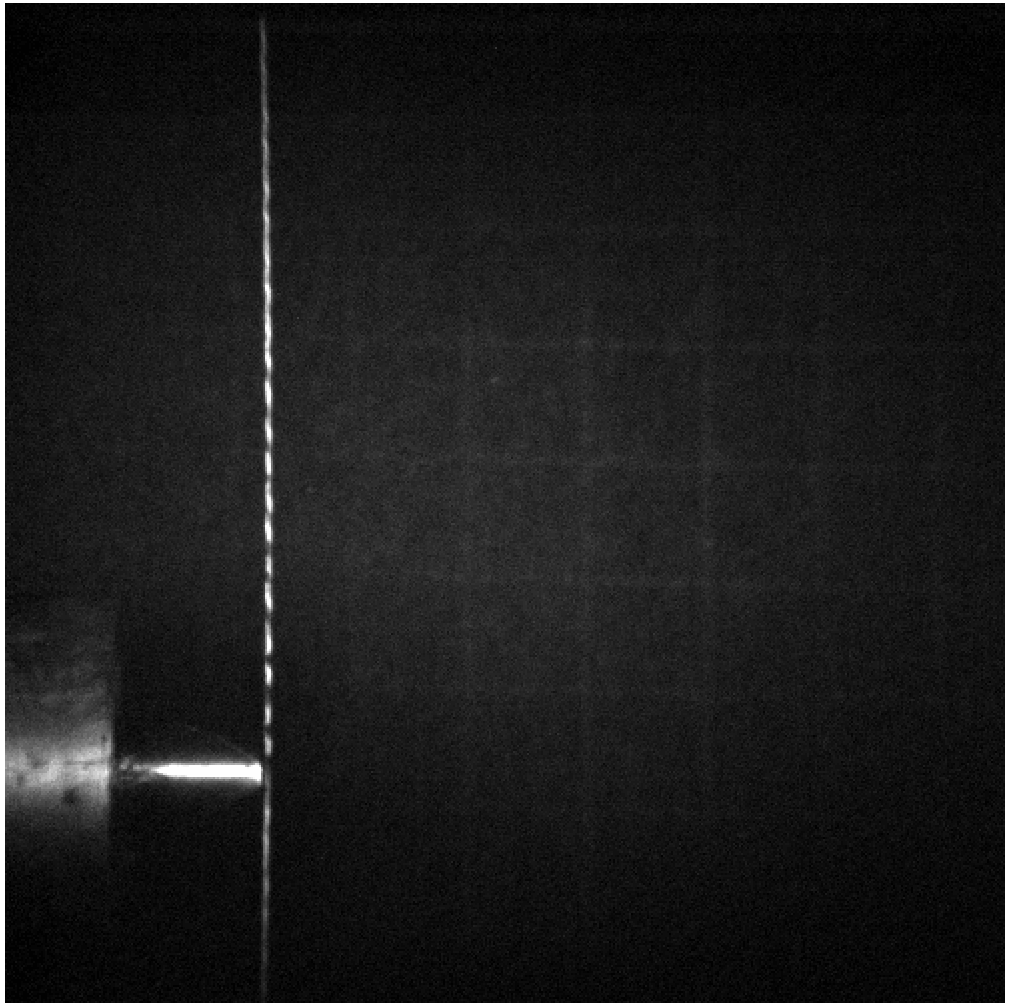
$$\varepsilon = 2^{-2/3}\left(\frac{V_0}{C_l}\right)^{4/3} = 0.63\left(\frac{V_0}{C_l}\right)^{4/3}$$

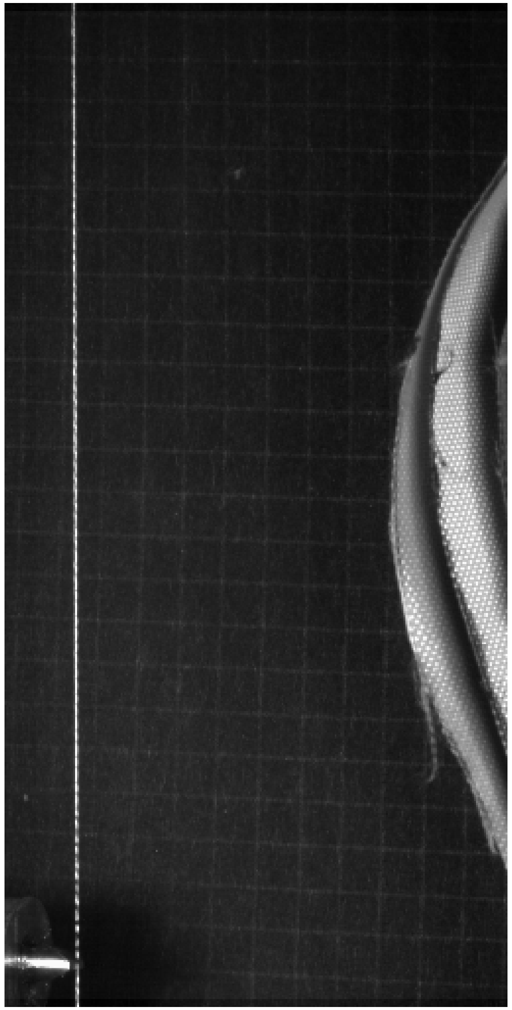
$$\sigma = 0.63\frac{\rho_0}{A_0}V_0^{4/3}C_l^{2/3}$$

Kevlar® KM2 Fiber Yarn Taken from a Fabric: Results



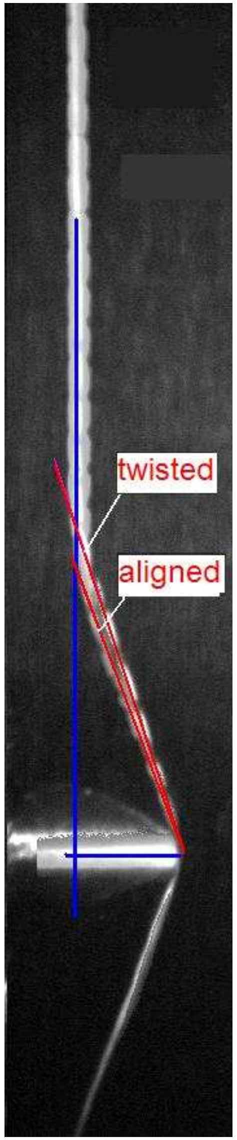
Transverse Impact Response of Twisted Kevlar® KM2 Fiber Yarn Taken from a Fabric

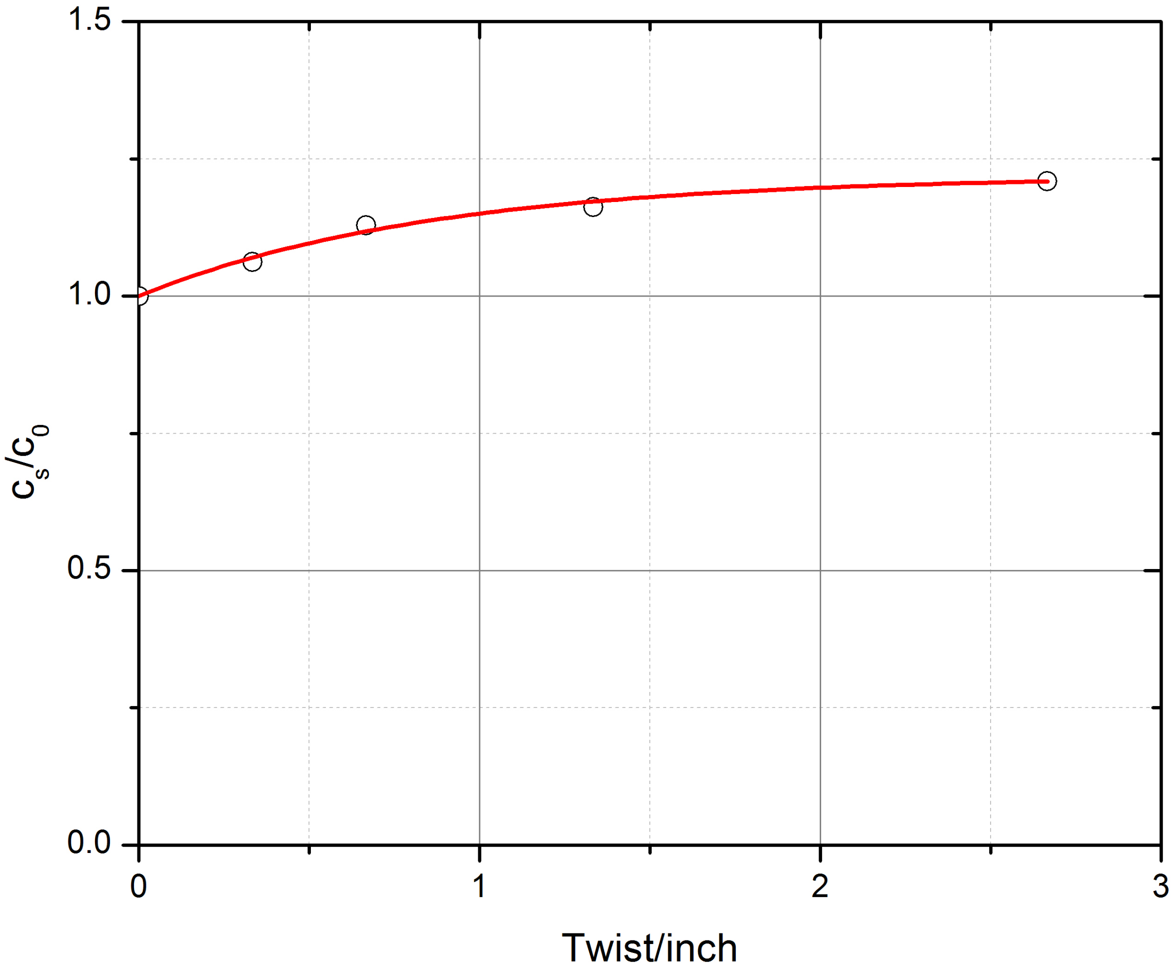




V=53 m/s

Transverse Impact Response of a Twisted Kevlar® KM2 Fiber Yarn Taken from a Fabric

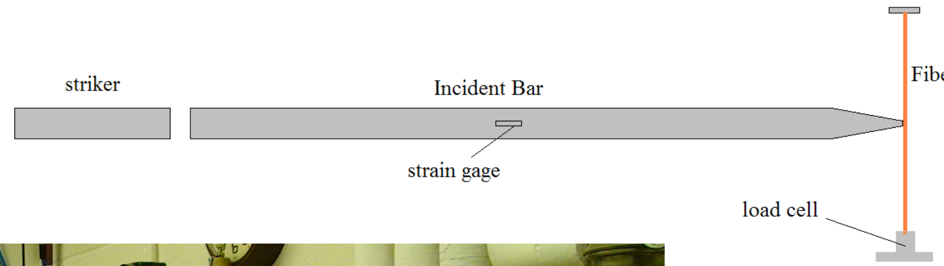


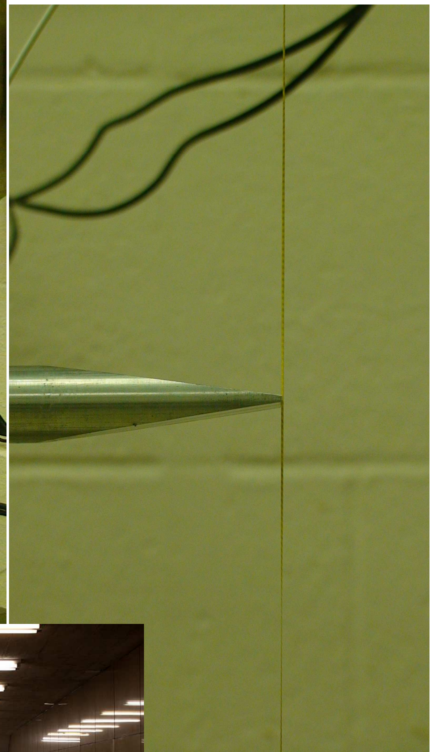


Patent Pending

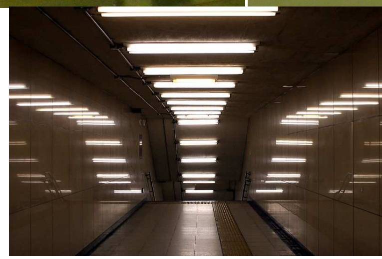
Transverse Impact Response of DuPont 600 Denier Kevlar® KM2 Fiber Yarns

- 600 den. Kevlar® KM2
  - 10-15'' long
  - Fiber yarn conditions
    - "As-received" Aligned
    - Twisted "As-received"
    - UV/aged aligned
    - UV/aged pre-twisted
    - Twisted UV/aged
- Impact Speed
  - 11 – 52 m/s (Hopkinson bar)
  - 150-320 m/s (Gas gun)
- Pre-loading Condition
  - Pre-tension: <0.5 N





UV/aged: exposed under fluorescent lamps for 10 months



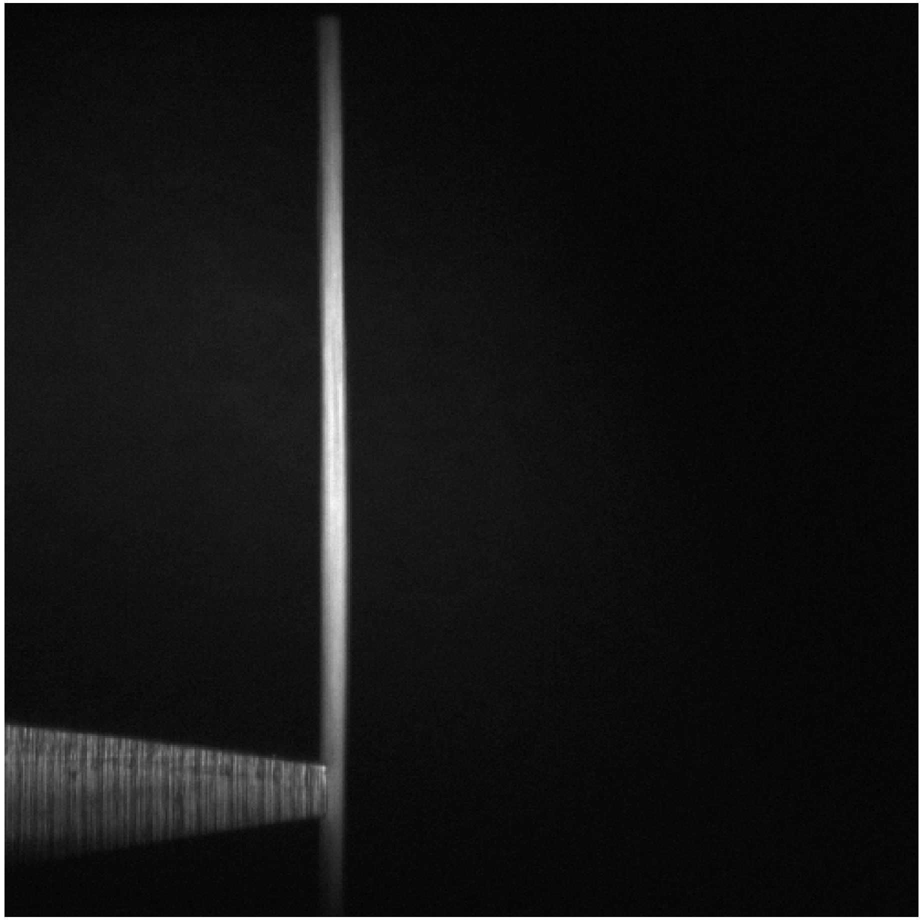
National Nuclear Security Administration

Sandia National Laboratories

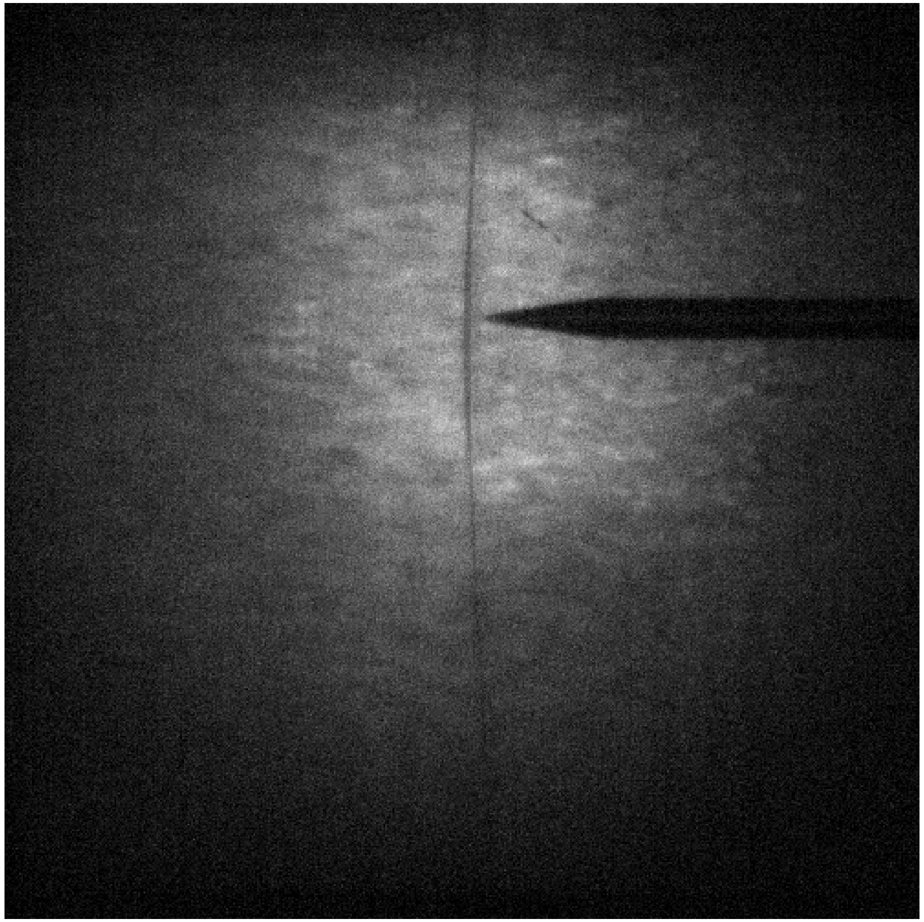
Testing Matrix of DuPont 600 Denier Kevlar® KM2 Fiber Yarns

Impact Speed (m/s)	Aligned – As received	Twisted – As received				UV/aged – Twisted	Aligned – UV/aged	Twisted – UV/aged			
		1/3	2/3	4/3	8/3			1/3	2/3	4/3	8/3
16	✓					✓					
21	✓					✓					
30	✓					✓					
43	✓					✓					
52	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
155	✓										
244	✓										
324	✓										

Transverse Impact Response of “As-Received” Aligned Fiber Yarns



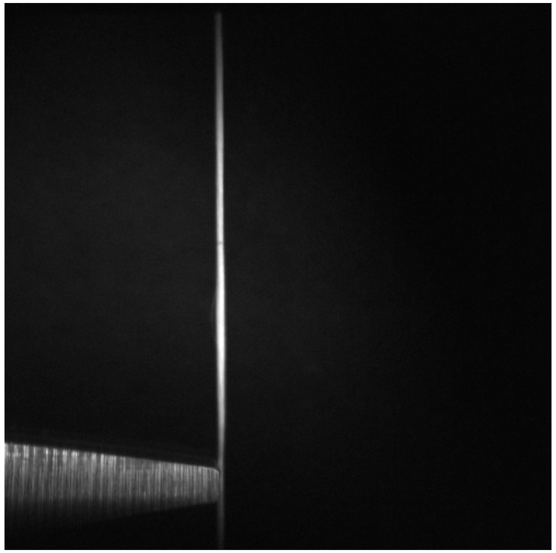
V=52 m/s

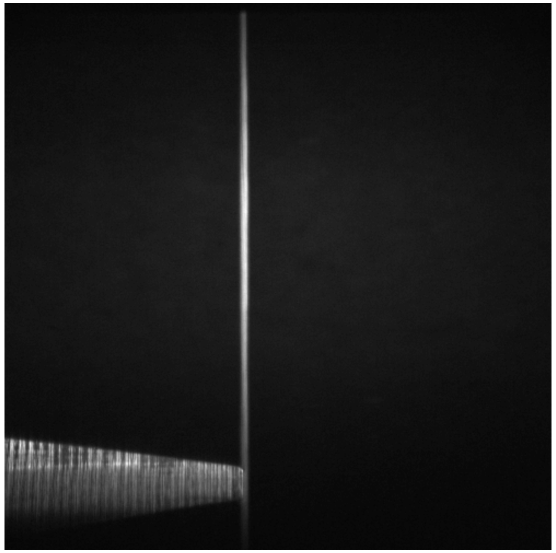


V=244 m/s

Transverse Impact Response of Fiber Yarns under Various Conditions (V=53 m/s)

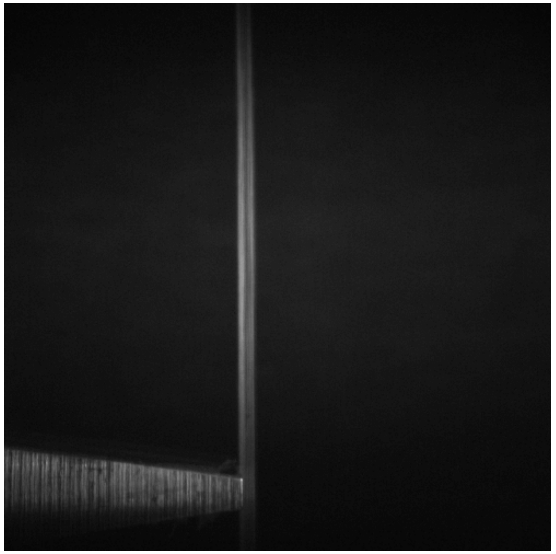
Twisted – "As-received"

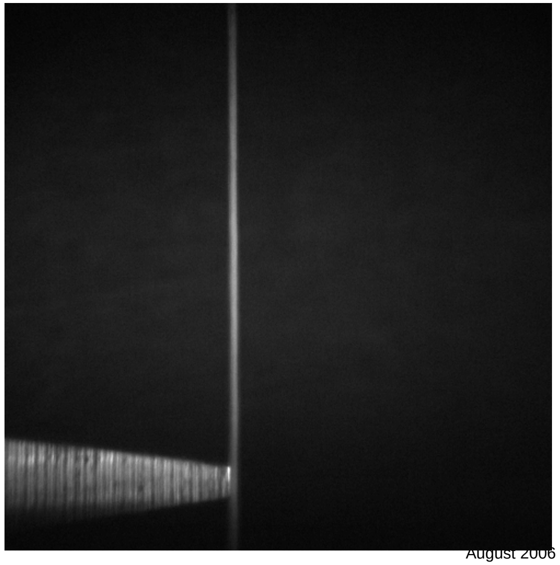




UV/aged – pre-twisted

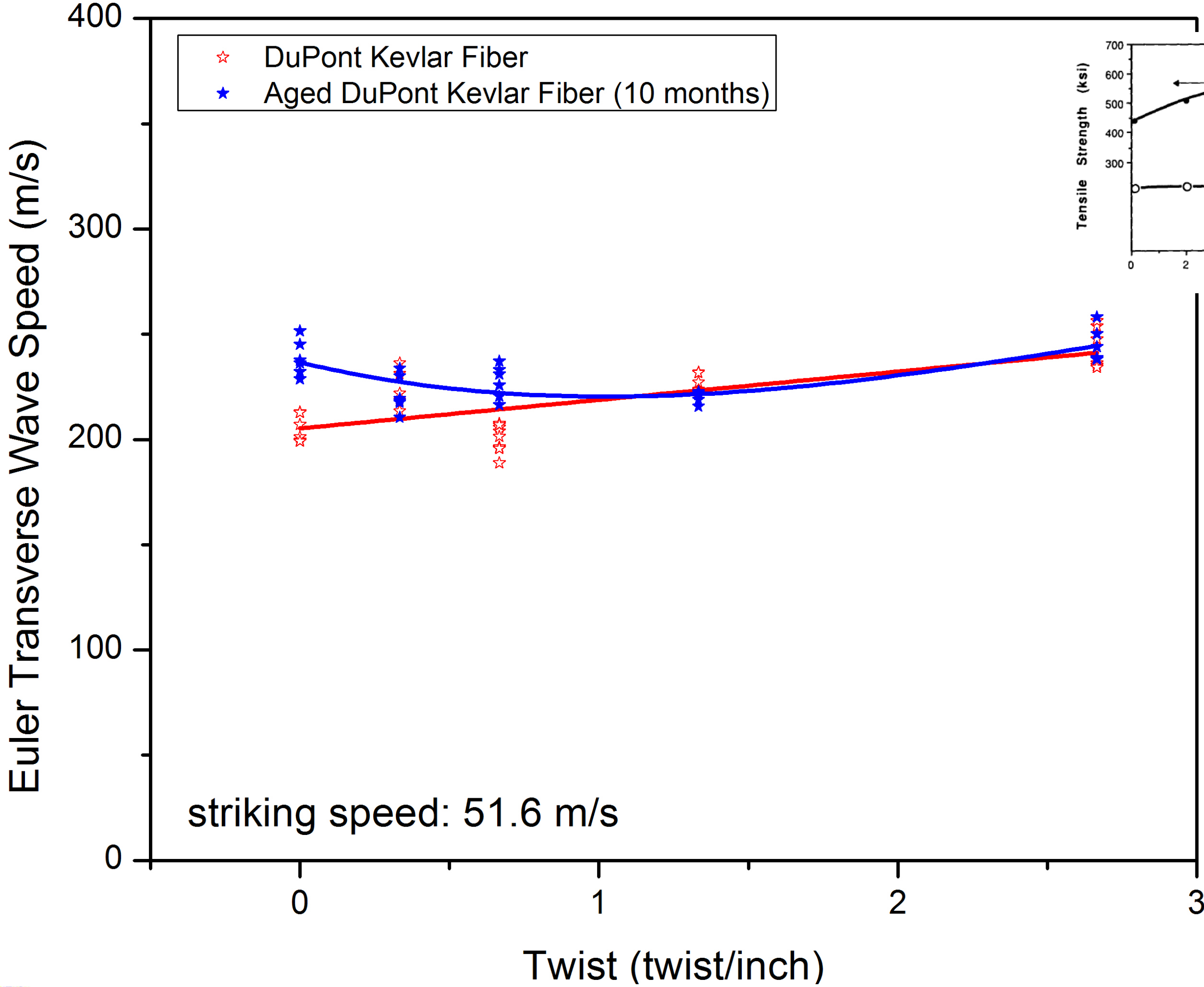
Aligned – UV/aged

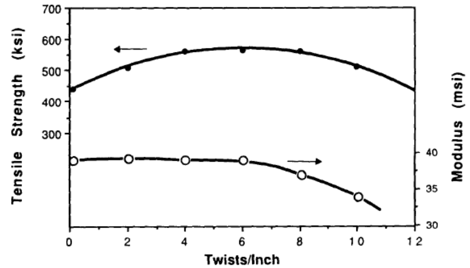




Twisted – UV/aged

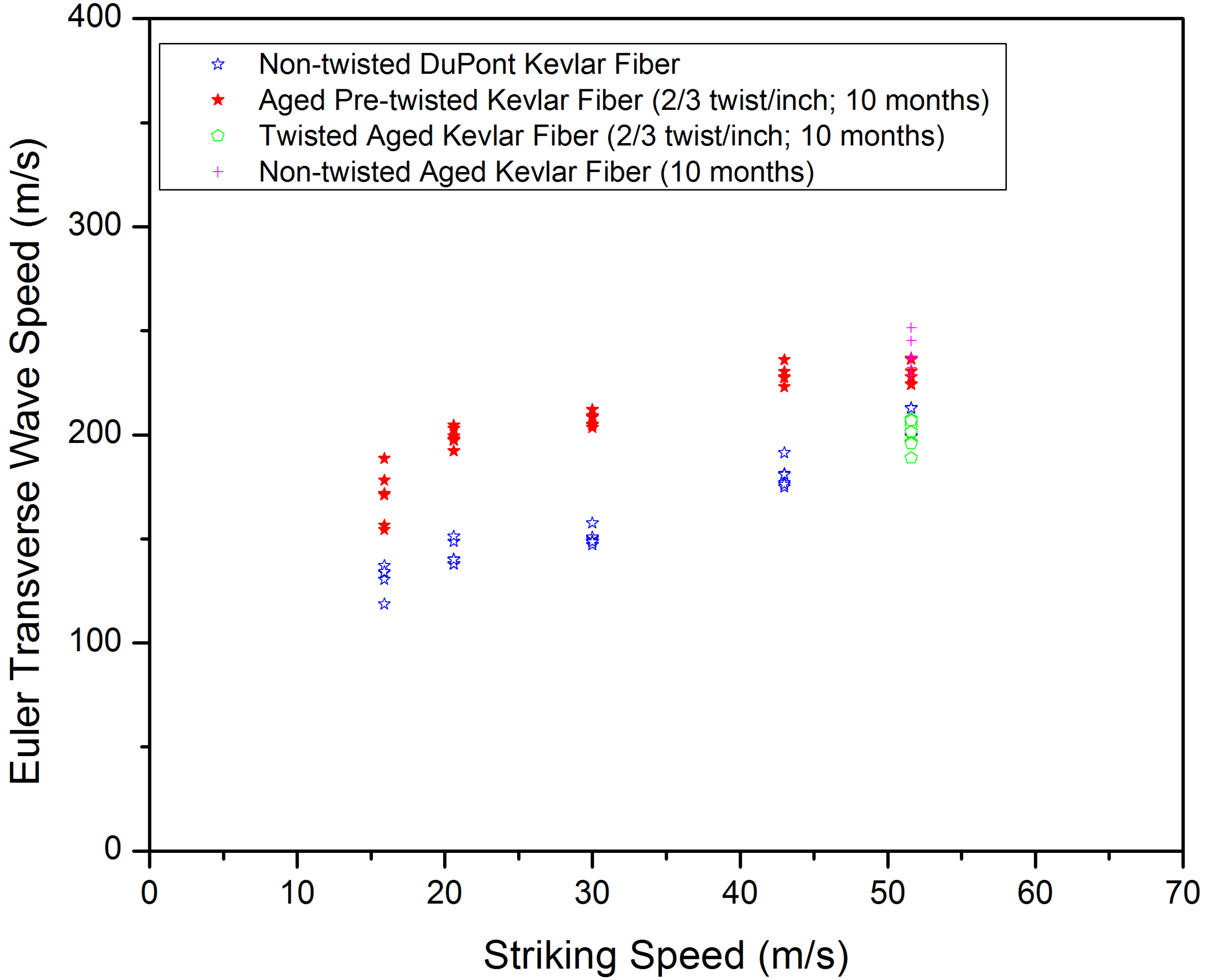
Effect of Twist and UV/Aging on Euler Transverse Wave Speed





IM et al. 1989

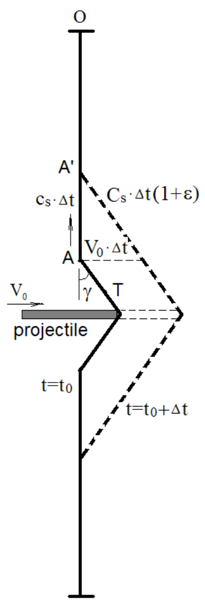
Effect of Striking Speed, Twist, UV/Aging on Euler Transverse Wave Speed



Ballistic Performance

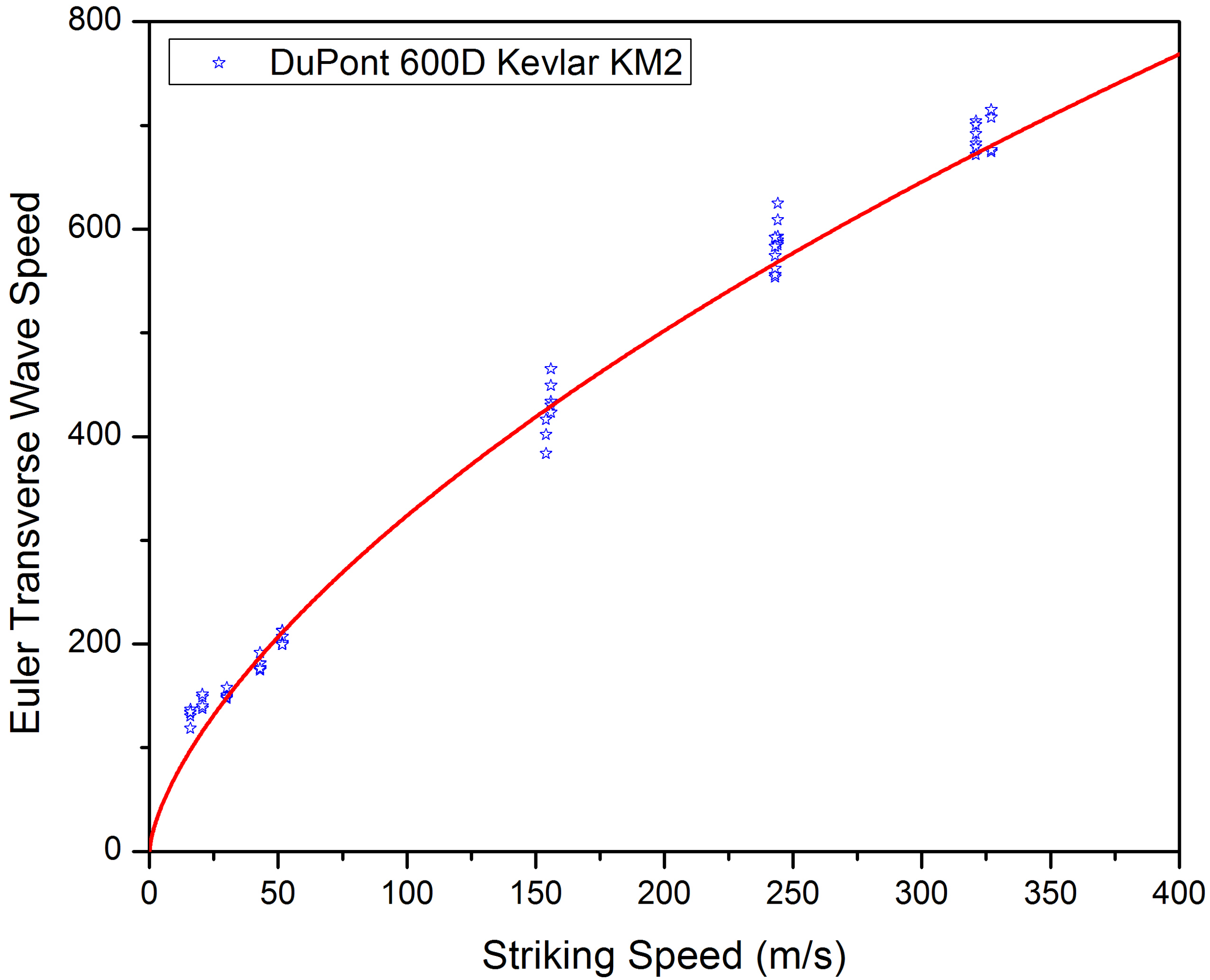
- **Transverse Wave**
  - **Transverse wave dissipates the impact energy subjected to the fiber yarn**
  - **A fast transverse wave makes more fiber yarns in a fabric involve in energy absorption, therefore dissipating the impact energy quickly**

- **Transverse Wave Speed depends on**
  - **Loading Conditions**
    - **Pre-tension load (*T_0=0* here)**
    - **Impact speed**
  - **Material properties**
    - **Longitudinal wave speed**
    - **Important in ballistic performance**



- **Criterion for Material Selection and Optimization**

Effect of Impact Speed on Euler Transverse Wave Speed (Data and Modeling)



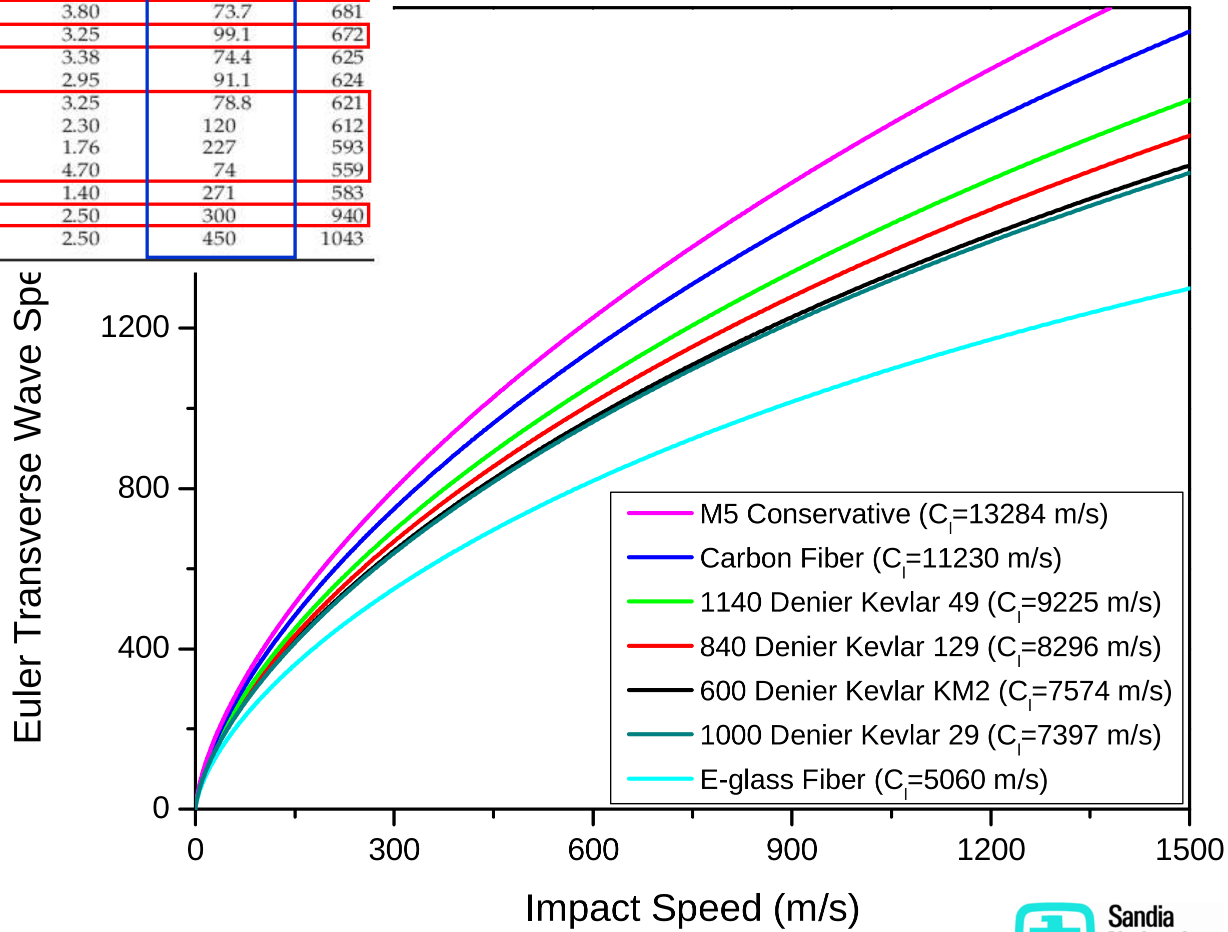
$$
\begin{cases}
c_s = \dfrac{V_0}{\tan\gamma} \\
T = \rho_0 C_l U \\
U = C_l \varepsilon \\
T \sin\gamma = \rho_0 C_s V_0 \\
c_s = C_s(1+\varepsilon) - U \\
V_0 = C_s(1+\varepsilon)\sin\gamma
\end{cases}
$$

Parametric Study: Longitudinal Wave Speed Effect

Theoretical Ballistic Performance of Common Fibers

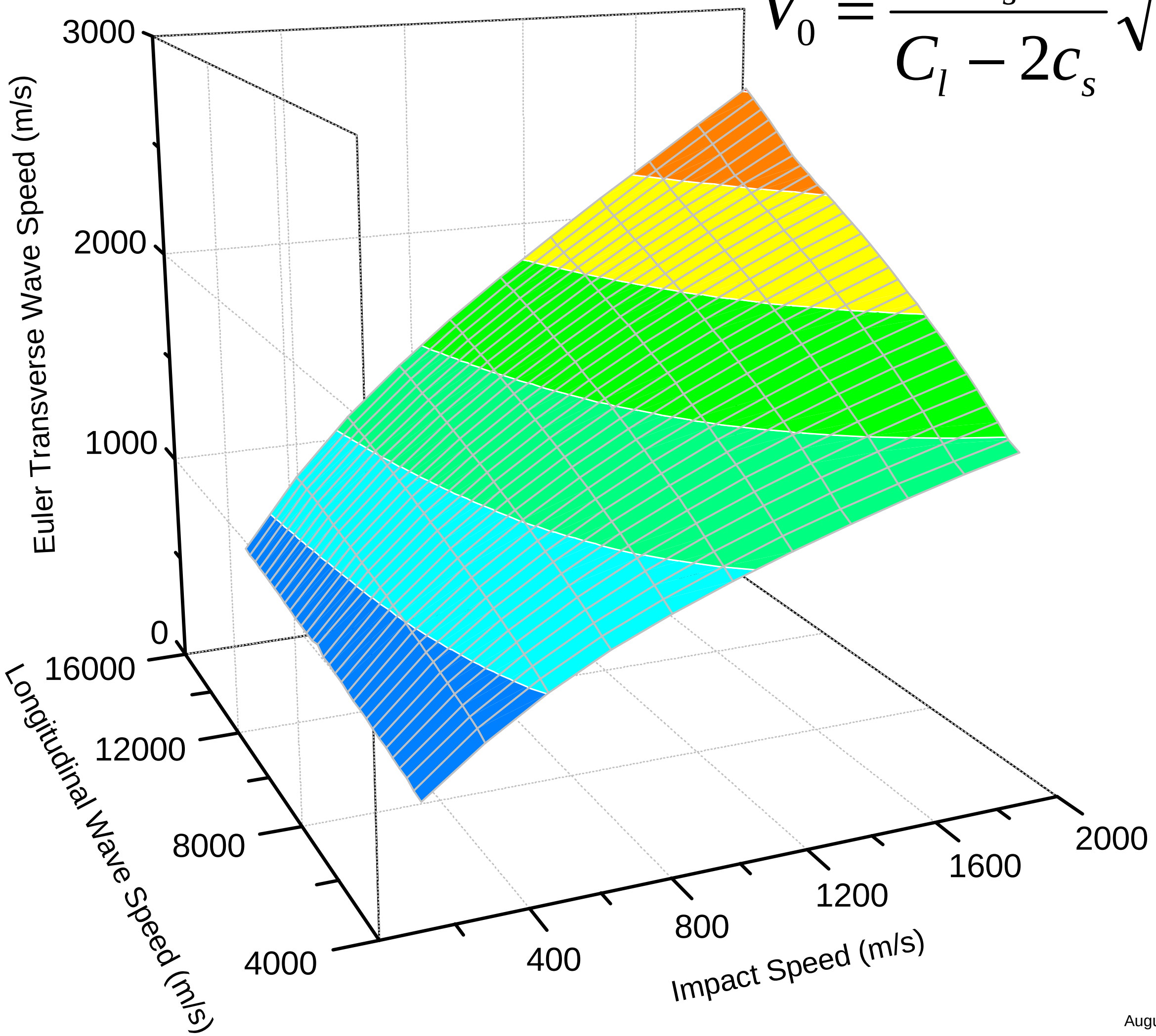
Fiber	Density (Calc.) (ρ) (g/cm³)	Strength (σ) (GPa)	Failure strain (ε) (%)	Modulus (E) (GPa)	$(U^*)^{1/3}$ (m/s)
PBO (as spun)	(1.56)	5.20	3.10	169	813
Spectra 1000	(0.97)	2.57	3.50	120	801
600 den. Kevlar KM2	(1.44)	3.40	3.55	82.6	682
850 den. Kevlar KM2	(1.44)	3.34	3.80	73.7	681
840 den. Kevlar 129	(1.44)	3.24	3.25	99.1	672
1,500 den. Kevlar 29	(1.44)	2.90	3.38	74.4	625
200 den. Kevlar 29	(1.44)	2.97	2.95	91.1	624
1,000 den. Kevlar 29	(1.44)	2.87	3.25	78.8	621
1,140 den. Kevlar 49	(1.41)	3.04	2.30	120	612
Carbon fiber	(1.80)	3.80	1.76	227	593
E-glass fiber	(2.89)	3500	4.70	74	559
M5 (2001 sample)	(1.74)	3.96	1.40	271	583
M5 Conservative	(1.70)	8.50	2.50	300	940
M5 Goal	(1.70)	9.50	2.50	450	1043

$$C_l = \sqrt{\frac{E}{\rho_0}} = \sqrt{\frac{1}{\rho_0}\frac{d\sigma}{d\varepsilon}}$$



Parametric Study: Effects of Longitudinal Wave Speed and Impact Speed

$$V_0 = \frac{c_s}{C_l - 2c_s}\sqrt{c_s\left(2C_l - 3c_s\right)}$$



Predictable Failure Strain

Theoretical Ballistic Performance of Common Fibers

Fiber	Density (Calc.) (ρ) (g/cm^3)	Strength (σ) (GPa)	Failure strain (ε) (%)	Modulus (E) (GPa)	$(U^*)^{1/3}$ (m/s)
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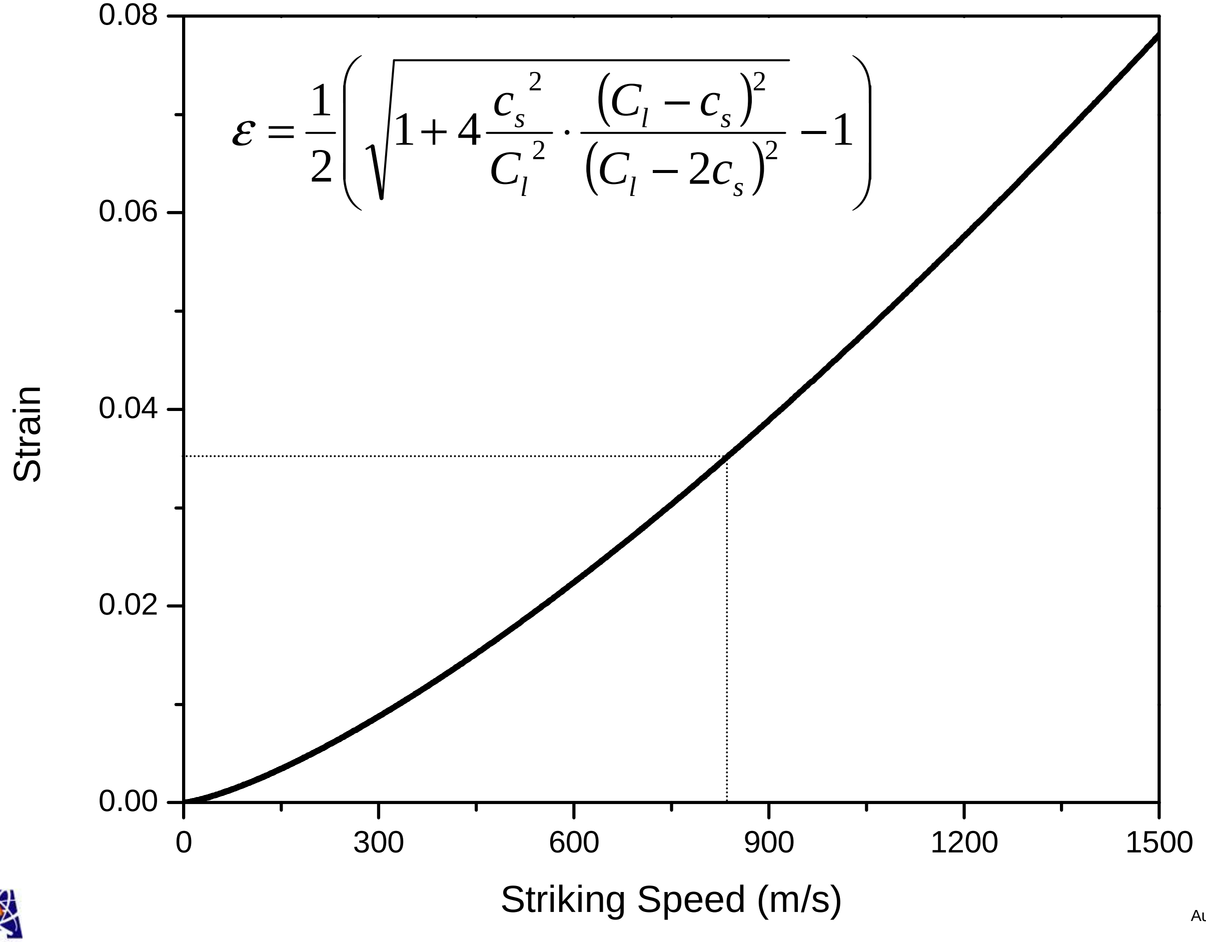
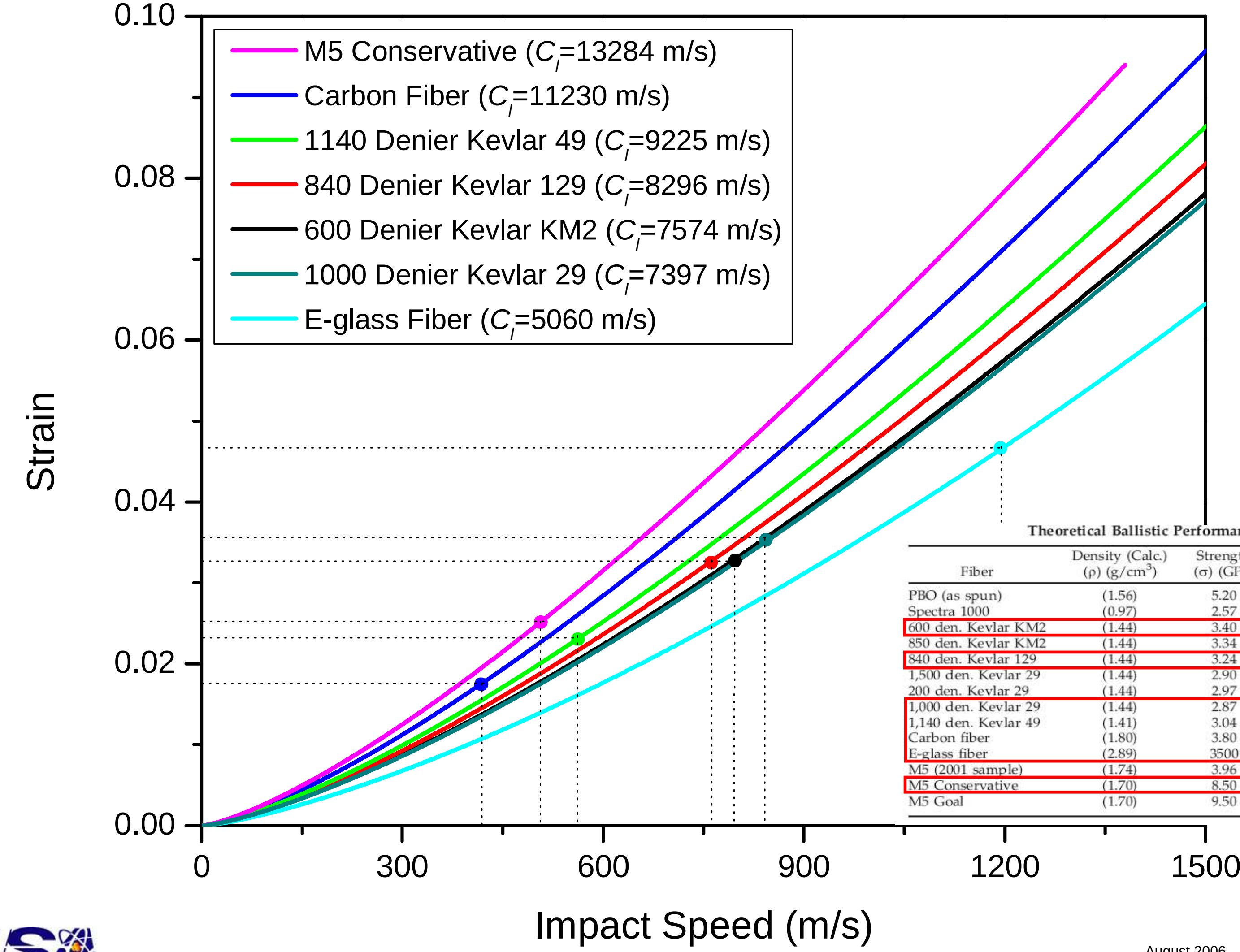
Spectra 1000	(0.97)	2.57	3.50	120	801
600 den. Kevlar KM2	(1.44)	3.40	3.55	82.6	682

$$C_l = \sqrt{\frac{E}{\rho_0}} = \sqrt{\frac{1}{\rho_0}\frac{d\sigma}{d\varepsilon}} = 7574 m/s$$



$$\varepsilon = \frac{1}{2}\left(\sqrt{1 + 4\frac{c_s^{\ 2}}{C_l^{\ 2}} \cdot \frac{(C_l - c_s)^2}{(C_l - 2c_s)^2}} - 1\right)$$

Parametric Study: Fiber Yarn Strain



Theoretical Ballistic Performance of Common Fibers

Fiber	Density (Calc.) (ρ) (g/cm³)	Strength (σ) (GPa)	Failure strain (ε) (%)	Modulus (*E*) (GPa)	$(U^*)^{1/3}$ (m/s)
PBO (as spun)	(1.56)	5.20	3.10	169	813
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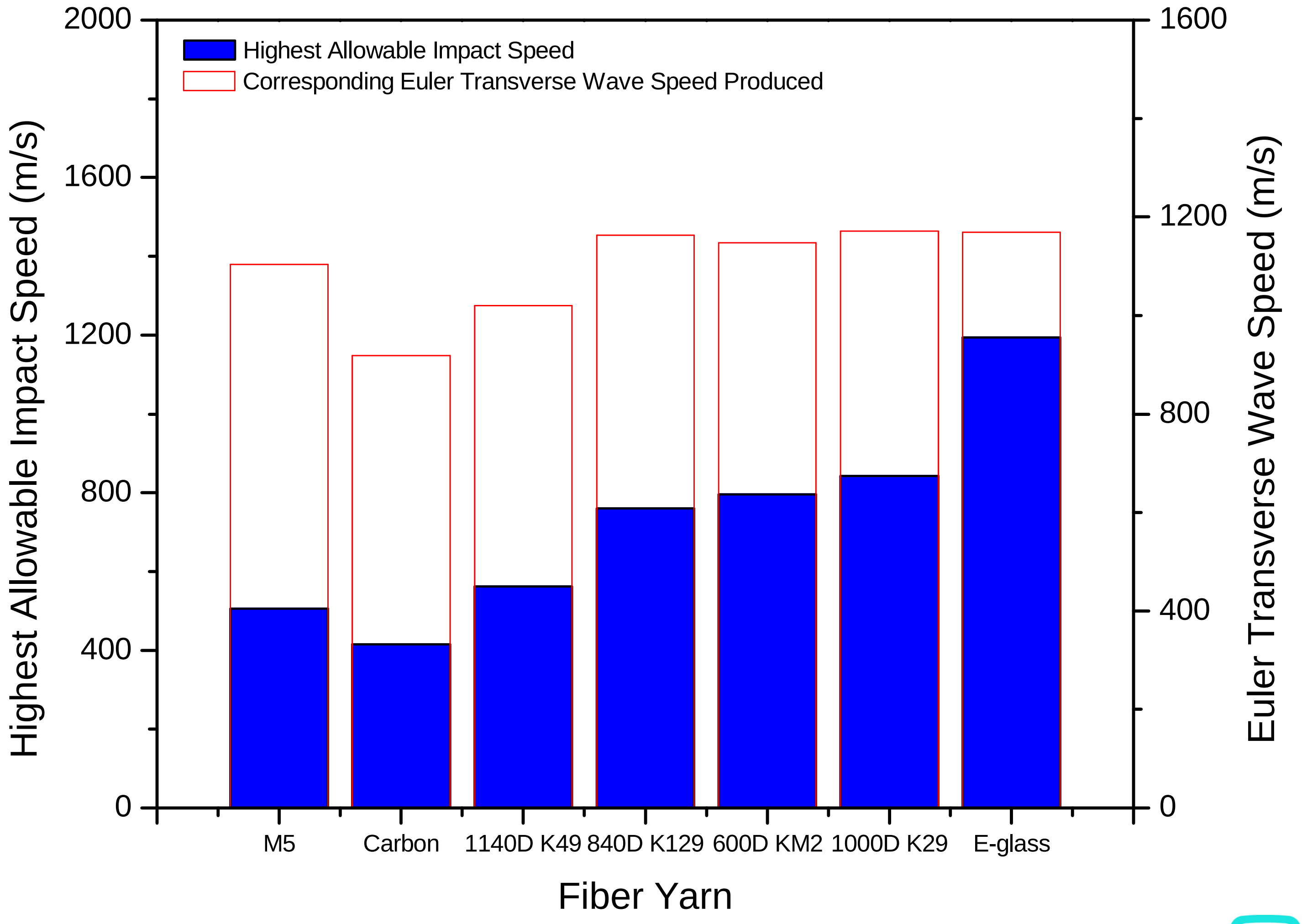
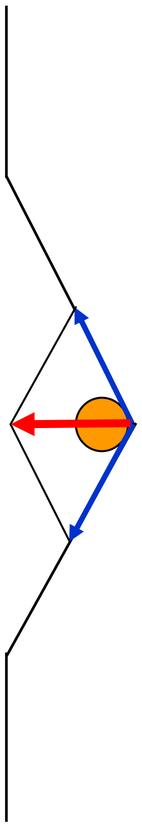
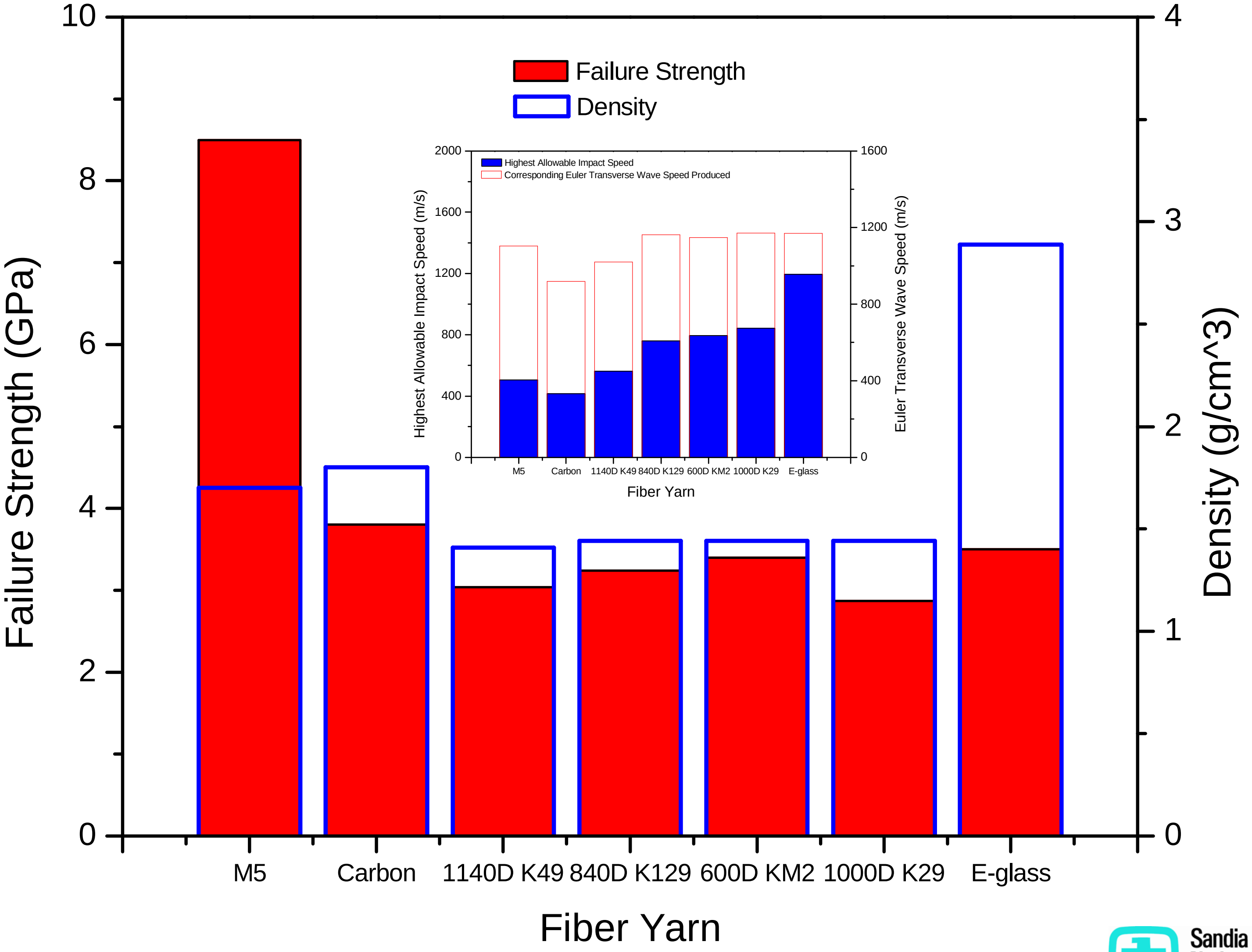
M5 Goal	(1.70)	9.50	2.50	450	1043

Highest Allowable Impact Speed



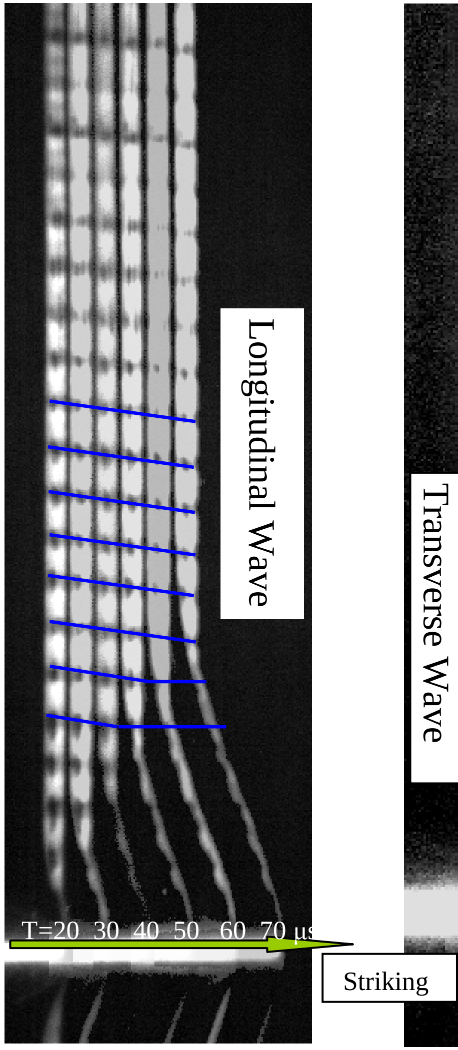
Failure Strength and Density

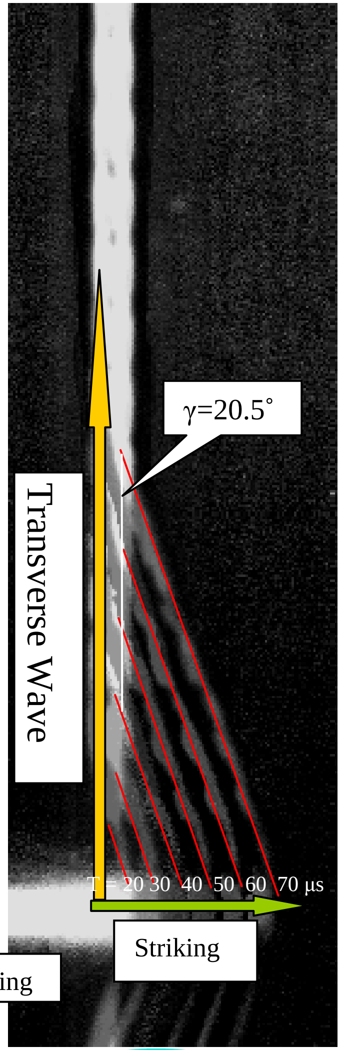




Summary (I)

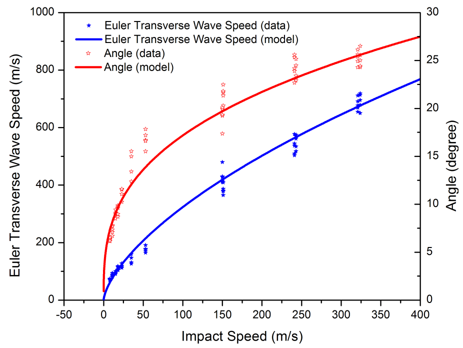
- When a linear-elastic fiber yarn is subjected to transverse impact, both longitudinal and transverse wave are generated
  - Longitudinal wave produces tension in the fiber yarn
  - Transverse wave speed changes the shape of the fiber yarn
    - Transverse wave speed is important in the ballistic performance of a fiber yarn.
    - A faster transverse wave speed
      - dissipates the impact energy faster;
      - avoids significant localization of strain in the fiber yarn

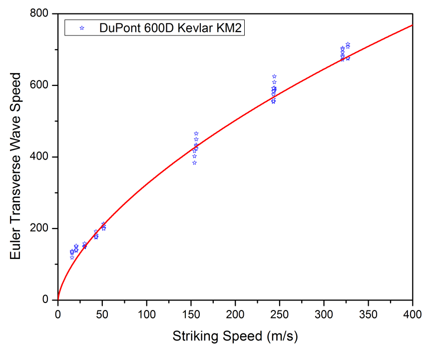




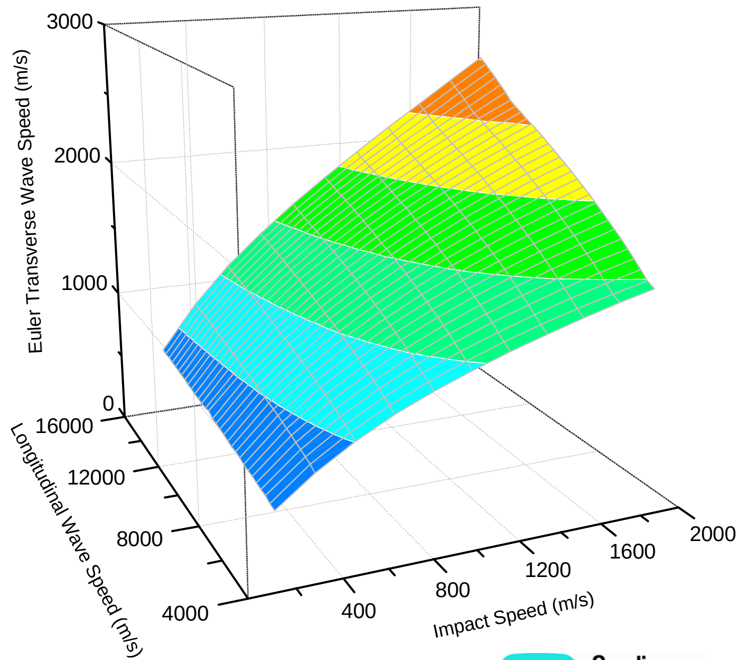
Summary (II)

- **Longitudinal wave speed is a material constant, depending on**
  - **Density**
  - **Modulus of elasticity**





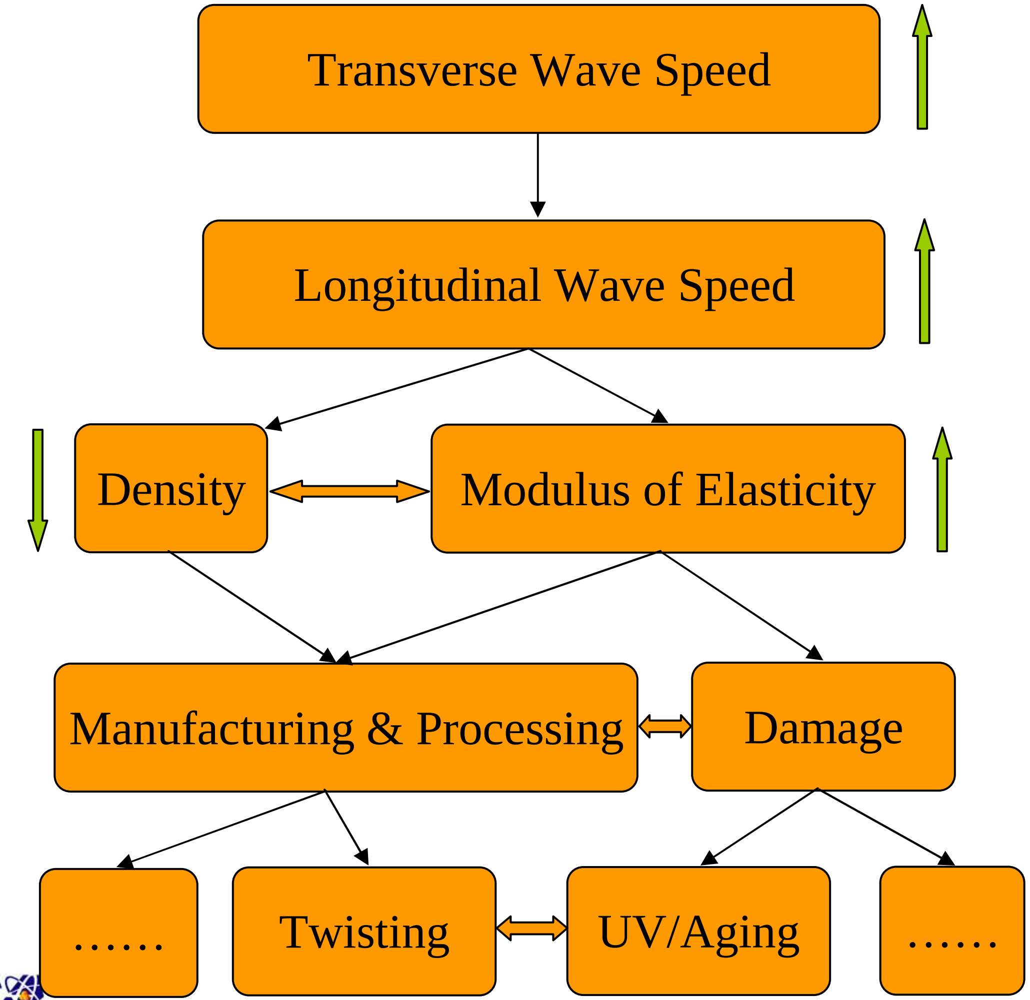
- **Transverse wave speed depends on**
  - **Material properties**
    - **Longitudinal wave**
  - **Loading conditions**
    - **Pre-tension load (*T_0~0* in this study)**
    - **Impact speed**
      - **Transverse wave speed increases with increasing impact speed**

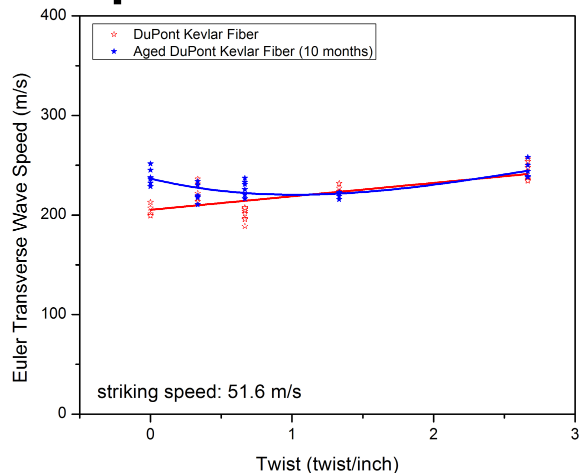


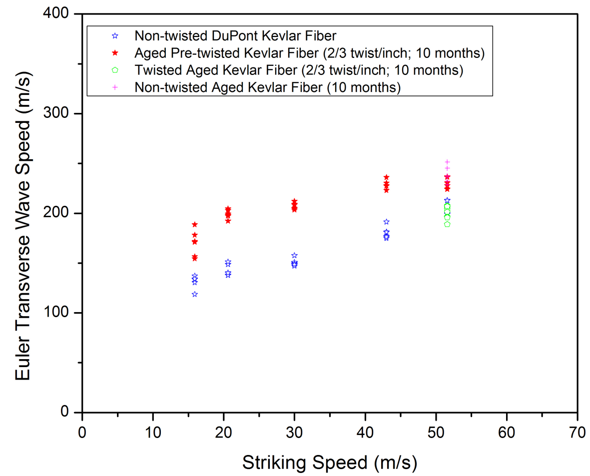
$$V_0 = \frac{c_s}{C_l - 2c_s}\sqrt{c_s\left(2C_l - 3c_s\right)}$$

Summary (II)

- **Effect of material properties on transverse wave speed**

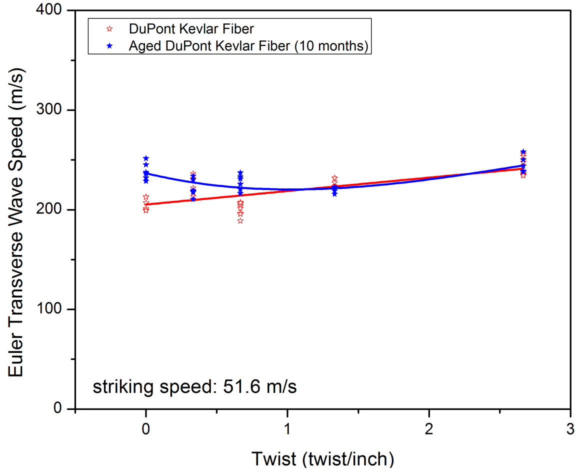


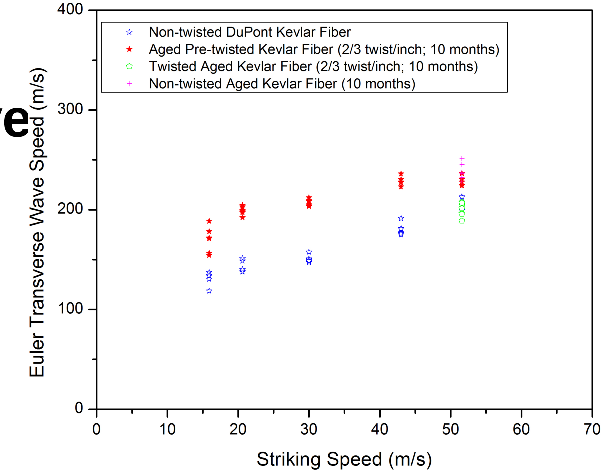




Summary (III)

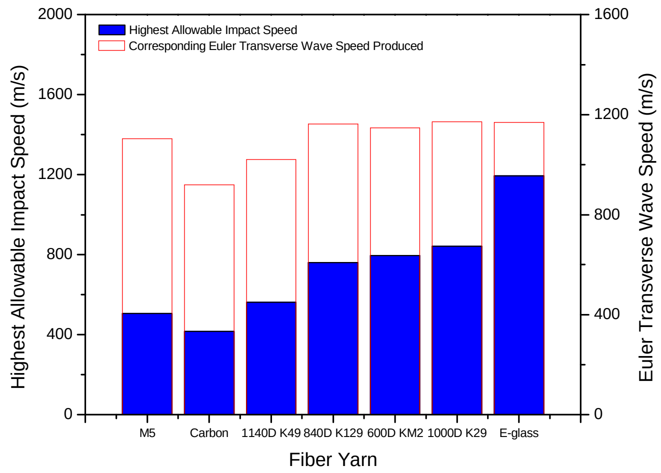
- **Effect of material properties on transverse wave speed**
  - **Twisting**
    - **Appropriate amount of twist may increase the transverse wave speed**
  - **UV/aging**
    - **Results show UV/aging may increase the transverse wave speed**
  - **Aged pre-twisted fiber yarn shows a significant increase in the transverse wave speed**
  - **Mechanism**
    - **Changes in material properties ?**
    - **Fiber interactions enhanced ✓**

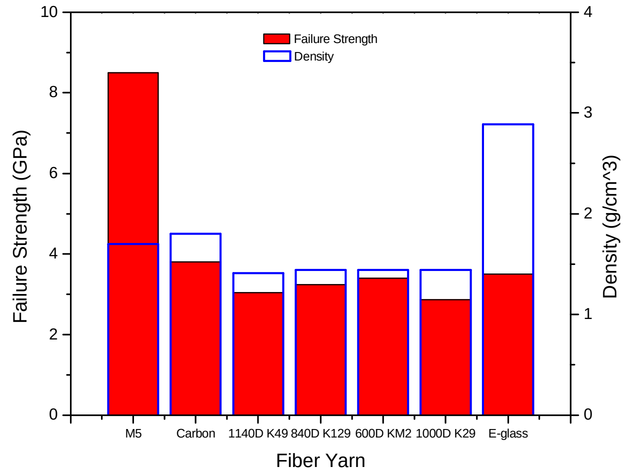




Summary (IV)

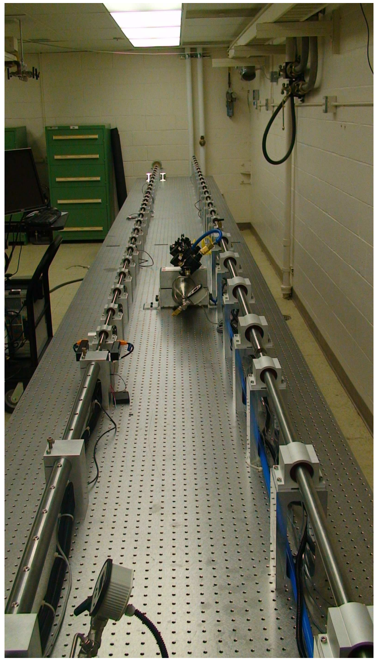
- **Selection and Optimization of Fiber Yarns for Better Ballistic Performance**
  - **Density**
  - **Modulus of Elasticity**
  - **Failure Strain**
  - **Highest Allowable Impact Speed**
  - **Failure Strength**
  - **Others**
    - **UV/aging Performance**
    - **Twisting Performance**
    - **Comfort**
      - **Flexibility**
      - **Formability**
      - **Air Circulation**

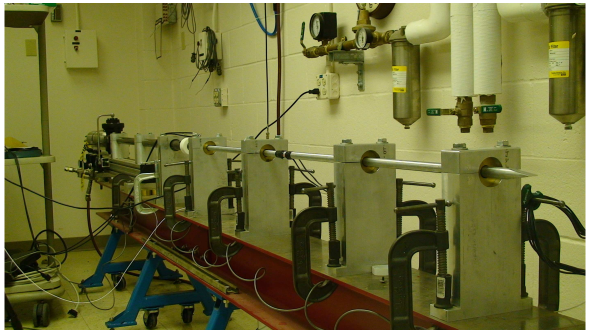




Future Directions

- Quantitative Determination of Fiber Yarn under High-rate Tension
  - Strain Rate Effects
    - Modulus of Elasticity
    - Failure Strain
    - Failure Strength
- Effect of Twist and/or UV/Aging on Material Properties
  - Modulus of Elasticity
  - Failure Strain
  - Failure Strength
- Effect of Interaction
  - Fiber Yarns
  - Fabric Layers
- Quantitative Optimization of Soft Body Armor
  - Fiber Yarns
  - Fabrics
  - Armor





Acknowledgement

- Dr. Mary Strzelecki @ DuPont
- Dr. Tucker Norton @ DuPont
- Dr. James Zheng, Chief Scientist, US Army
- Sandia LDRD Program

THANK YOU FOR YOUR TIME!