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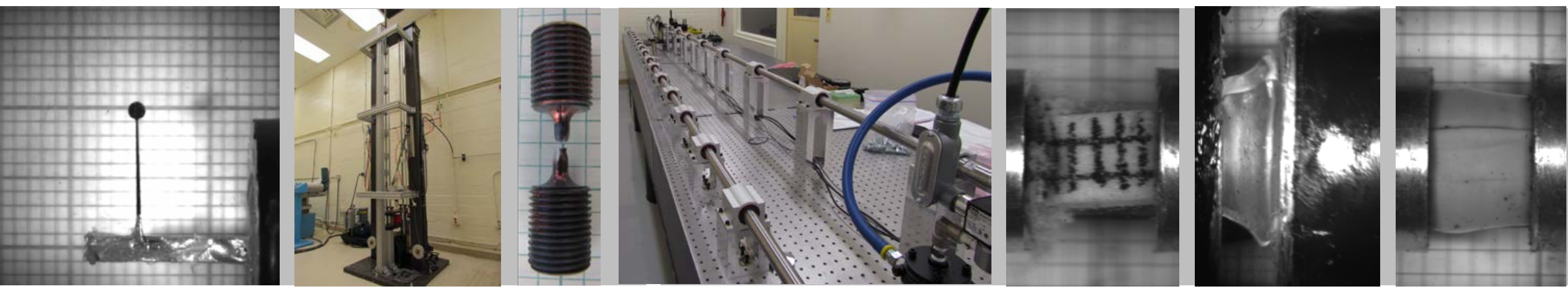

Frequency Response of Shock Mitigation through Foam Materials

Bo Song (1558)

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Experimental Impact Mechanics Lab. (EIML)

Sandia National Laboratories

- Location: B860/122B
- Lead/Principal Investigator: Bo Song (1558)
- Facilities:
  - *1"-diameter split Hopkinson compression bar (Kolsky compression bar)*
  - *1"-diameter split Hopkinson tension bar (Kolsky tension bar)*
  - *1"-diameter "dropkinson" bar for intermediate-rate tensile testing*
  - *3"-diameter split Hopkinson compression bar (Kolsky compression bar)*
- Instrument/Equipment
  - *Teledyne LeCroy 4-channel high-speed digital oscilloscope*
  - *Teledyne LeCroy 8-channel high-speed digital oscilloscope*
  - *Keyence VHX-5000 digital microscope (20X-5000X)*
  - *Vishay 4-channel signal conditioner*
  - *Custom made laser displacement measurement system*
  - *1200^{o}C electrical furnace*
  - *MTI 15kW induction heater*
  - *Instron environmental chamber (-100 - 350^{o}C)*
  - *Buehler diamond saw*
  - *Thermocouple welder*
  - *Kirana ultra-high speed digital camera (coming soon)*
  - *NI acquisition and control system (coming soon)*

- Partnership with:
  - *Terminal Ballistic Hopkinson Bar Lab*
  - *Structure Mechanics Lab (MTS)*
  - *Shock Mechanics Lab (Drop tables)*
  - *Area III – Mechanical Shock Facility (Gas gun, horizontal actuator)*
  - *Area III – Terminal Ballistic Lab*

EIML Capabilities (What Can We Do?)

- **Dynamic Characterization of Materials**
  - *Dynamic stress-strain response of materials in compression or tension (shear coming soon)*
  - *Dynamic failure and fracture of materials*
  - *Strain-rate Range: ~100 – 10,000 s^{-1}*
  - *Temperature Range: -100 – 1200^{o}C*
  - *Stress state: uniaxial stress; triaxial stress (in compression only)*
  - *Materials covered: ceramics, alloys, composites, glasses, polymers, foams, biological tissues, concretes, sands, soil, etc*

- **Dynamic Characterization of Component/Small Structures**
  - *Dynamic structural testing with preload capability (compression or tension)*
  - *Wave Propagation/Interaction*
  - *Shock Mitigation*
  - *Dynamic Interface Problem*
  - *Component/Device Functionality/Survivability in Abnormal Mechanical Environments*
    - *High-g, high-frequency impact and vibration*
  - *Impact Sensor characterization*
- **Rate-dependent Model Validation**
  - *High rate, high frequency, etc*

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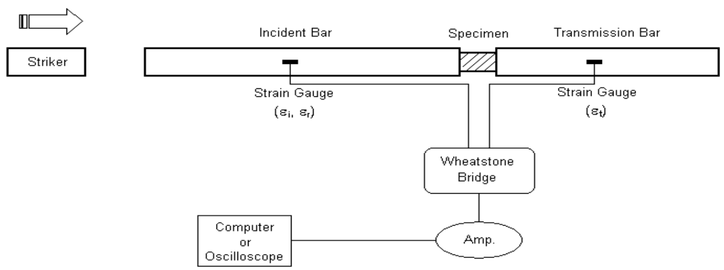
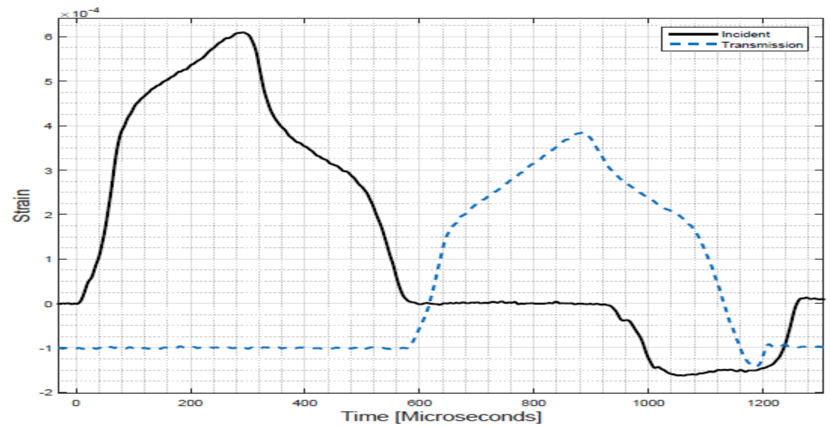
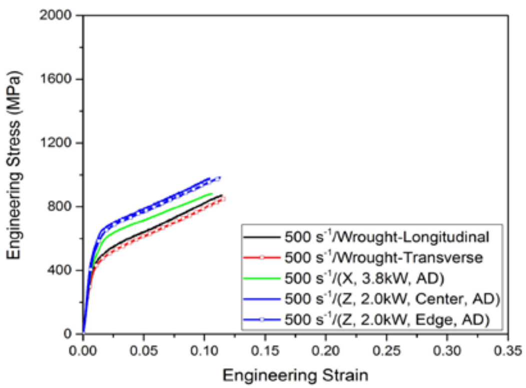
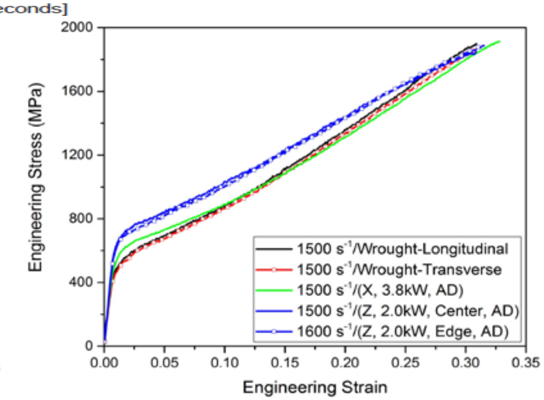
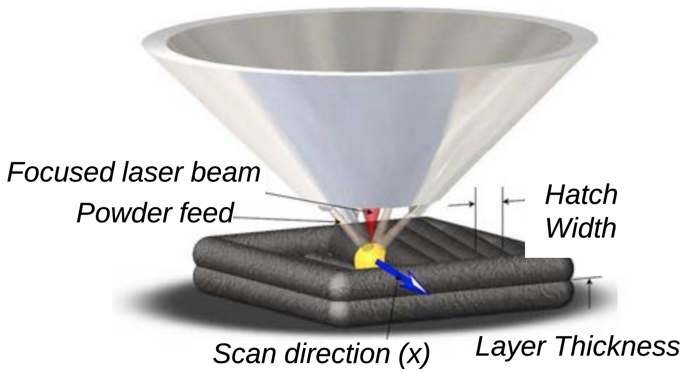
Dynamic Material Characterization Examples

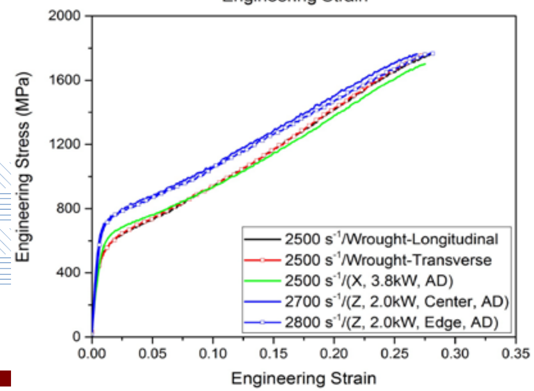


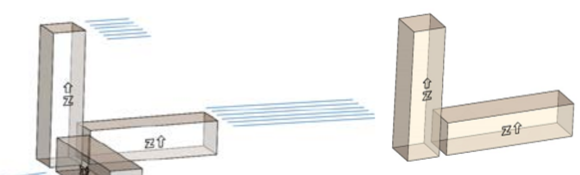


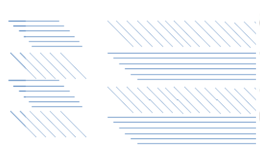




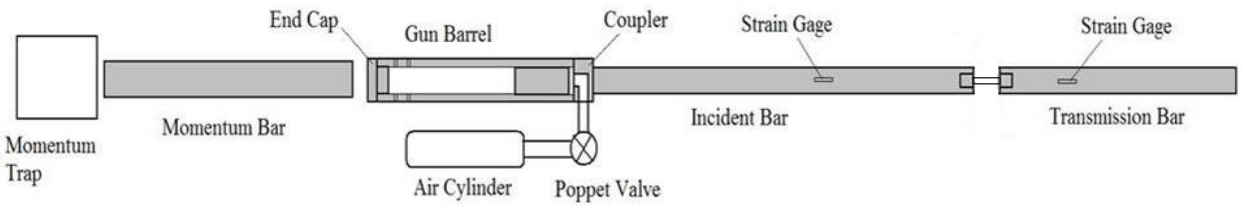


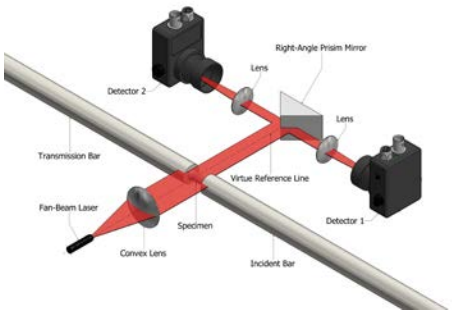


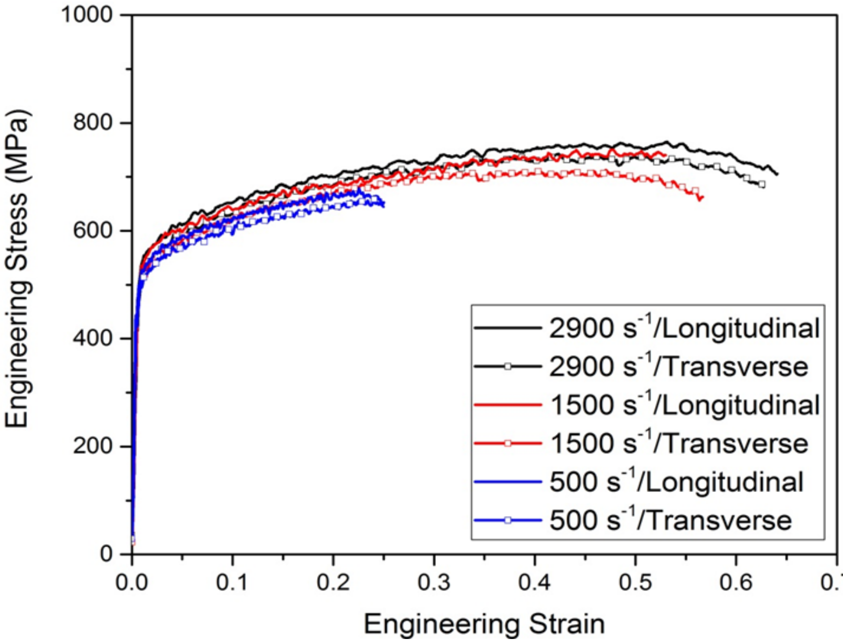

Sample Geometry

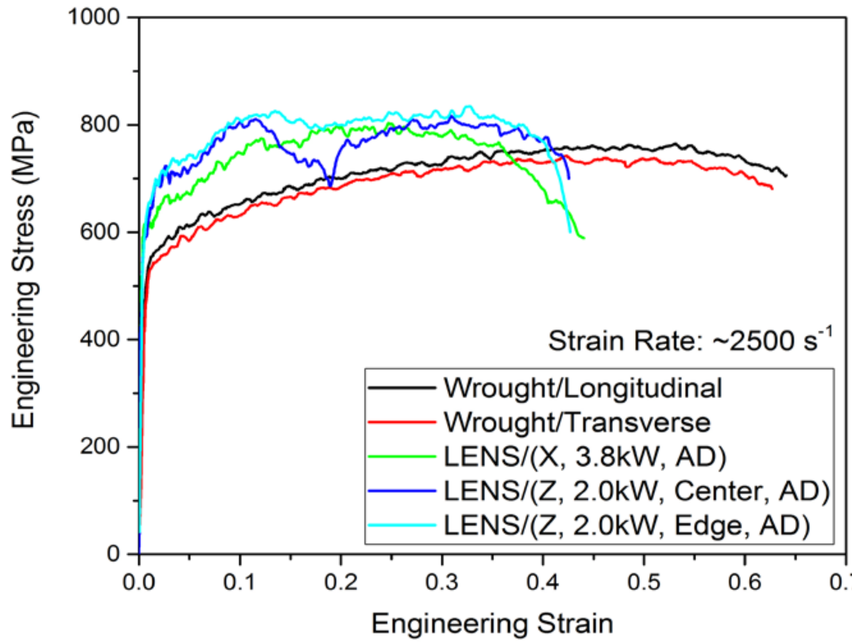

Schematic raster fill patterns

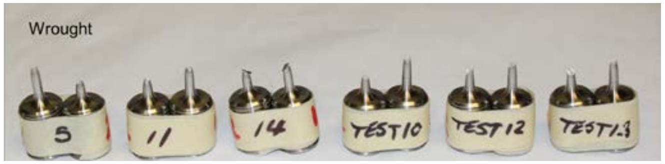
Dynamic Material Characterization Examples

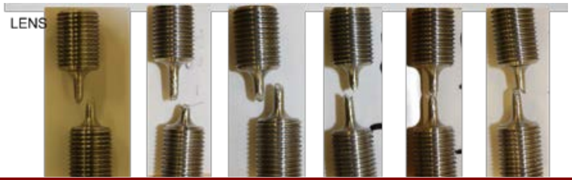






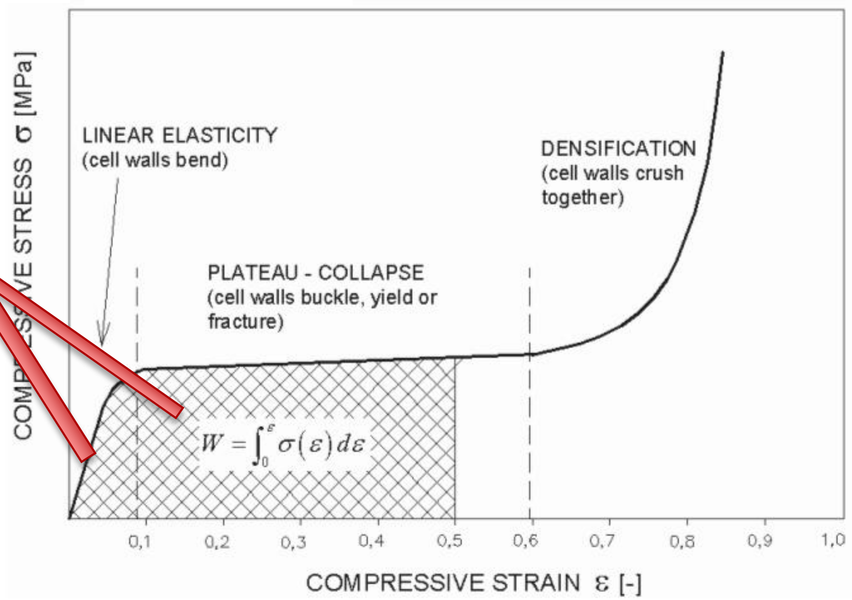






Characteristics and Applications of Foam Materials

- **Light weight (low density)**
  - Good for transportation
- **Excellent vibration damper**
  - Comfort
  - Protection (sensitive devices)
- **Excellent shock/impact energy absorber**
  - Protection (human, sensitive devices, hazard materials, etc)
- **Application-orientated materials design**
  - Material properties, particularly under impact loading
  - Structural response in abnormal (shock/impact) mechanical environments

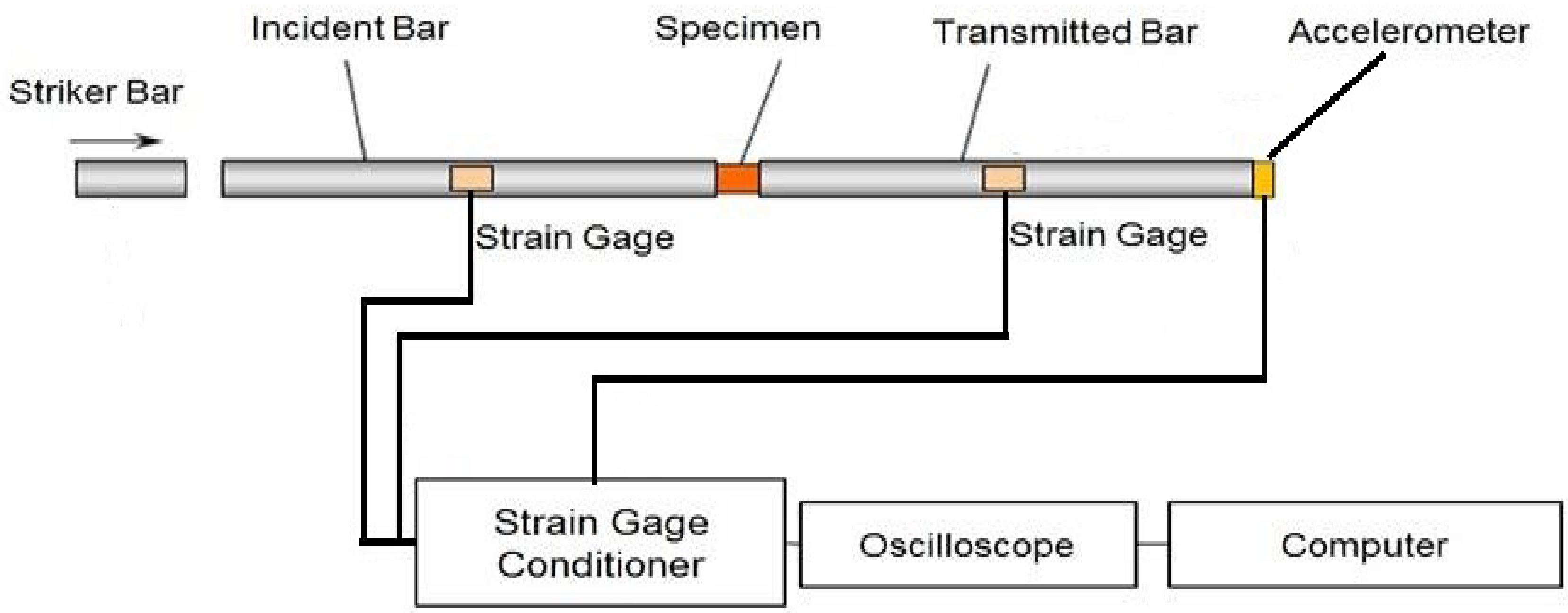


Size/geometry independent

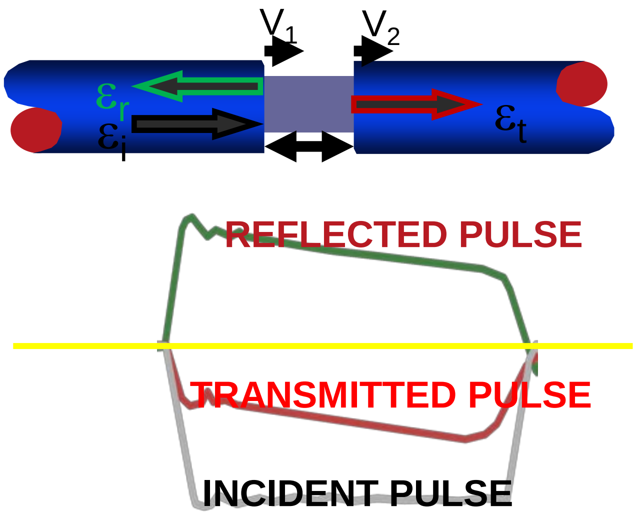
Size/geometry dependent

Shock Mitigation Characterization of Polymeric Foams

- Time- and Frequency-Based Shock Mitigation Analyses



Time-Based Shock Mitigation Analysis



Incident Energy $E_i(t) = A_0 C_0 E_0 \int_0^t \varepsilon_i(t)^2 \, dt$

Reflected Energy $E_r(t) = A_0 C_0 E_0 \int_0^t \varepsilon_r(t)^2 \, dt$

Transmitted Energy $E_t(t) = A_0 C_0 E_0 \int_0^t \varepsilon_t(t)^2 \, dt$

Input Energy

$$E_{input}(t) = E_i(t) - E_r(t) = A_0 C_0 E_0 \int_0^t \left[\varepsilon_i^{\,2}(t) - \varepsilon_r^{\,2}(t)\right] dt$$

Output Energy $E_{output}(t) = E_t(t) = A_0 C_0 E_0 \int_0^t \varepsilon_t(t)^2 \, dt$

Energy Dissipation (Absorbed Energy) $\Delta E(t) = E_{input}(t) - E_{output}(t)$

$$= A_0 C_0 E_0 \int_0^t \left[\varepsilon_i^{\,2}(t) - \varepsilon_r^{\,2}(t) - \varepsilon_t^{\,2}(t)\right] dt$$

Energy Dissipation Ratio

$$\delta(t) = \frac{\Delta E(t)}{E_{input}(t)}$$

Frequency-Based Shock Mitigation Analysis

$$\varepsilon(f) = B(f)e^{-j(2\pi f + \phi)}$$

Incident Energy Spectrum Density $S_i(f) = A_0 C_0 E_0 |B_i(f)|^2$

Reflected Energy Spectrum Density $S_r(f) = A_0 C_0 E_0 |B_r(f)|^2$

Transmitted Energy Spectrum Density $S_t(f) = A_0 C_0 E_0 |B_t(f)|^2$

$$E(f) = \int_f^{f+\Delta f} S(f)df = A_0 C_0 E_0 \int_f^{f+\Delta f} |B(f)|^2 df \approx A_0 C_0 E_0 |B(f)|^2 \Delta f$$

<u>*Parseval's theorem*</u> $E = A_0 C_0 E_0 \int_0^{\infty} \varepsilon(t)^2 dt = A_0 C_0 E_0 \int_{-\infty}^{+\infty} |B(f)|^2 df$

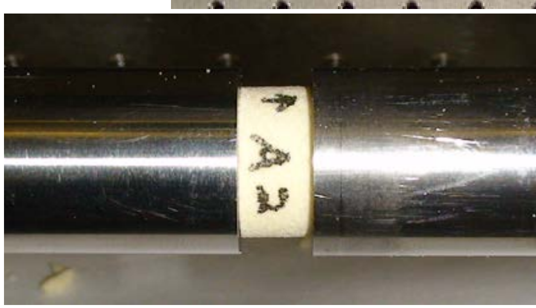
Energy Dissipation (Absorbed Energy) $\Delta(f) = E_i(f) - E_r(f) - E_t(f)$
$= A_0 C_0 E_0 \left(|B_i(f)|^2 - |B_r(f)|^2 - |B_t(f)|^2\right)\Delta f$

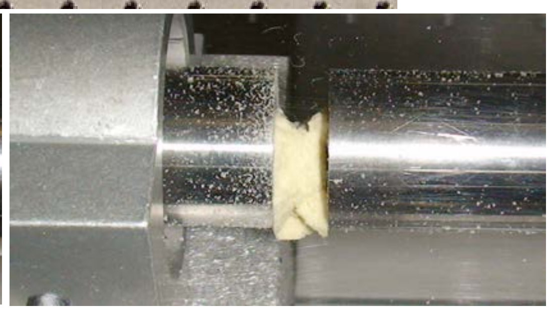
Energy Dissipation Ratio

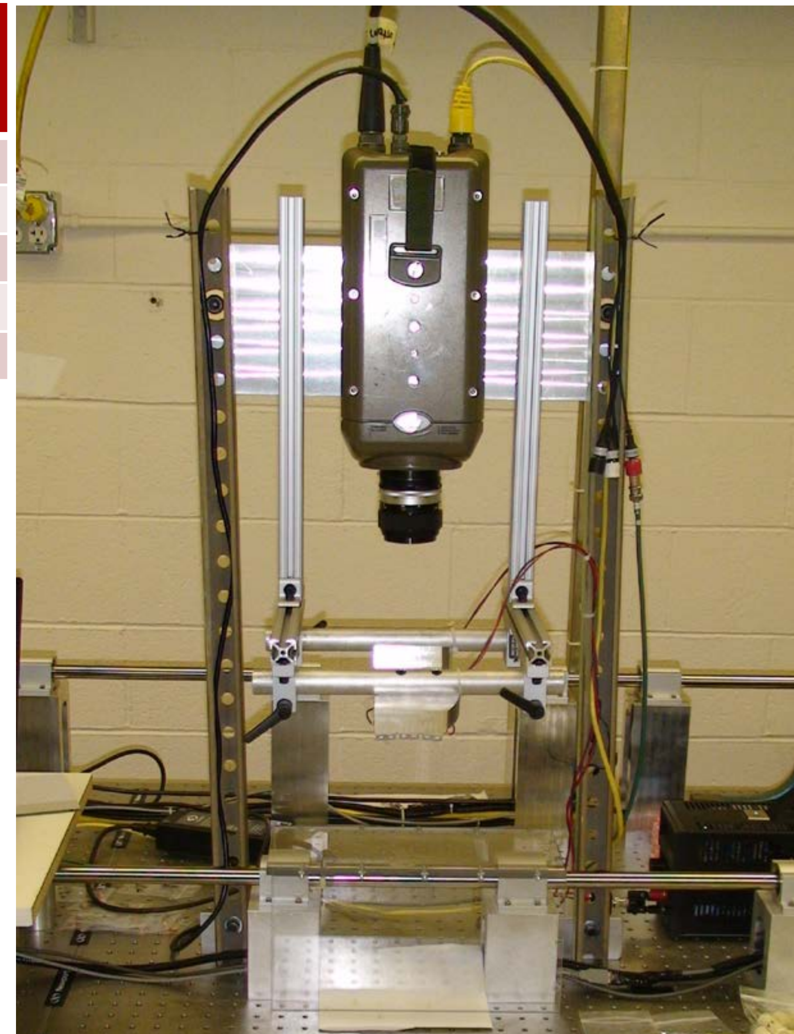
$$\delta(f) = \frac{\Delta(f)}{E_i(f) - E_r(f)} = 1 - \frac{|B_t(f)|^2}{|B_i(f)|^2 - |B_r(f)|^2}$$

Frequency-Based Shock Mitigation Analysis on 20-PCF PMDI Foam

Sample No.	Diameter (mm)	Thicknes s (mm)	Density ($x10^3$ kg/m^3)	Impact Speed (m/s)
B-4	15.3	7.6	0.31	16
B6-1	15.4	7.6	0.31	38
A-3	15.2	15.3	0.34	16
B-5	15.4	15.3	0.31	16
A-6	15.3	30.5	0.32	16

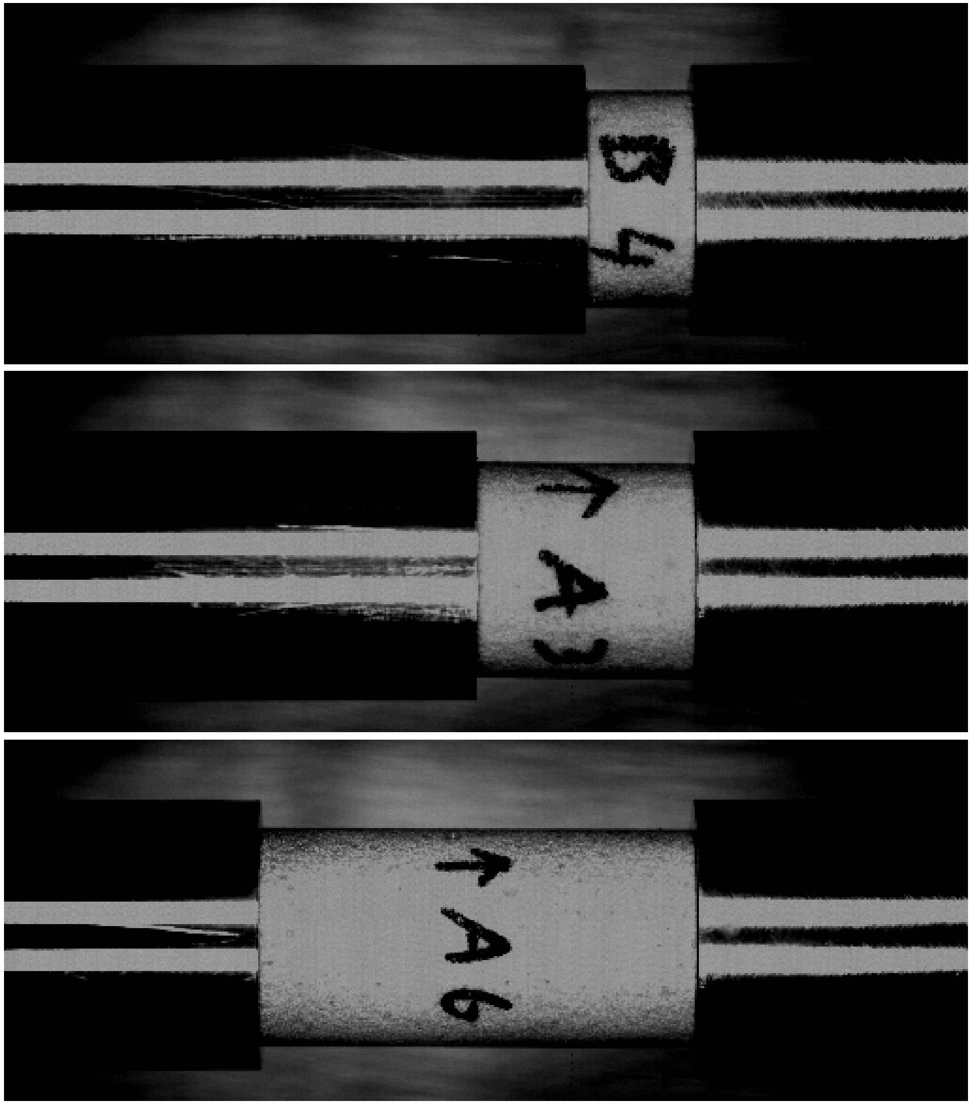




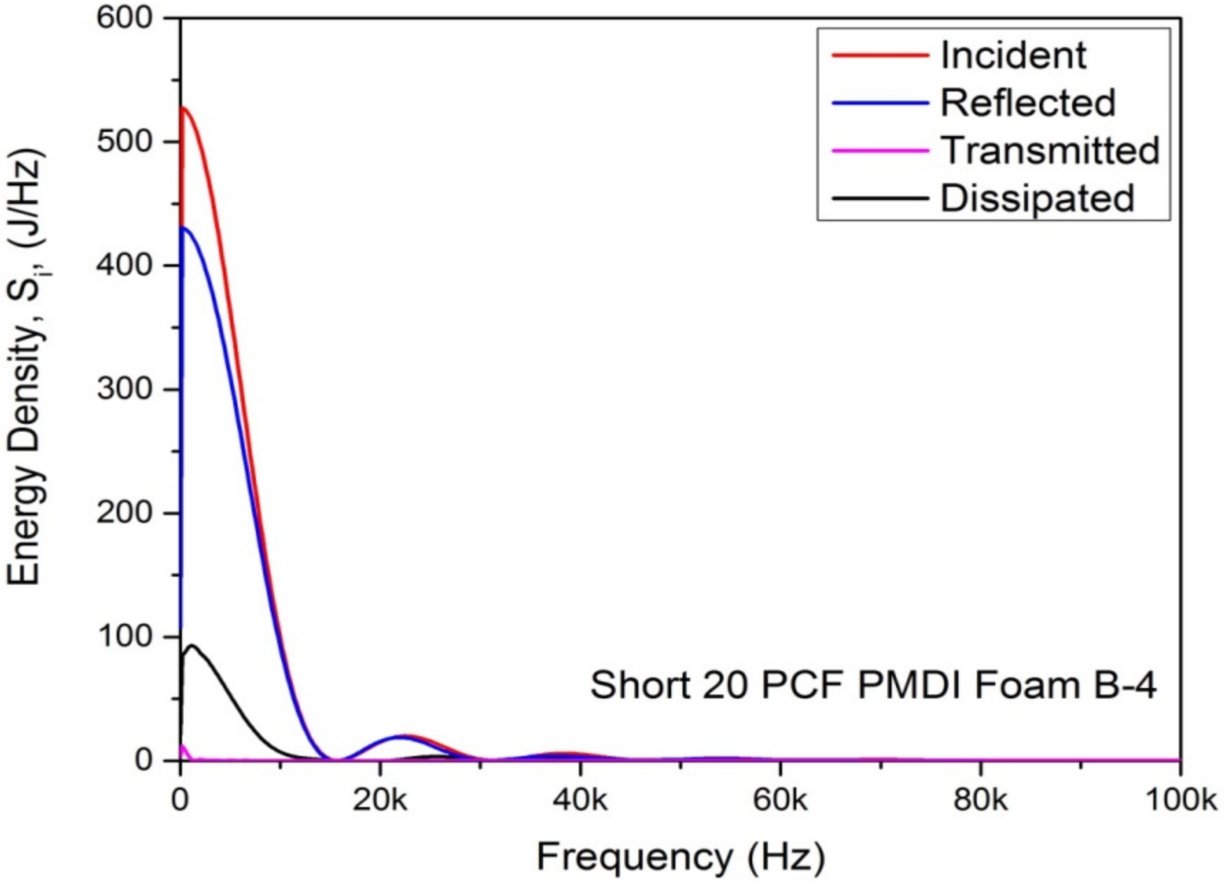


Frequency-Based Shock Mitigation Analysis on 20-PCF PMDI Foam

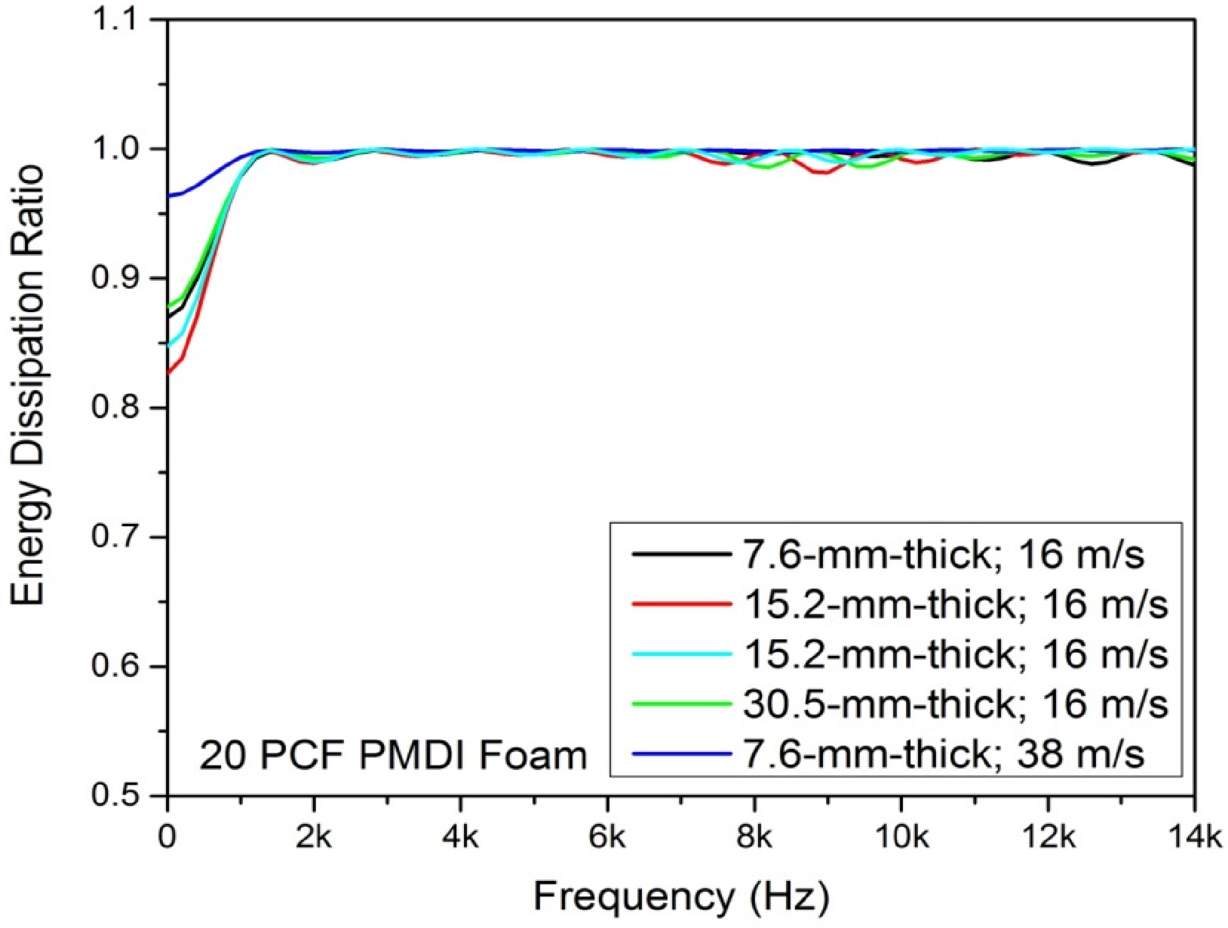
V = 16 m/s



Frequency-Based Shock Mitigation Analysis on 20-PCF PMDI Foam

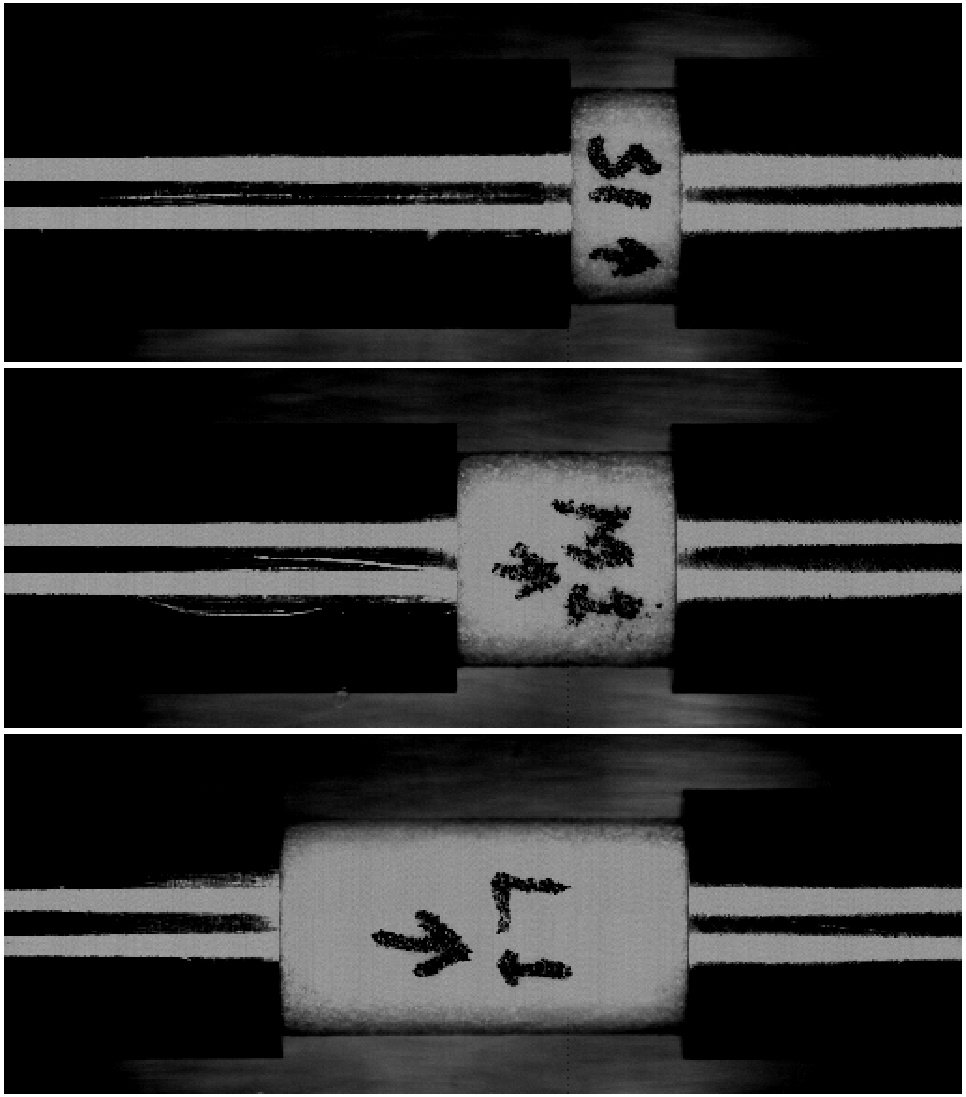


Frequency-Based Shock Mitigation Analysis on 20-PCF PMDI Foam

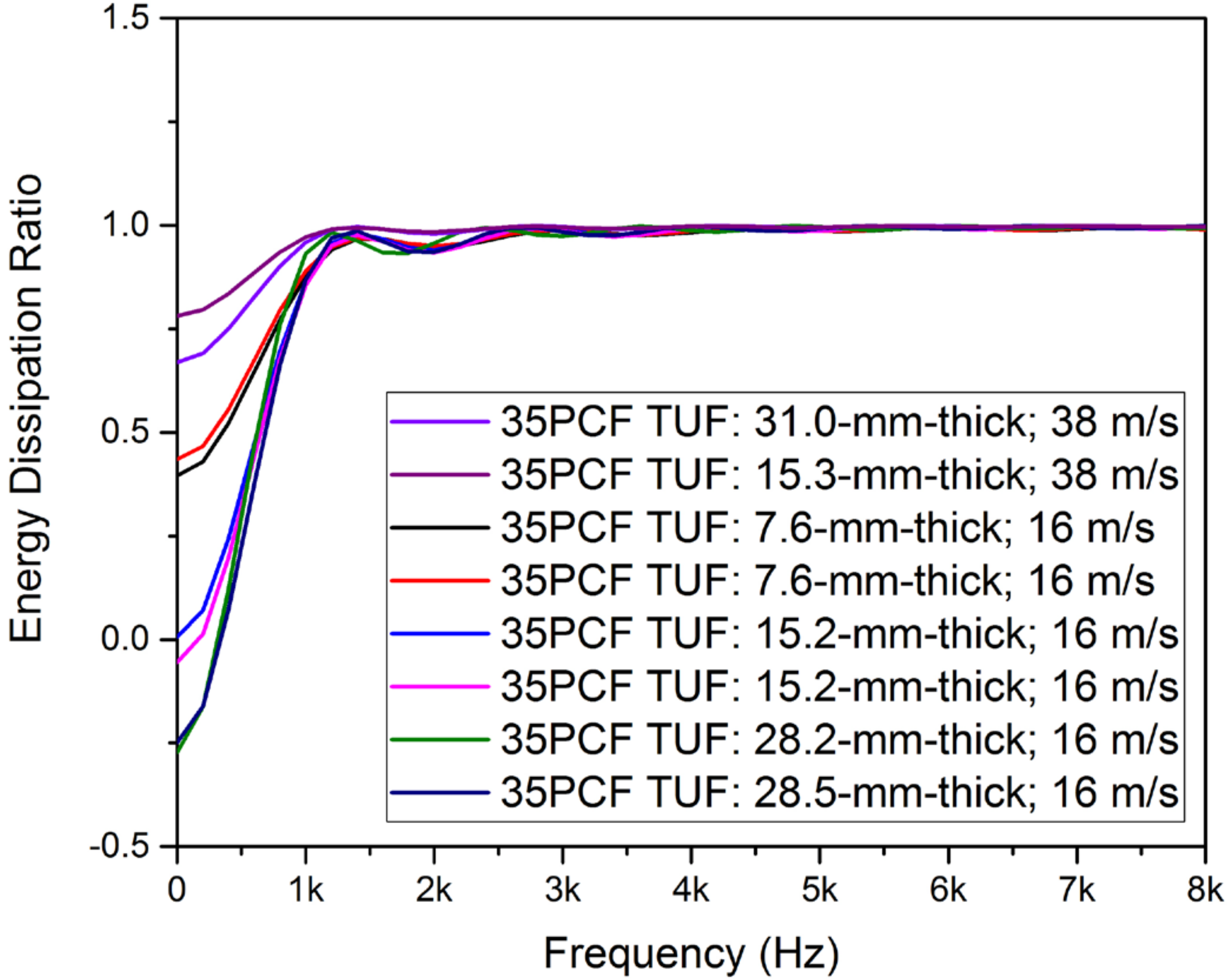


Frequency-Based Shock Mitigation Analysis on 35-PCF Tuf-Foam

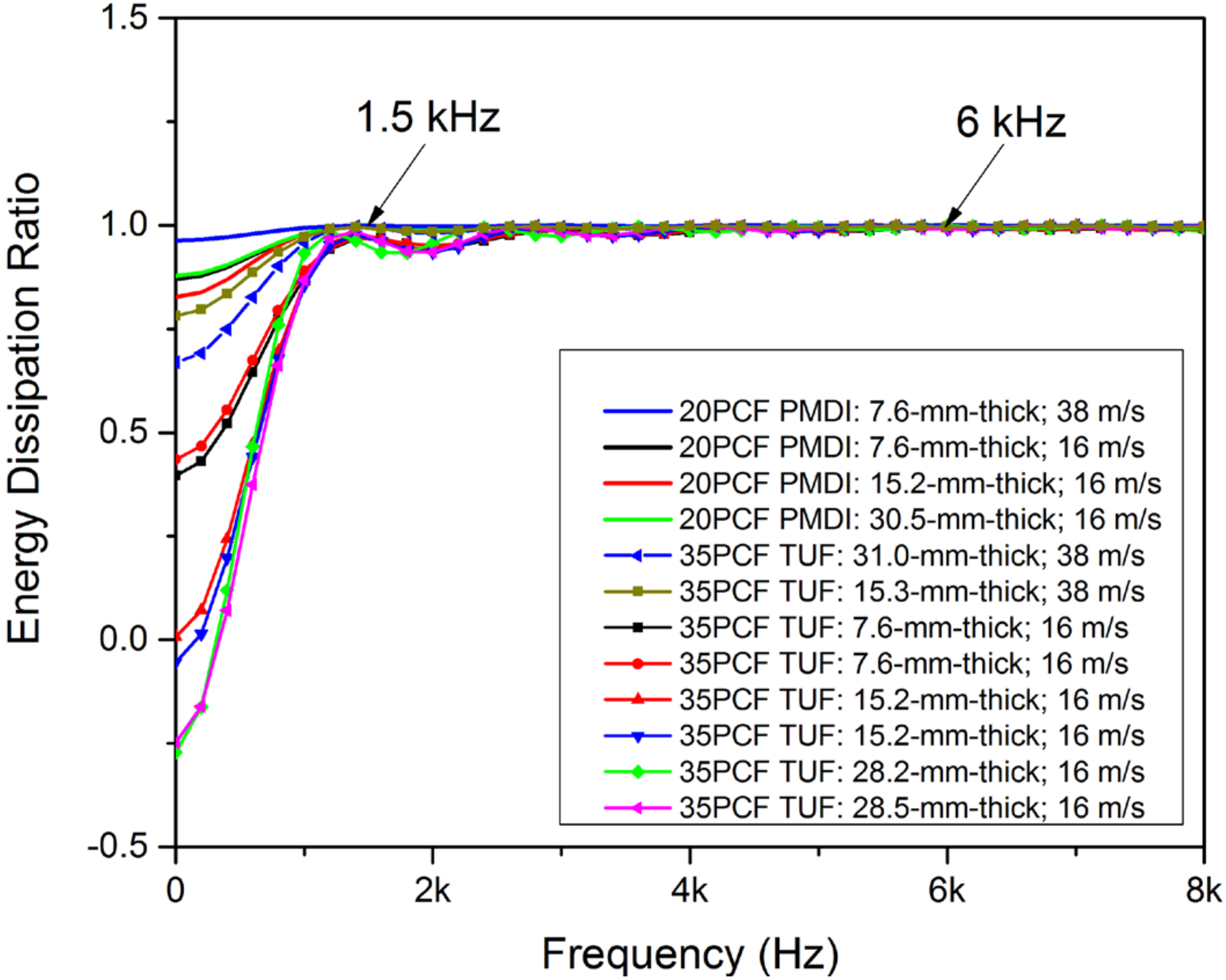
V = 16 m/s



Frequency-Based Shock Mitigation Analysis on 35-PCF Tuf-Foam



Shock Mitigation Comparison between 20-PCF PMDI and 35-PCF Tuf-Foam



Summary

This Presentation

- Frequency-based analysis on shock mitigation characteristics of foam materials
    - Extended to several other shock mitigation/isolation materials and structures

Our Mission

- Develop advanced experimental and diagnostic techniques for scientific discovery
- Provide high-fidelity experimental data on dynamic response of materials and structures for rate-dependent material model development and validation

We are highly motivated and looking forward to any kind of internal and/or external collaboration/partnership, particularly with universities, on fundamental research and applications