87th Shock and Vibration Symposium
New Orleans, LA, October 17-20, 2016
SAND2016-10500C

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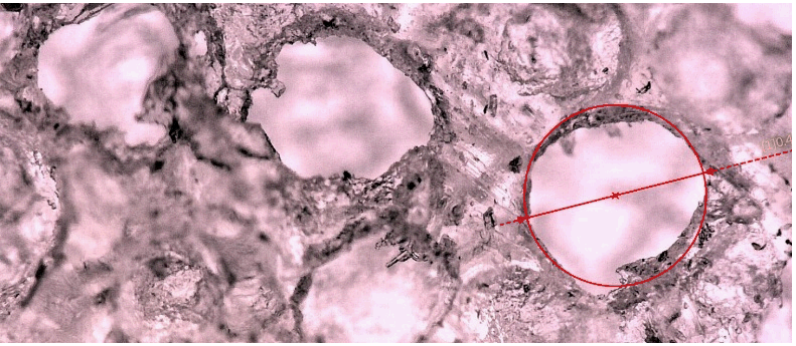

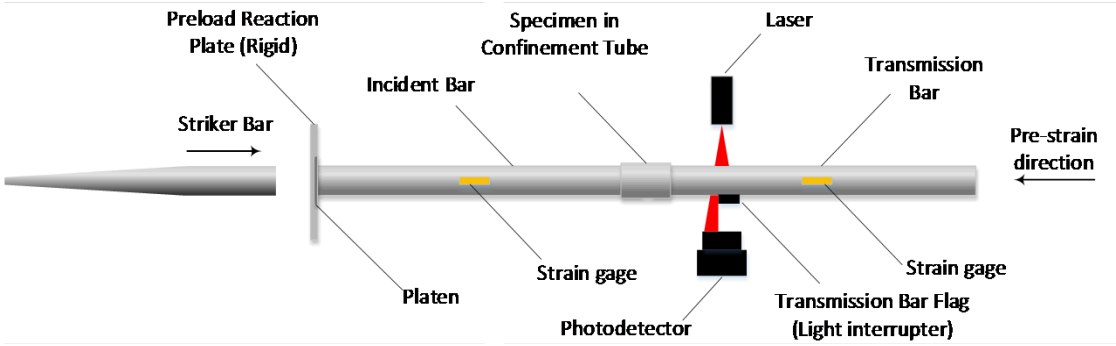

Frequency-based Impact Energy Dissipation in Silicone Foam and Rubber

Brett Sanborn and Bo Song

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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Shock Isolation/Mitigation

- General principle for shock mitigation:

Maximize energy absorption,
Minimize transmitted force and acceleration

- Area under the stress-strain curve prior to densification (**time domain**)
- What about the **frequency-domain**?

- When silicone foam is used as a shock or vibration pad:
  - Stress-state is triaxial
  - Lateral confinement
  - Experiences preloads due to manufacture/assembly process

Shock Isolation/Mitigation

- Foams and rubbers are primary materials used as shock isolators and mitigators
- Foams and rubbers have different properties that affect performance
  - Nonlinear stress-strain response
  - Strain-rate effects
  - Stress-state effects
- Example
  - It might be desirable to completely isolate a battery so that external accelerations, vibrations, and frequencies do not damage the battery
  - No other signals must be passed through the shock isolation material
  - Goal is ***complete isolation*** using Silicone Foam

Vibration isolation:
bus driver seat

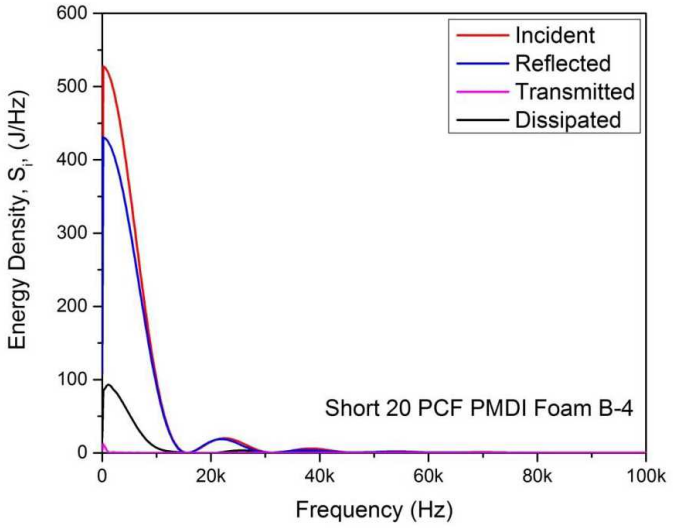


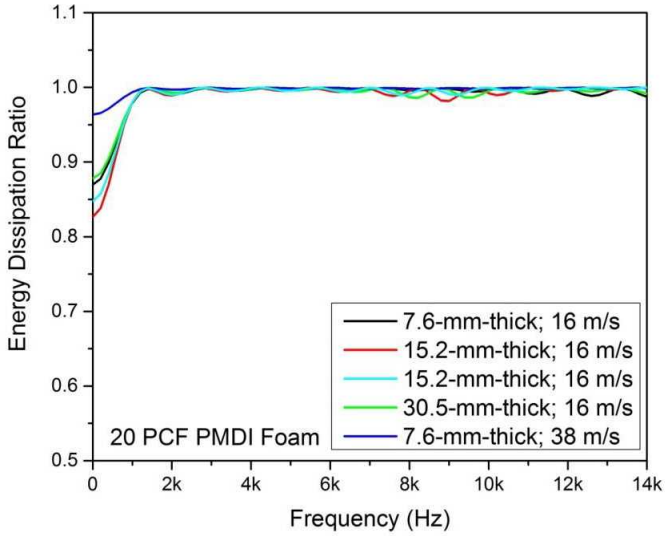
Fig. 1.
Seats selected for use in this study.

Blood et al. Whole body vibration exposures in metropolitan bus drivers: a comparison of three seats. J Sound Vib, 2010

Previous Work

- **B. Song, K. Nelson. (2015) Dynamic Characterization of Frequency Response of Shock Mitigation of a Polymethylene Diisocyanate (PMDI) Based Rigid Polyurethane Foam. *Latin American Journal of Solids and Structures* 12(9):1790-1806**
  - Cutoff frequency was **independent** of **specimen thickness**
  - Cutoff frequency was **dependent** on **impact speed**
  - **Cutoff frequency ~1.5 kHz**
    - **Above 1.5 kHz, almost 100% of the energy was dissipated**
    - **Below 1.5 kHz, dissipation was down to ~83%**
  - **PMDI foam is a good shock mitigation material**

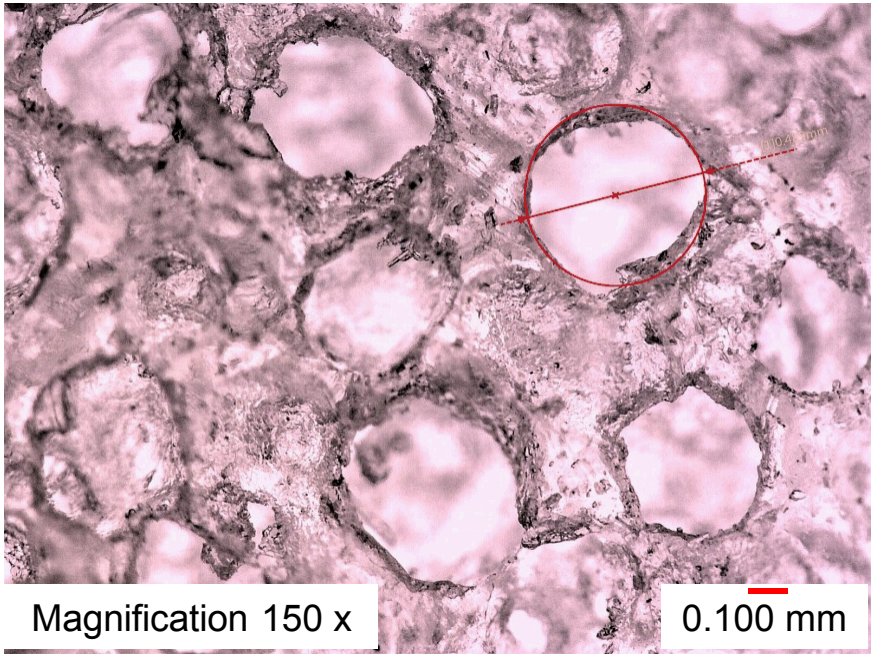


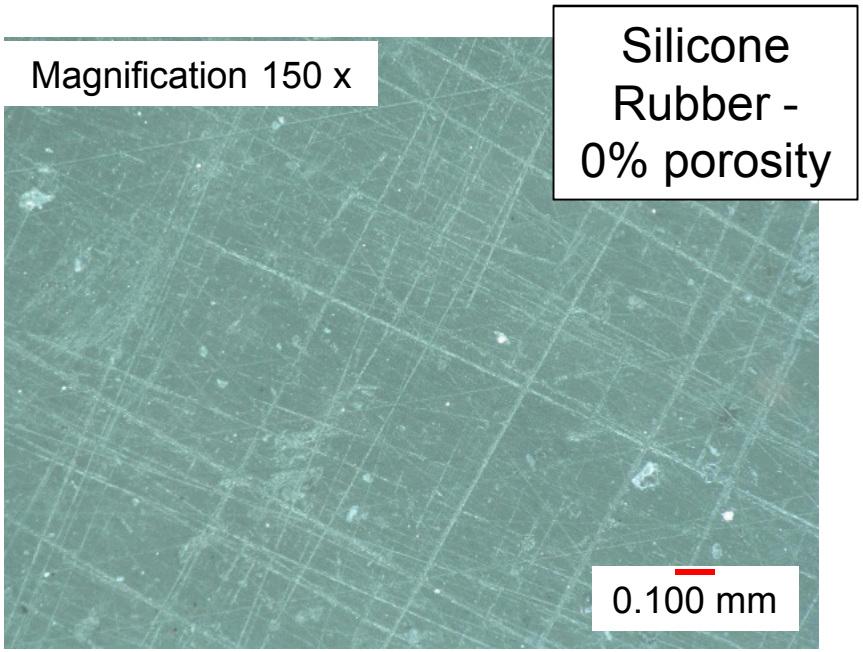


Material

- **Silicone foam**
- Open Cell
- **Density**: 608 ± 21.85 kg/m^3
- **Diameter**: 25.37 ± 0.08 mm to match bars
- **Thickness**: 5.33 ± 0.006 mm
- Average cell size: ~0.5 mm

- **Silicone Rubber**
- Solid Rubber (no cells)
- **Density**: 1153 kg/m^3
- **Diameter**: 25.37 ± 0.08 mm
- **Thickness**: 1.93 mm





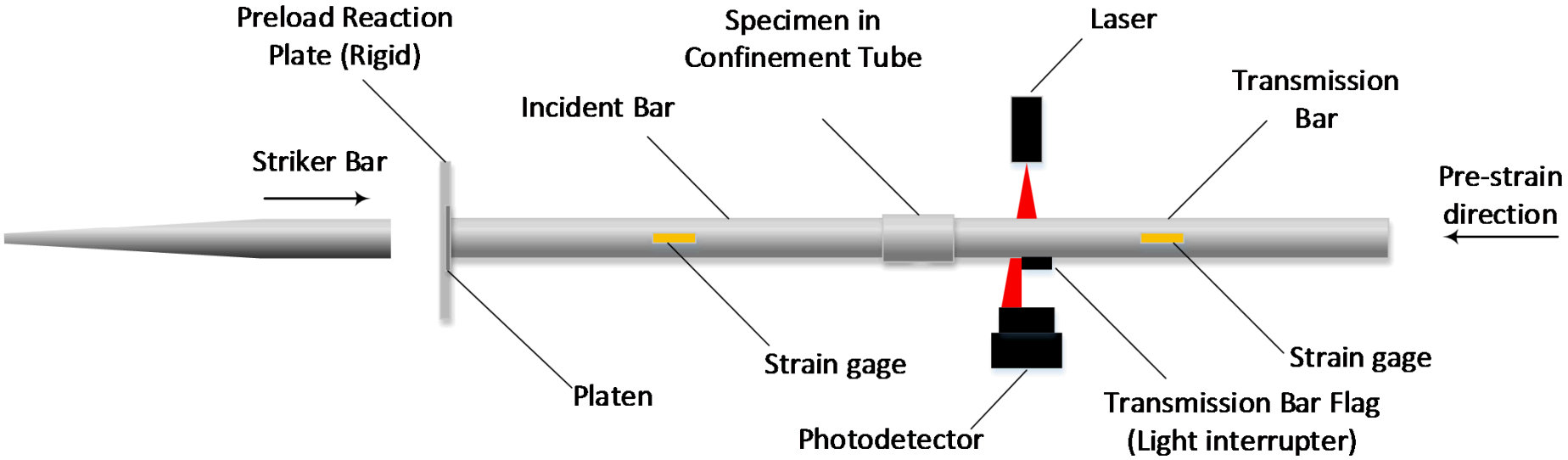
Experimental Plan

- Silicone Foam was subjected to different levels of pre-strain at two impact speeds
- Silicone Rubber was not pre-strained but was subjected to three impact speeds

Material	Density (kg/m^3)	Diameter (mm)	Thickness (mm)	Applied Pre-Strain (%)	Impact Speed (m/s)
Silicone Foam	608 ± 21.85	25.37 ± 0.08	5.25	0, 13, 23.3, 33.5	5.6, 12.8
Silicone Rubber	1153	25.37 ± 0.08	1.93	0	5.6, 12.8, 22.4

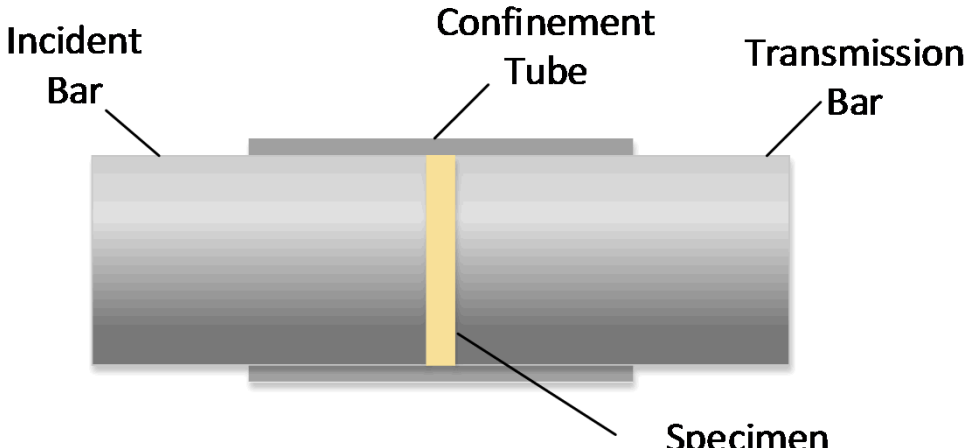
Kolsky Compression Bar with Pre-load Capability

- Kolsky compression bar with passive confinement tube
- Pre-strain is applied to the specimen via the transmission bar
- Laser is used to measure displacement during pre-straining



Confinement Tube

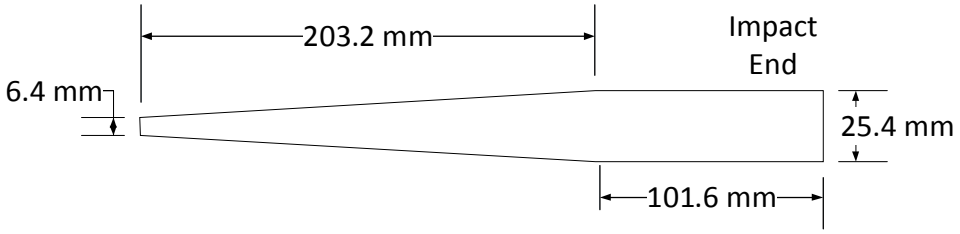
- Silicone foam specimen is held under passive confinement
- Tube material is 4340 steel
- Force generated during pre-strain at the highest level is ~50 N

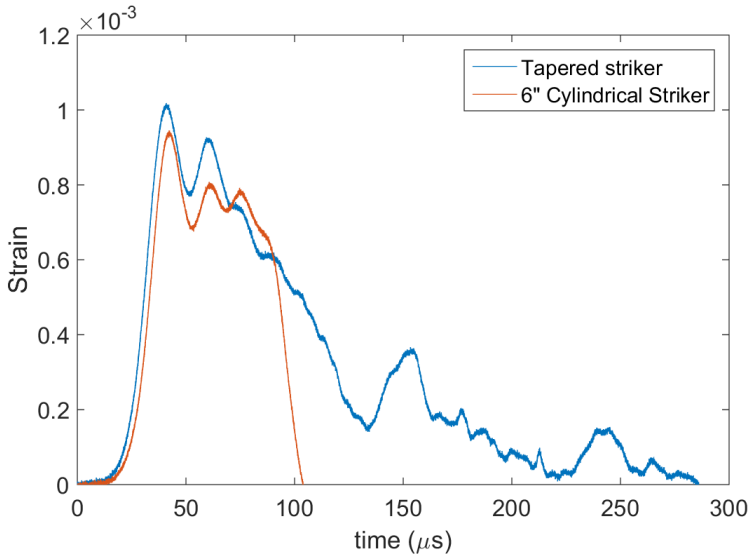


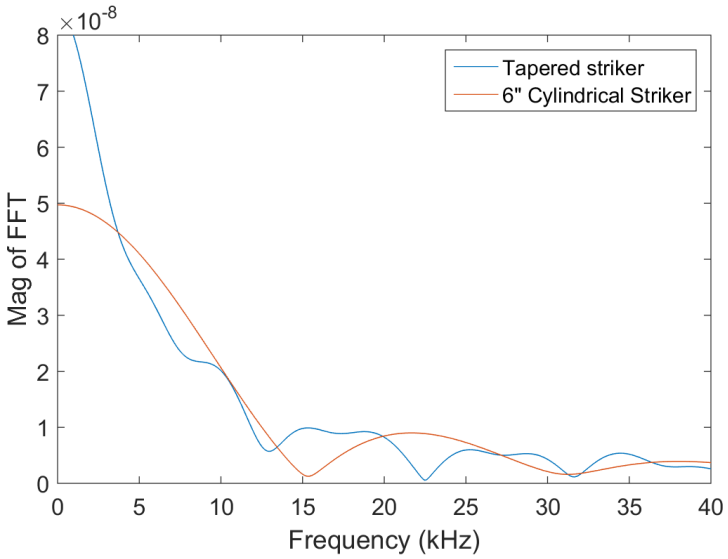
Confinement Tube Cutaway

Tapered Tungsten Striker

- Tapered striker was used to increase the range of frequency content
- Taper + impedance mismatch causes long unloading tail
- Increases the maximum frequency content from 15 to 23 kHz
- No pulse shaper or grease was used







Frequency Domain Energy Dissipation

- Time domain bar strain signals have the Fourier transform

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

- $B(f)$, f, and ϕ are the magnitude, frequency, and phase of the Fourier transform
- The energy spectrum density for each signal is

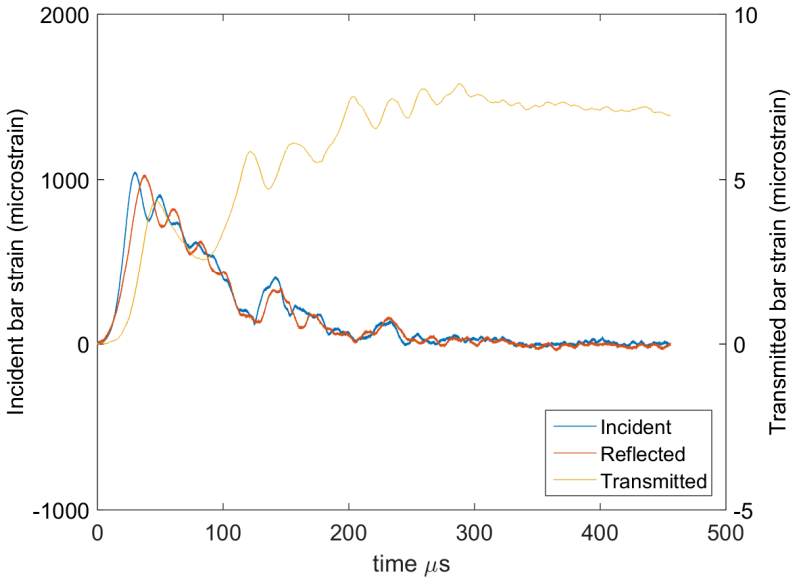
$$S_i(f) = A_0C_0E_0|B_i(f)|^2 \qquad S_r(f) = A_0C_0E_0|B_r(f)|^2 \qquad S_t(f) = A_0C_0E_0|B_t(f)|^2$$

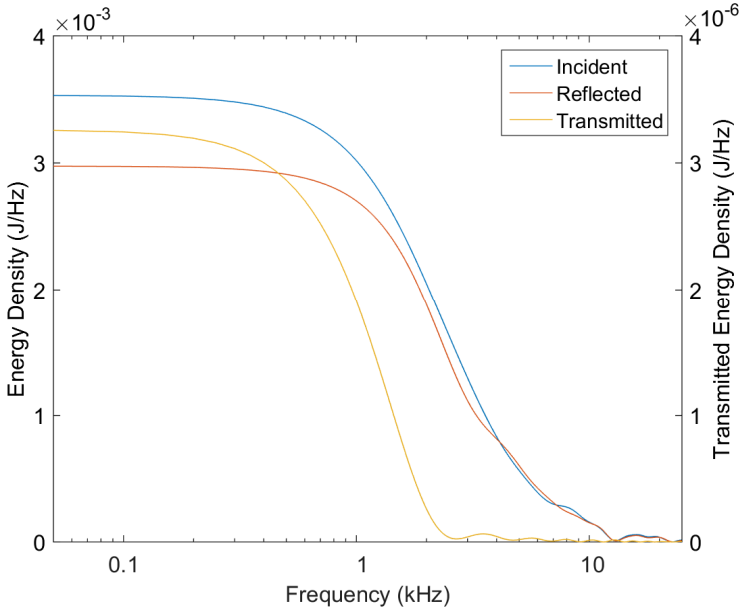
- Energy dissipation ratio as a function of frequency is

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

Experimental Results

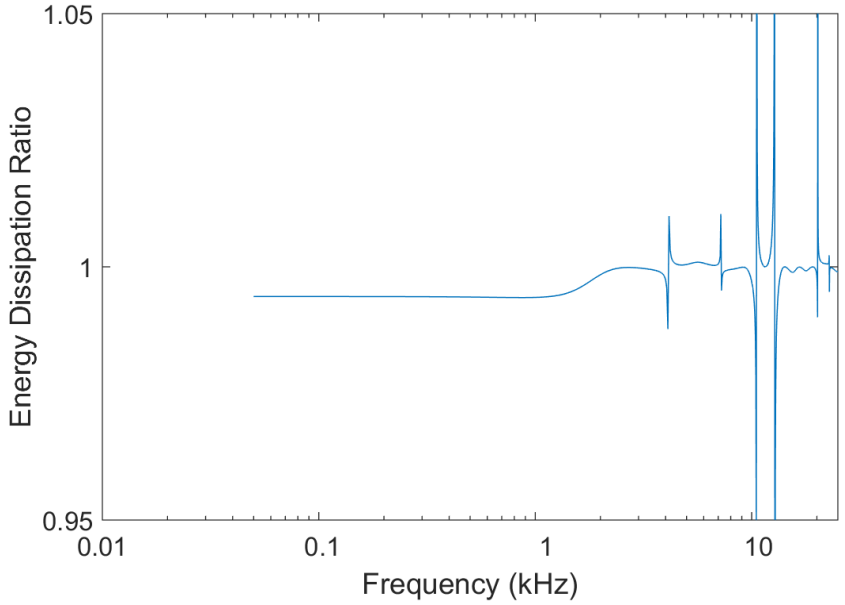
- Time-domain strain histories
  - Strain history is taken out until pulse overlap occurs on the transmission bar
  - Transmitted pulse does not decrease because the foam is not stiff enough to push the bars back
- Frequency-domain energy behavior
  - Reflected energy is higher at 4-7 kHz => discontinuities in energy dissipation ratio
  - What causes this? Frequency shift?

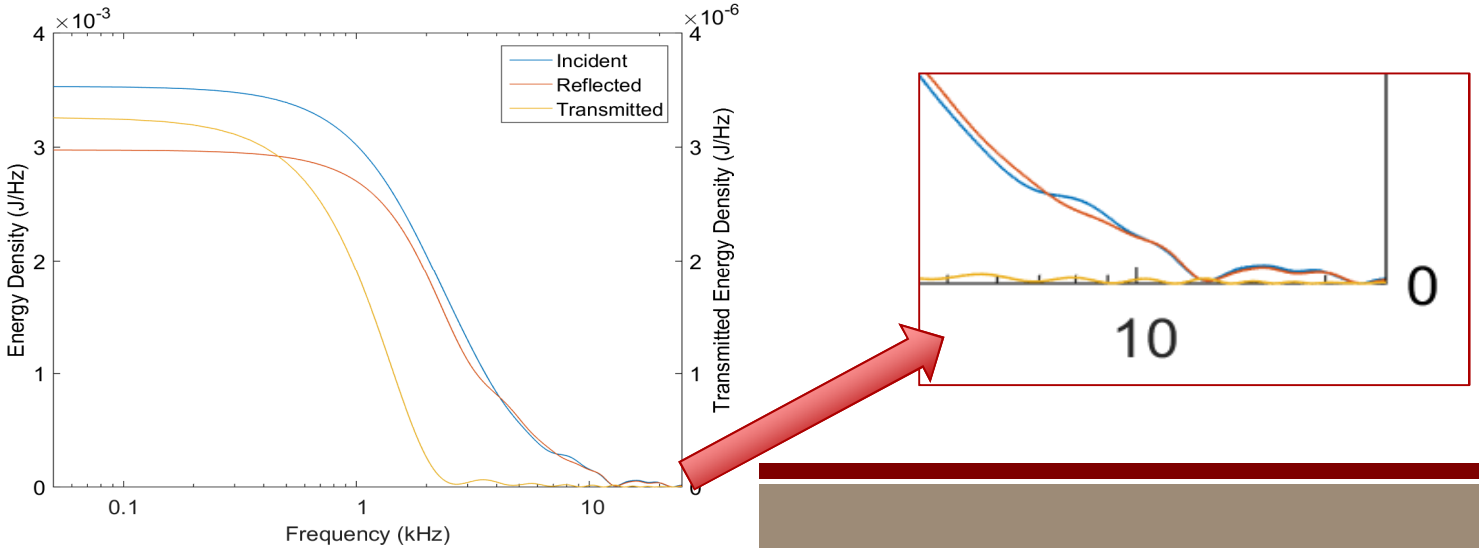




Energy Dissipation Ratio

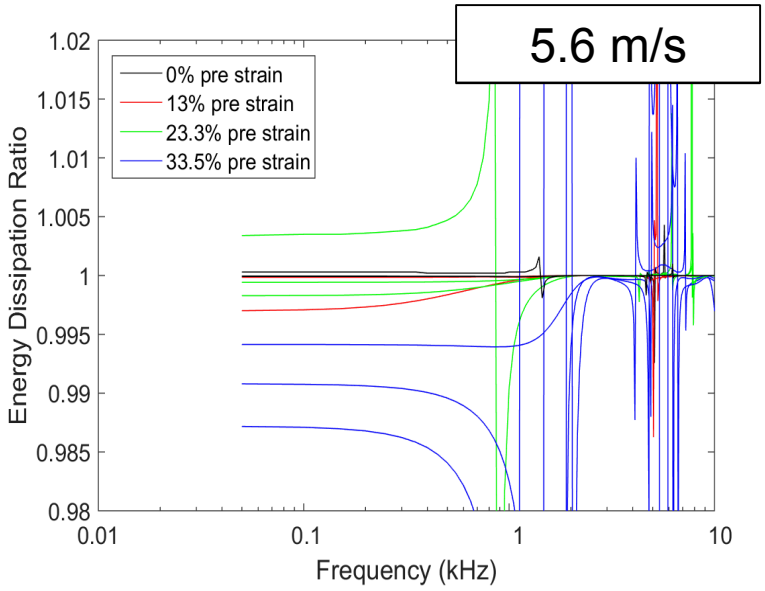
- Energy Dissipation Ratio
  - Silicone Foam sample pre-strained to 33.5%
  - Initial energy dissipation ratio was 0.995
  - Cutoff frequency of 2.65 kHz
  - After the cutoff frequency, energy dissipation stabilizes at nearly 1 (total dissipation)

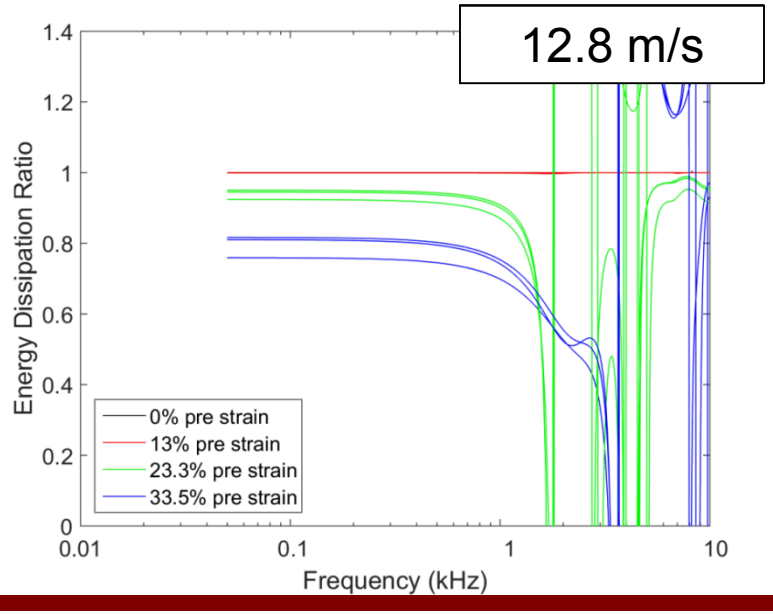




Dissipation as a function of impact speed and pre-strain

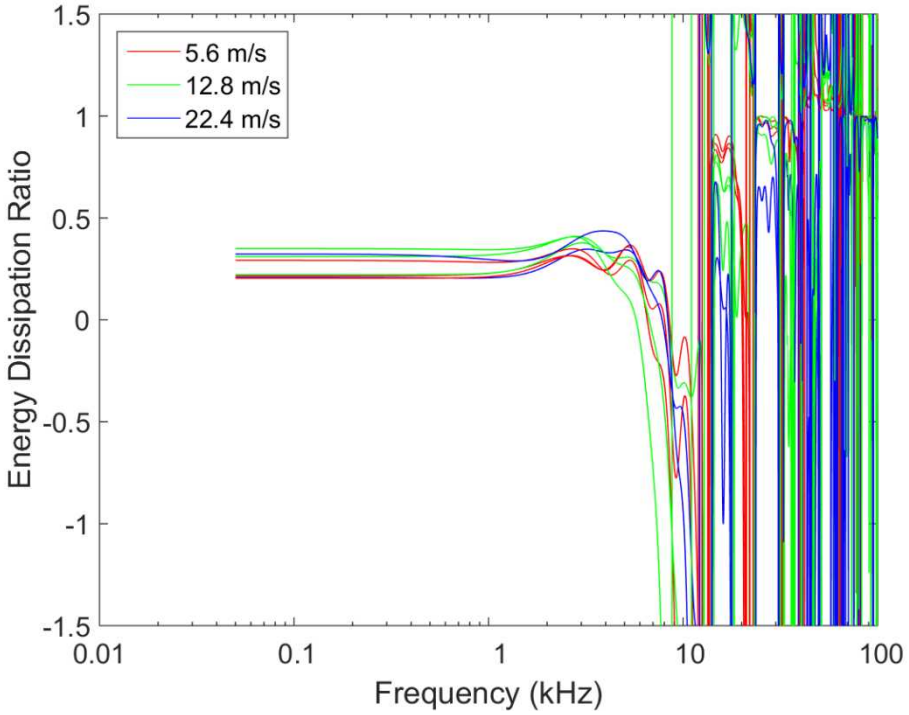
- 5.6 m/s - energy dissipation may depend on pre-strain
  - More than 98% of energy was dissipated by the foam
- 12.8 m/s – with increasing pre-strain, less energy is dissipated at higher pre-strain
- For 0 and 13% pre-strain, nearly 100% of energy is dissipated at 12.8 m/s





Energy Dissipation Through Silicone rubber

- Energy dissipation was lower than all experiments on foam

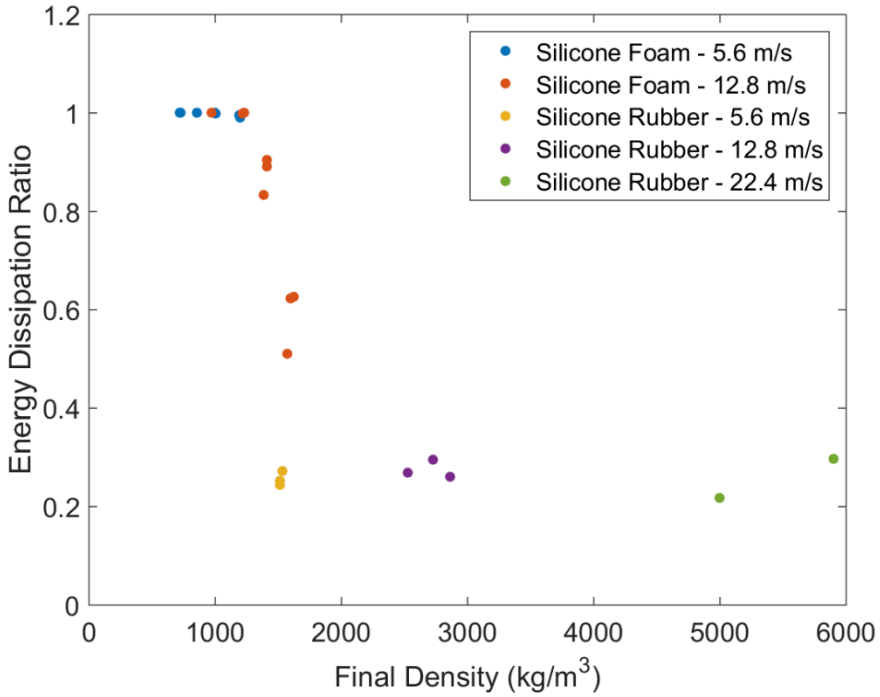


Possible Mechanism

- Calculated the final density of the specimen at the end of dynamic loading

$$\rho_{final} = \frac{l_0 * \rho_0}{(l_0 - l)}$$

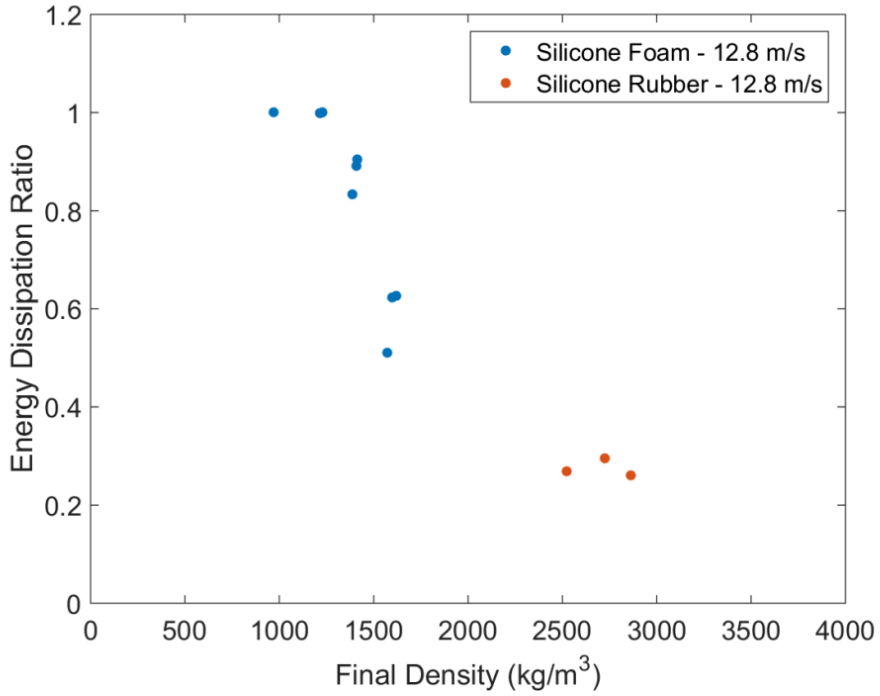
ρ_0 = initial density
l_0 = gage length
l = deformed length
=> static + dynamic



- Critical density between 1200-1400 kg/m^3 at which the energy dissipation ratio drops off
- A lower bound of 0.25 dissipation ratio is apparent

Effect at Single Impact Velocity

- Plot of single impact speed
- Cutoff density
- Saturated dissipation ratio



Conclusions

- Kolsky compression bar used to characterize silicone foam and rubber in the frequency domain
- Tapered tungsten striker was used to extend the maximum frequency applied to the sample
- Different levels of pre-strain was applied to silicone foam to mimic assembly in components
- Silicone rubber was used to investigate possible differences in energy dissipation behavior
- Silicone foam impacted at 12.8 m/s and pre-strained to 0 and 13% dissipated 99.5% of impact energy. As pre-strain increased, energy dissipation ratio decreased
- Silicone rubber did not show an effect of impact speed on energy dissipation behavior
- As the final density of the specimen increased to a threshold of approximately 1200-1400 kg/m^3, the energy dissipation ratio decreased to a plateau value of approximately 0.25.
- Future work includes subjecting silicone foam to higher pre-strains to investigate the cutoff density effect