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Impact Mechanical Response and Shock/Impact Mitigation of Polymeric Foam Materials

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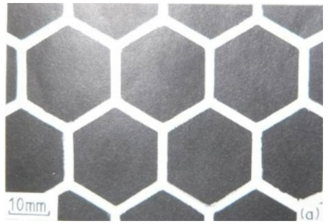
Outline

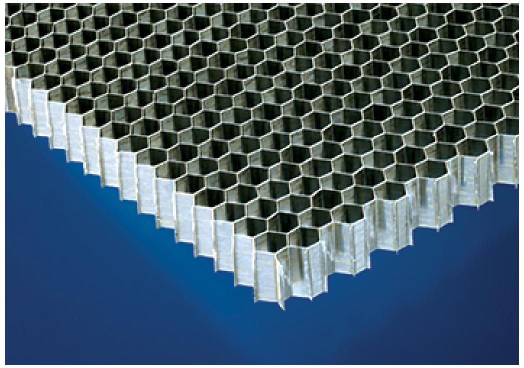
- **Background**
- **Impact Response of Polymeric Foams**
  - Dynamic Experimental Techniques
  - Experimental Results of Various Polymeric Foams
- **Shock/Impact Mitigation Characterization of Polymeric Foams**
  - Experiments
  - Energy Dissipation
- **Summary**

Cellular and Foam Materials

Cellular Materials

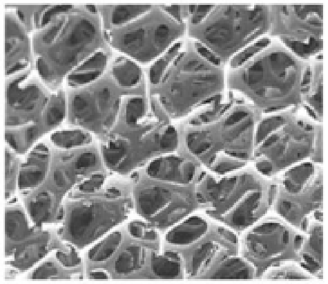
Honeycombs (2D)



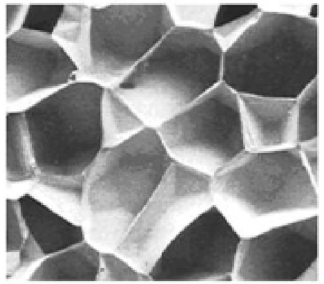


Foams (3D)

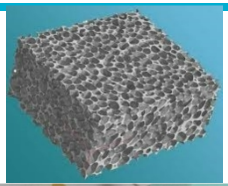
Open Cell



Closed Cell

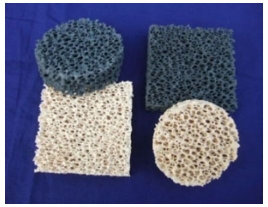


Metallic Foams



Polymeric Foams

Others
(Glass Foam, Ceramic Foam, Cement Foam, etc)



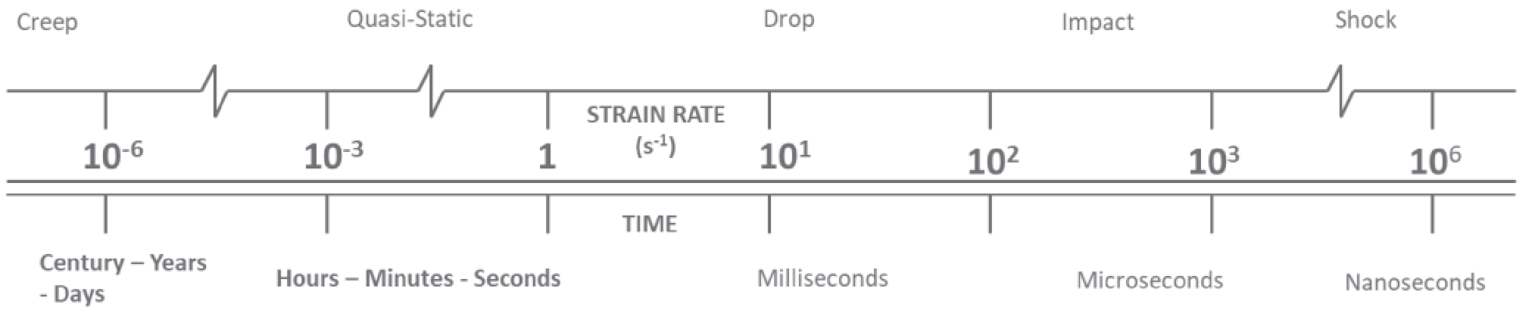
Elastomeric (hyperelastic) Foams — Silicone Foam

Elastic-plastic Foams — Epoxy, Polystyrene, Polyurethane -based Foams (TDI, PMDI, Tuf-Foam)

Elastic-brittle Foams — Syntactic Foam (i.e., with glass microballoons)

Gibson and Ashby, 1997, Cellular Solids: Structure and Properties, 2nd Ed., Cambridge

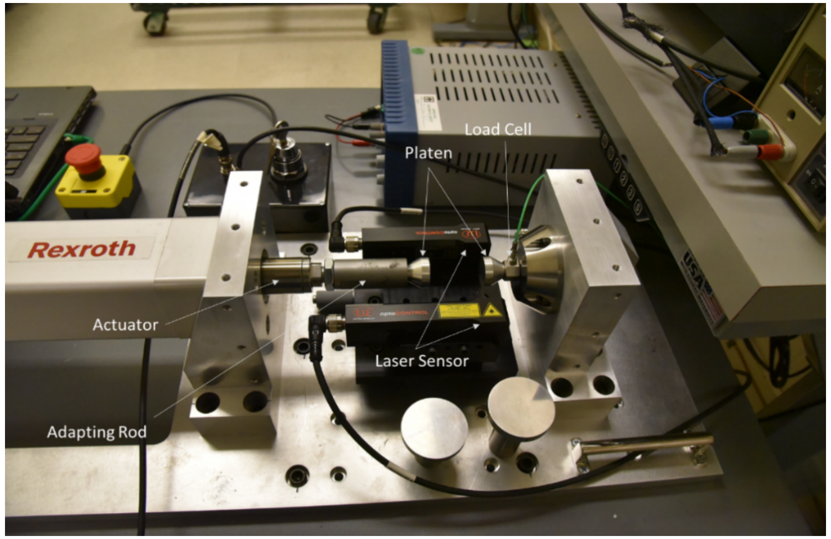
Dynamic Experimental Techniques



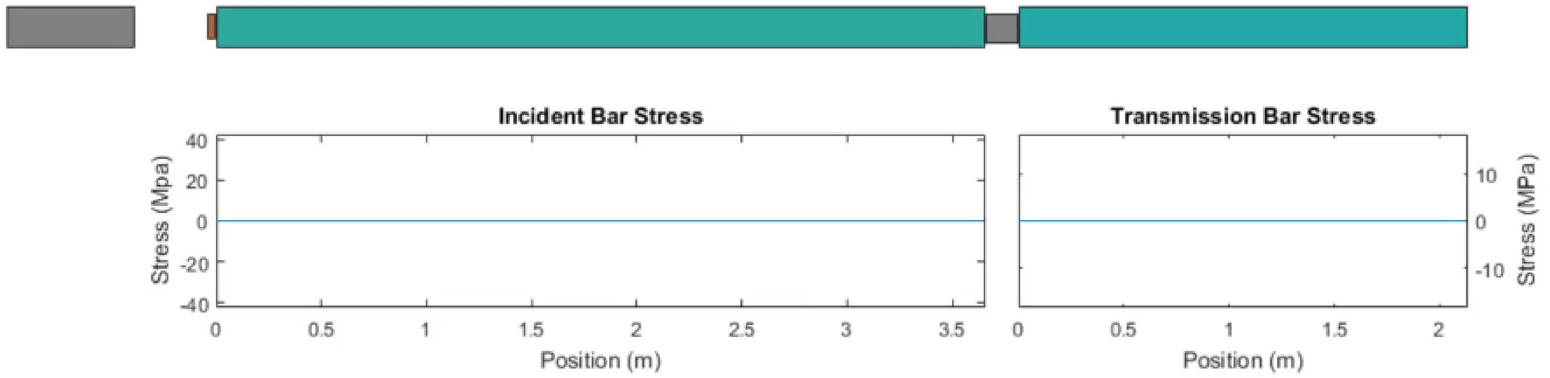
Intermediate-Rate Actuator

Kolsky Bar (a.k.a. Split Hopkinson Bar)

Gas Gun (plate impact)



Kolsky Bar (Split Hopkinson Bar)



$$\dot{\varepsilon} = \frac{V_1 - V_2}{l_s} = \frac{C_0}{l_s}(\varepsilon_i - \varepsilon_r - \varepsilon_t)$$

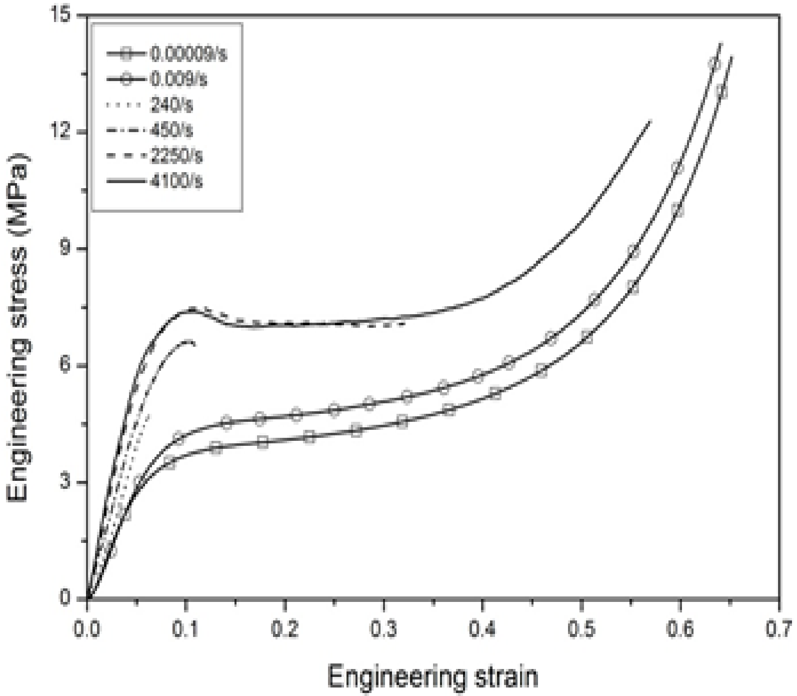
$$\varepsilon = \int_0^t \dot{\varepsilon}(\tau)\, d\tau$$

$$\sigma = \frac{F_1 + F_2}{2A_s} = \frac{E_0 A_0}{2A_s}(\varepsilon_i + \varepsilon_r + \varepsilon_t)$$

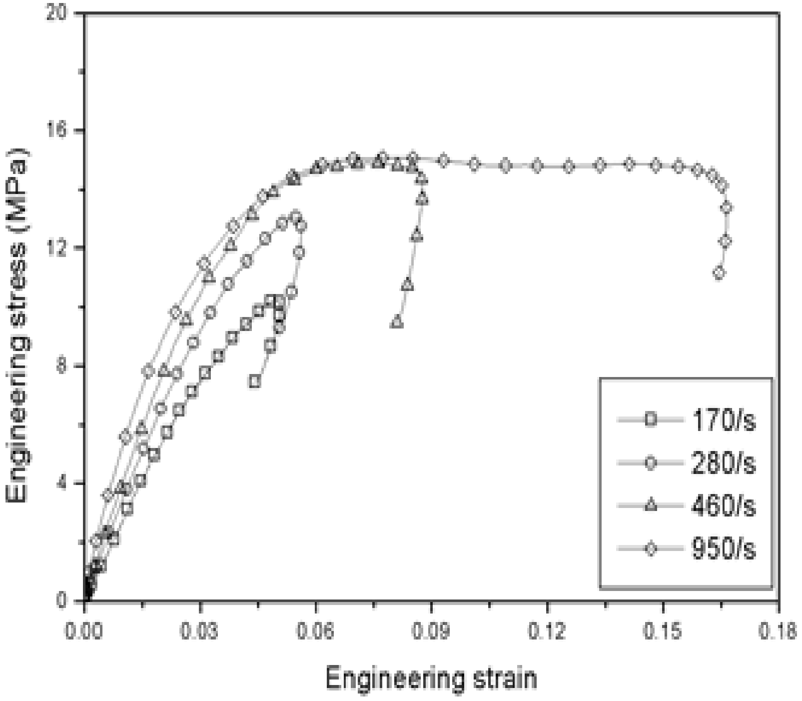
$$\sigma \sim \varepsilon$$

Dynamic Stress-Strain Response of Elastic-Plastic Foam Materials

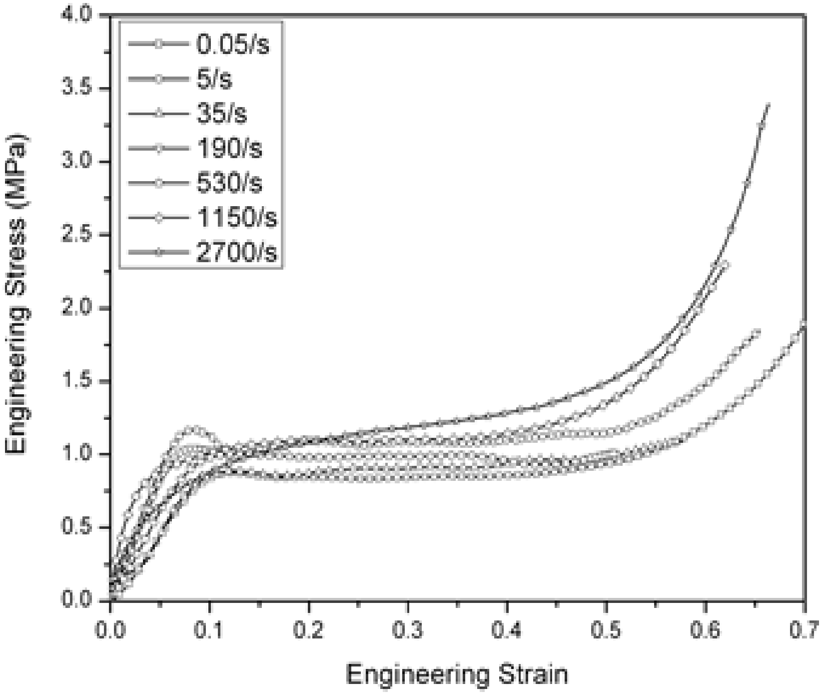
Polyurethane Foam (0.24×10^3 kg/m^3)



Polystyrene Foam (0.40×10^3 kg/m^3)

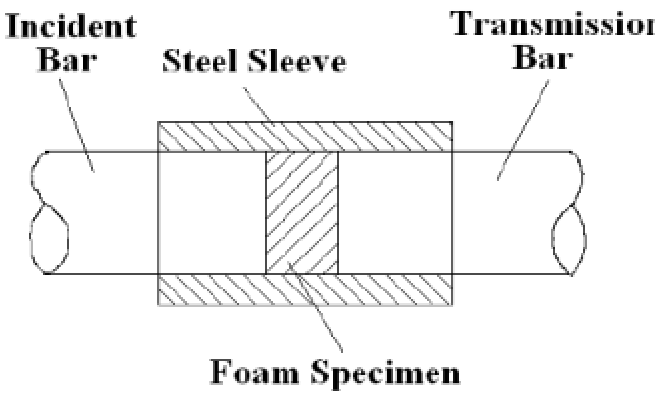


Epoxy Foam (0.12×10^3 kg/m^3)

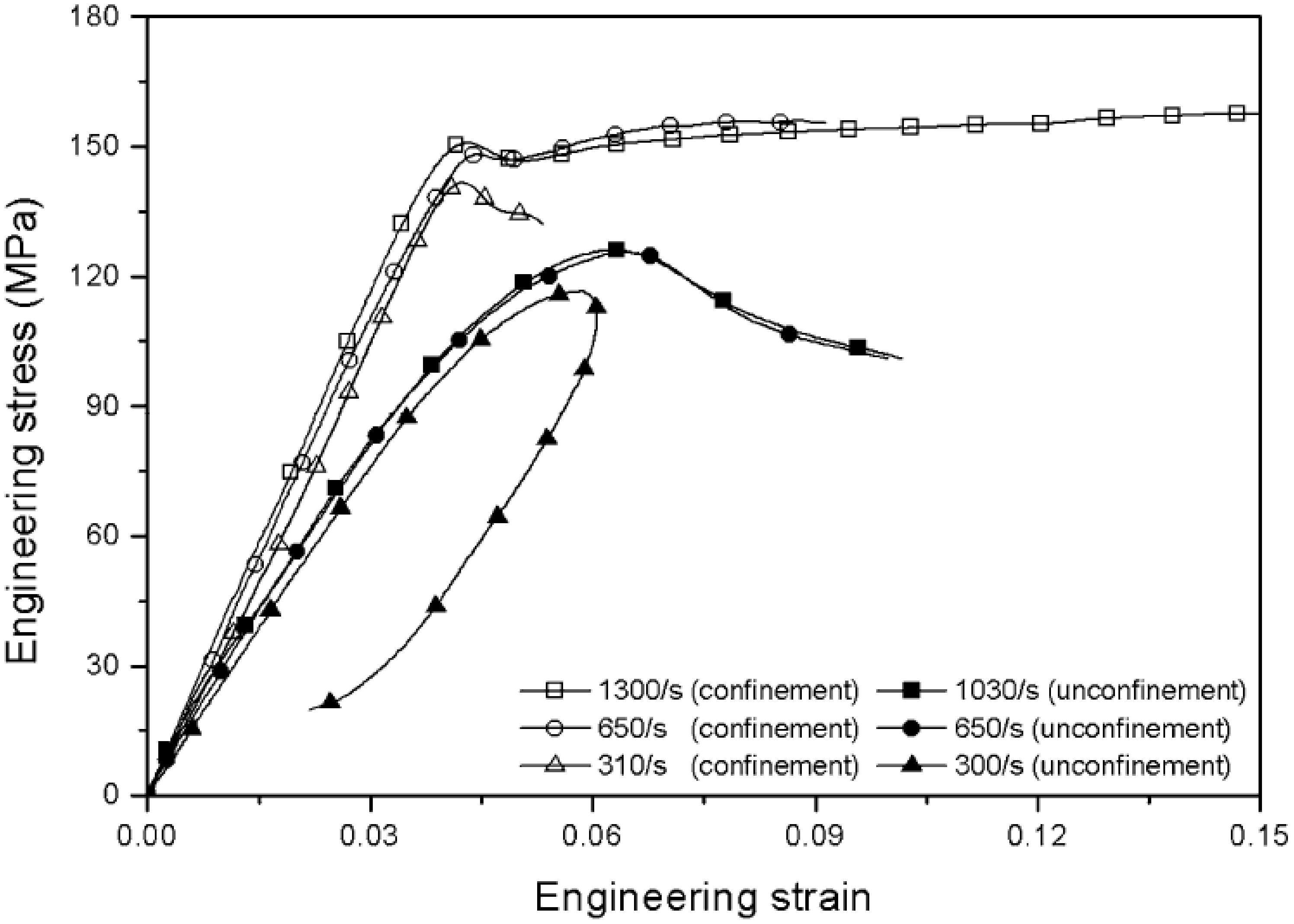


The stress-strain response depends on density, temperature, stress state, etc.

Dynamic Stress-Strain Response of Elastic-Brittle Foam Materials

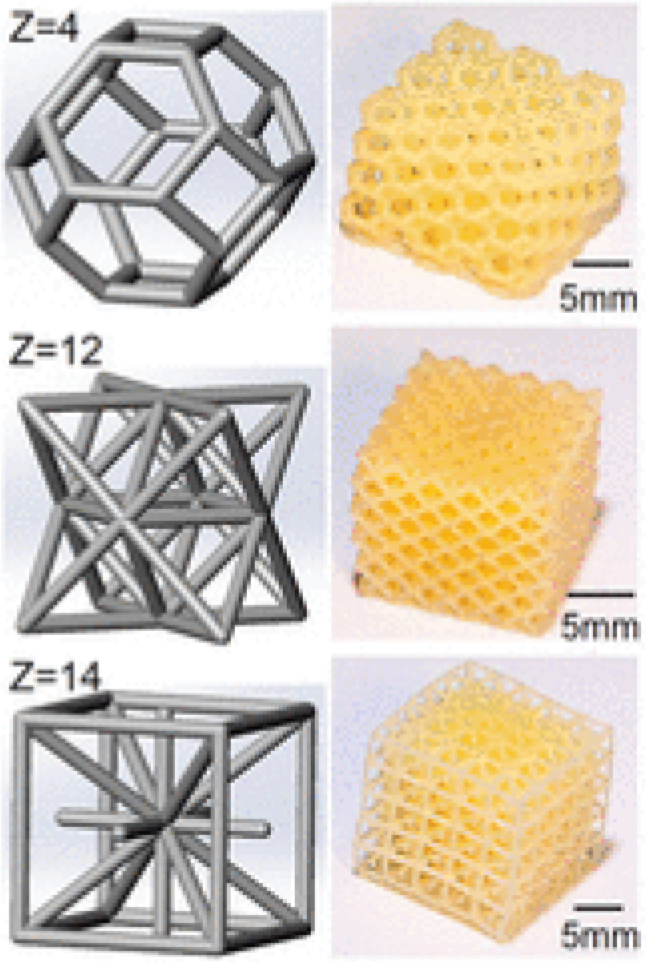


Unconfined versus Confined



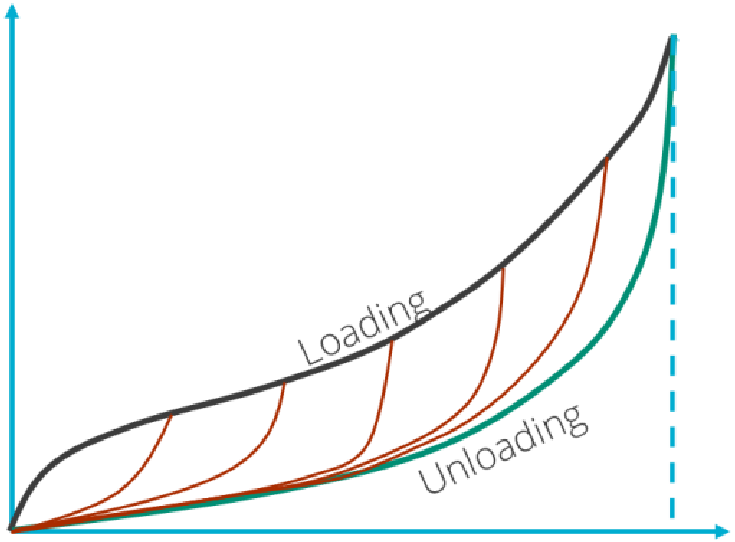
Dynamic Stress-Strain Response of Hyperelastic Foam Materials

Liquid Crystal Elastomer (LCE) Lattice Foam



It has been very challenging to dynamically characterize such soft lattice foam materials at high strain rates with a Kolsky compression bar, due to relatively large (long) specimen size and low wave speed.

Kolsky compression bar is also not able to be used to characterize the unloading stress-strain response for such soft materials, which is critical for energy dissipation calculation.



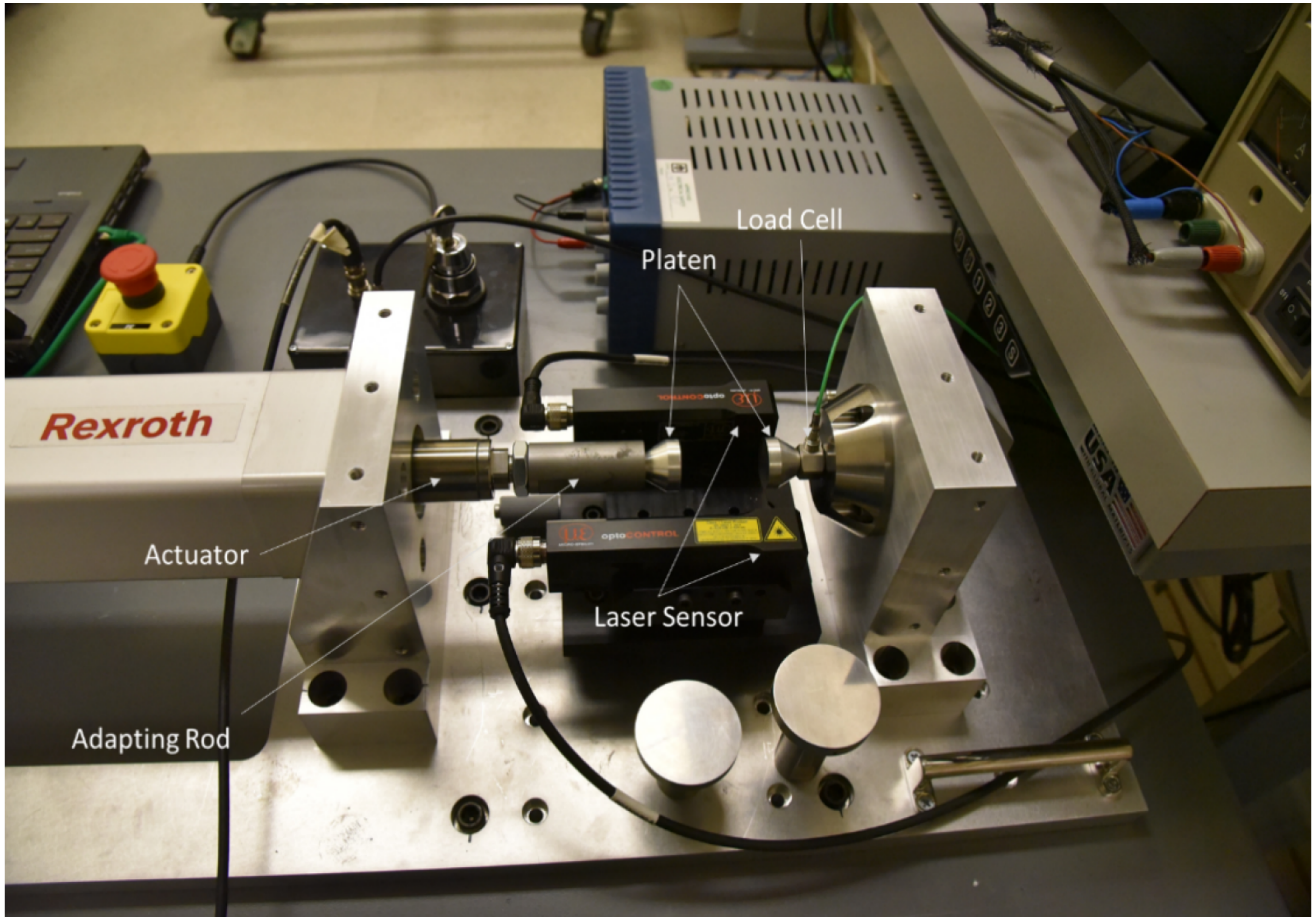
Energy dissipation:

$$\Delta = E_{loading} - E_{unloading} = \int_{loading} \sigma d\varepsilon - \int_{unloading} \sigma d\varepsilon$$

Energy dissipation ratio:

$$\delta = \frac{\Delta}{E_{loading}} = 1 - \frac{\int_{unloading} \sigma d\varepsilon}{\int_{loading} \sigma d\varepsilon}$$

Bench-top Intermediate-Strain-Rate Test Apparatus



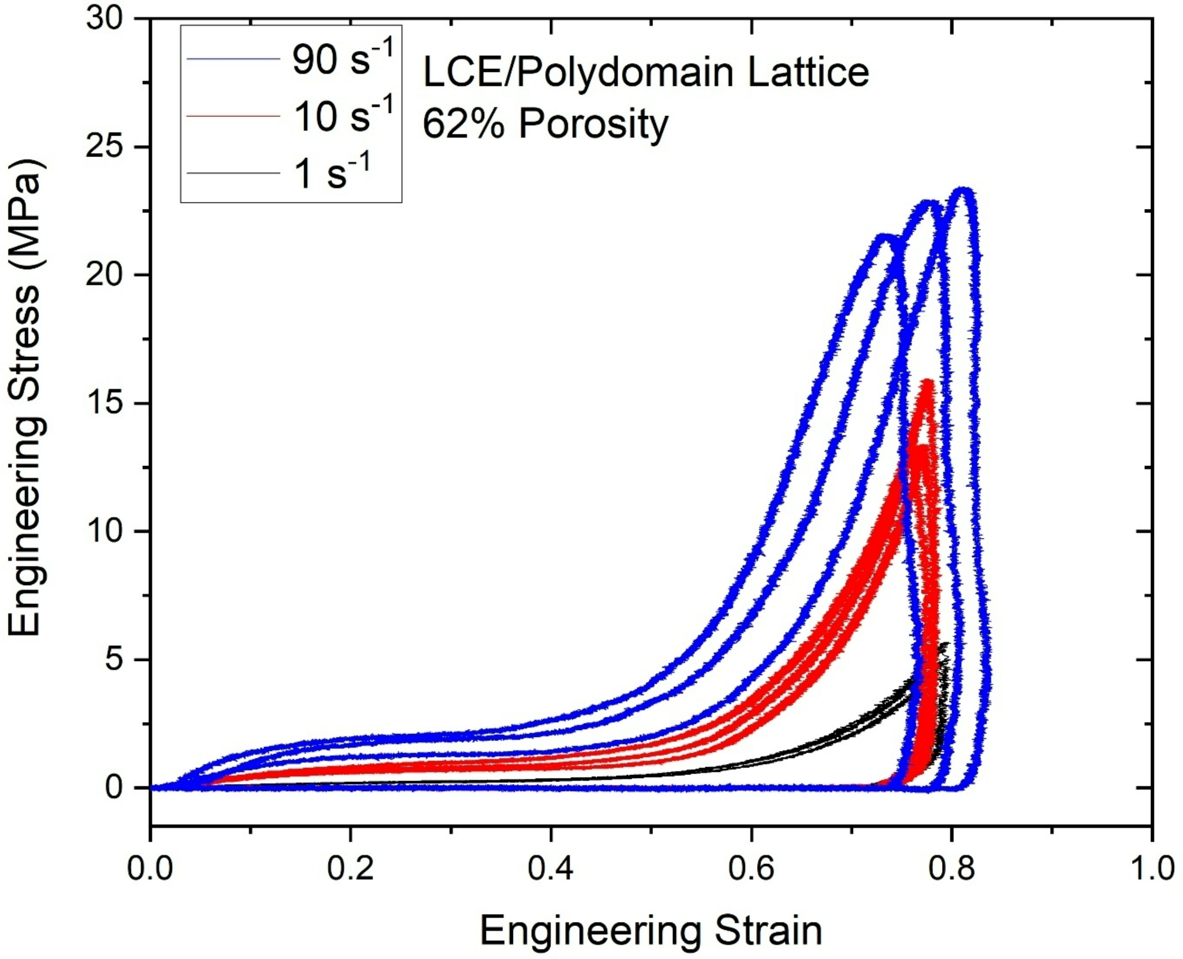
Rexroth® high speed electromechanical actuator

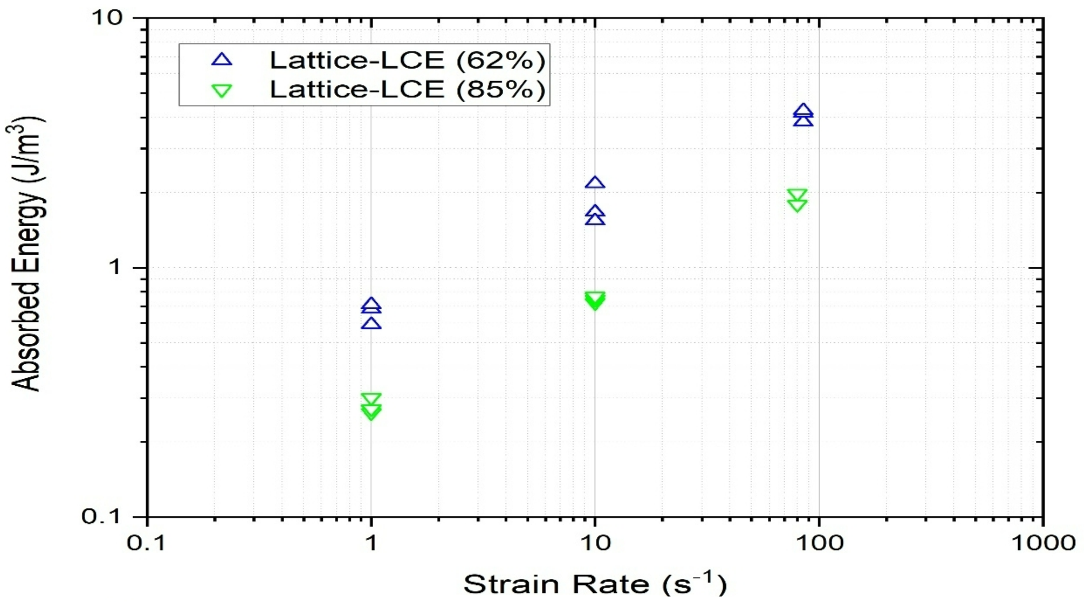
- Maximum impact velocity: ~1.9 m/s
- Maximum travel distance: 6" (~150 mm)
- Maximum acceleration: ~400 m/s^2
- Load capacity: 3000 lbs (~13300 N)

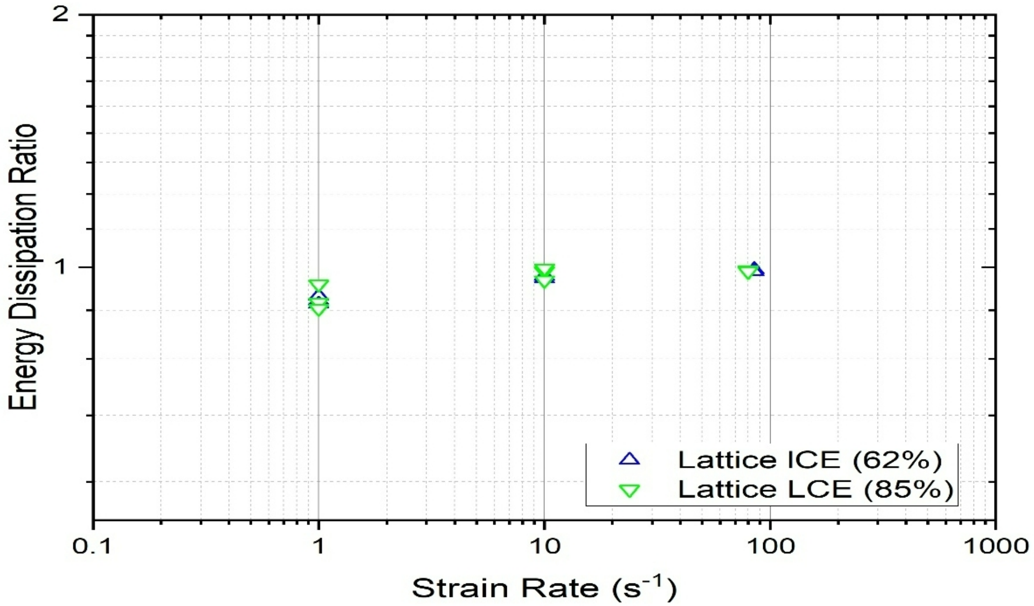
For a 10 mm (diameter) by 5 mm (thickness) specimen,

- Maximum stress: ~170 MPa
- Maximum strain rate: ~380 s^{-1}

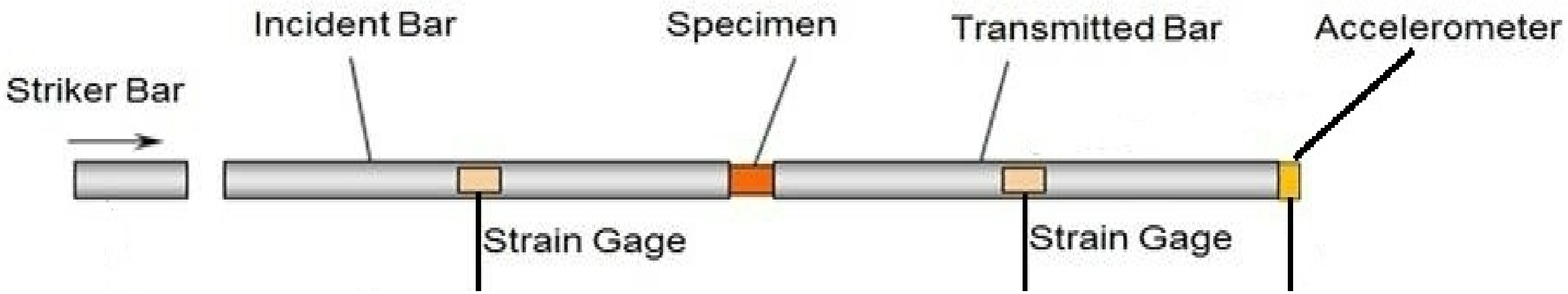
Loading-Unloading Stress-Strain Response at Intermediate Rates







Shock Mitigation Analyses with a Kolsky Compression Bar (Time Domain)



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

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

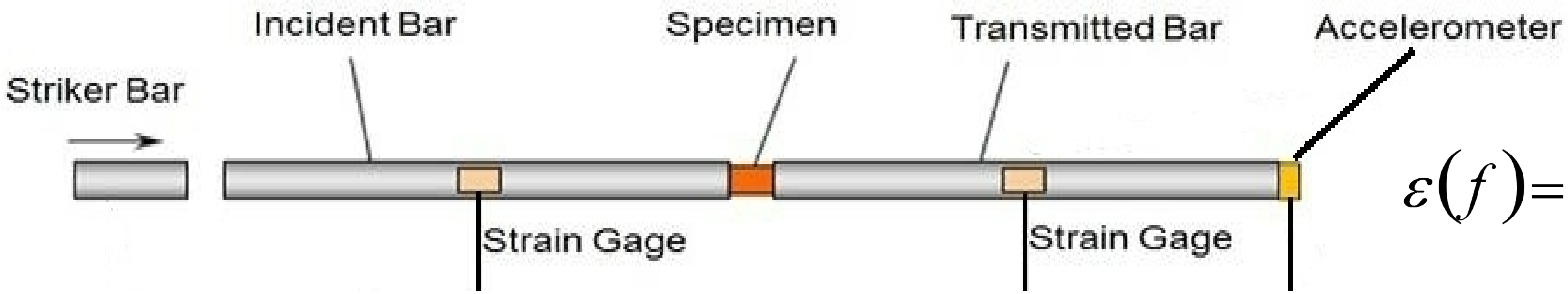
Energy Dissipation (Absorbed Energy)

$$\Delta E(t) = E_{input}(t) - E_{output}(t) = A_0 C_0 E_0 \int_0^t \left[\varepsilon_i^2(t) - \varepsilon_r^2(t) - \varepsilon_t^2(t)\right] dt$$

Energy Dissipation Ratio

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

Shock Mitigation Analyses with a Kolsky Compression Bar (Frequency Domain)



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

Incident Energy Spectrum Density

$$S_i(f) = A_0 C_0 E_0 |B_i(f)|^2$$

Reflected Energy Spectrum Density

$$S_r(f) = A_0 C_0 E_0 |B_r(f)|^2$$

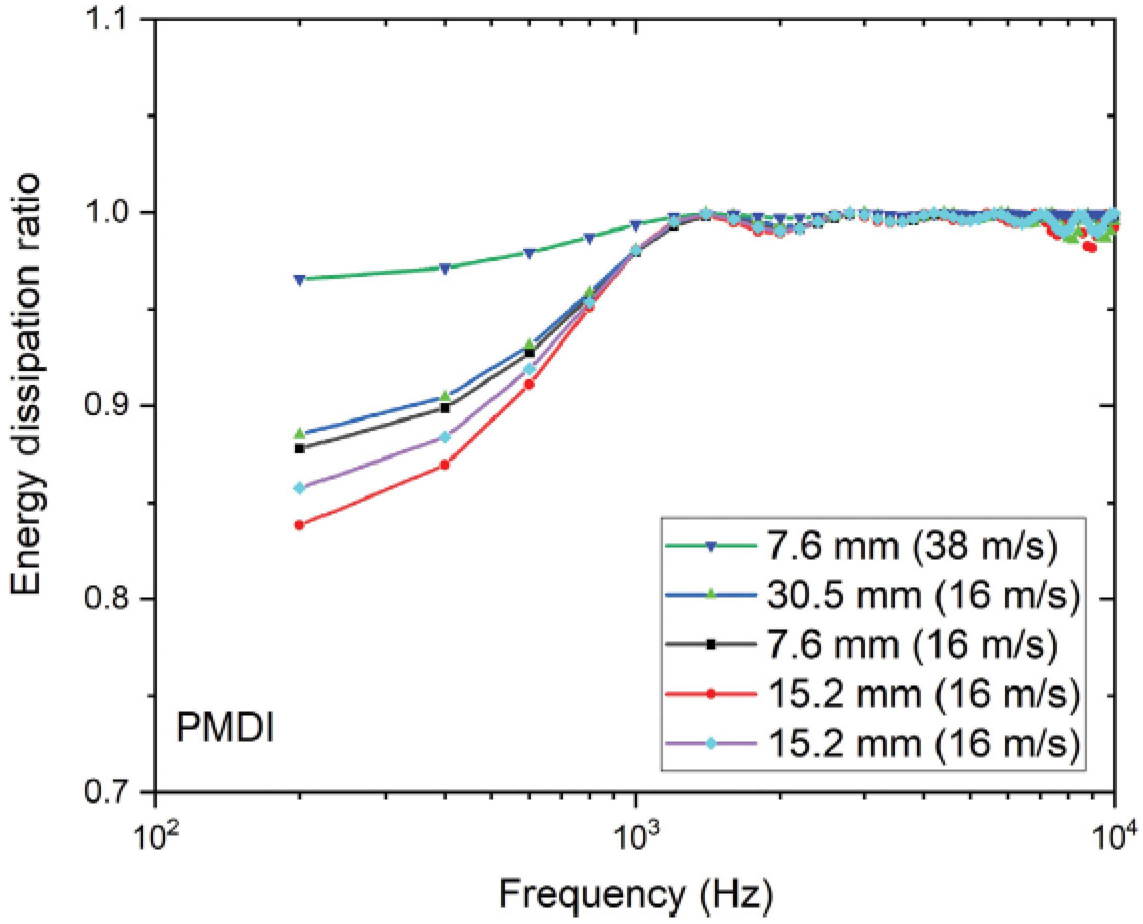
Transmitted Energy Spectrum Density

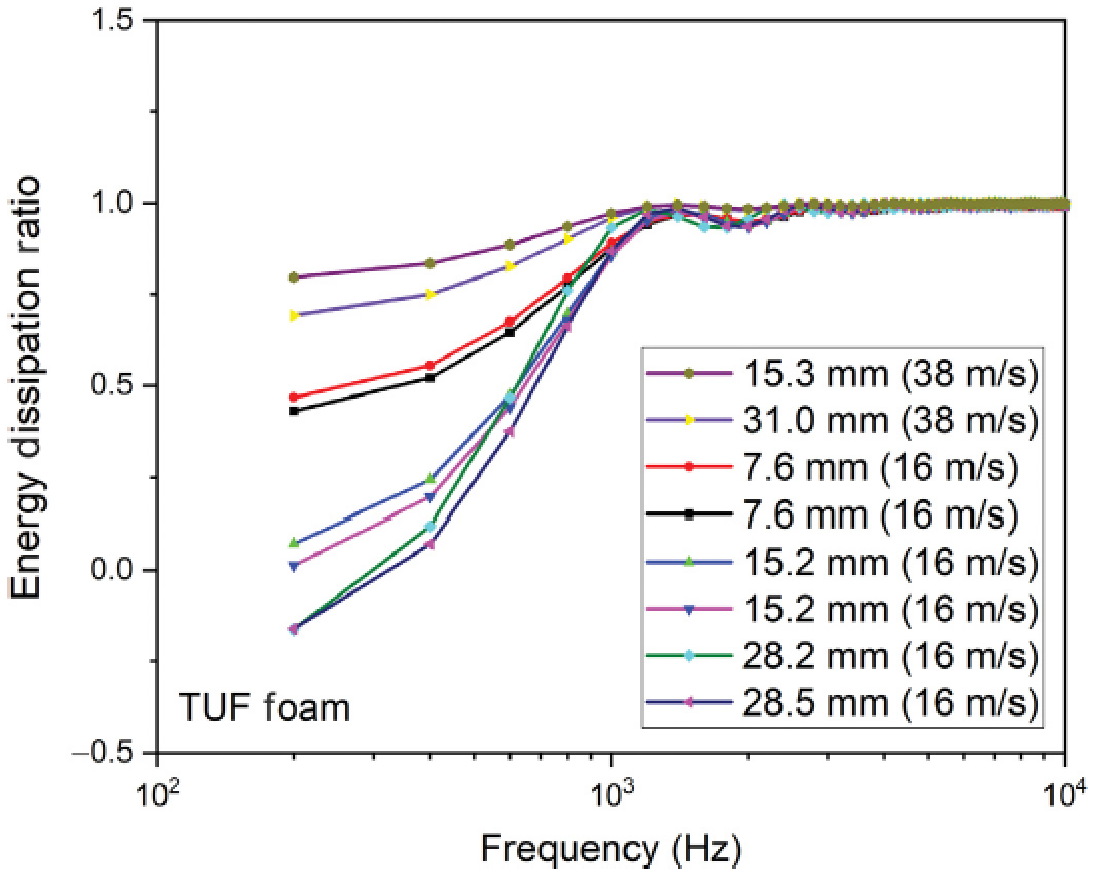
$$S_t(f) = A_0 C_0 E_0 |B_t(f)|^2$$

Energy Dissipation Ratio

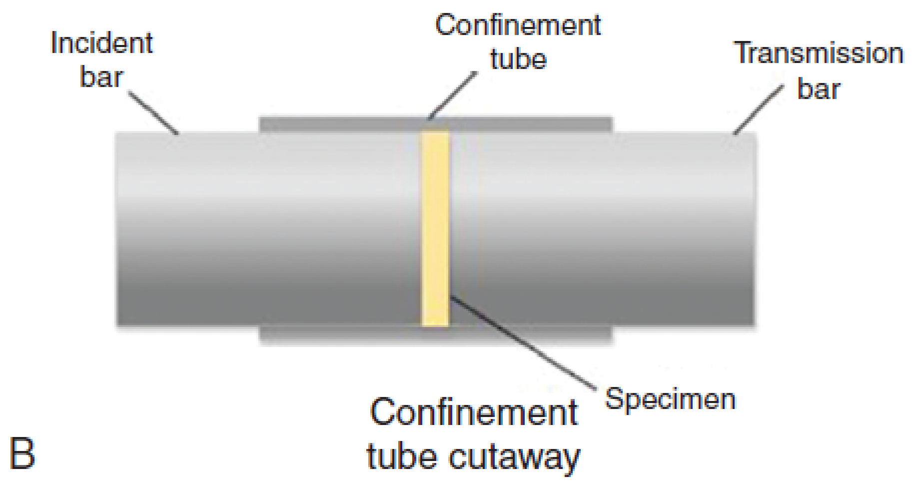
$$\delta(f) = \frac{\Delta(f)}{E_i(f) - E_r(f)} = 1 - \frac{|B_t(f)|^2}{|B_i(f)|^2 - |B_r(f)|^2}$$

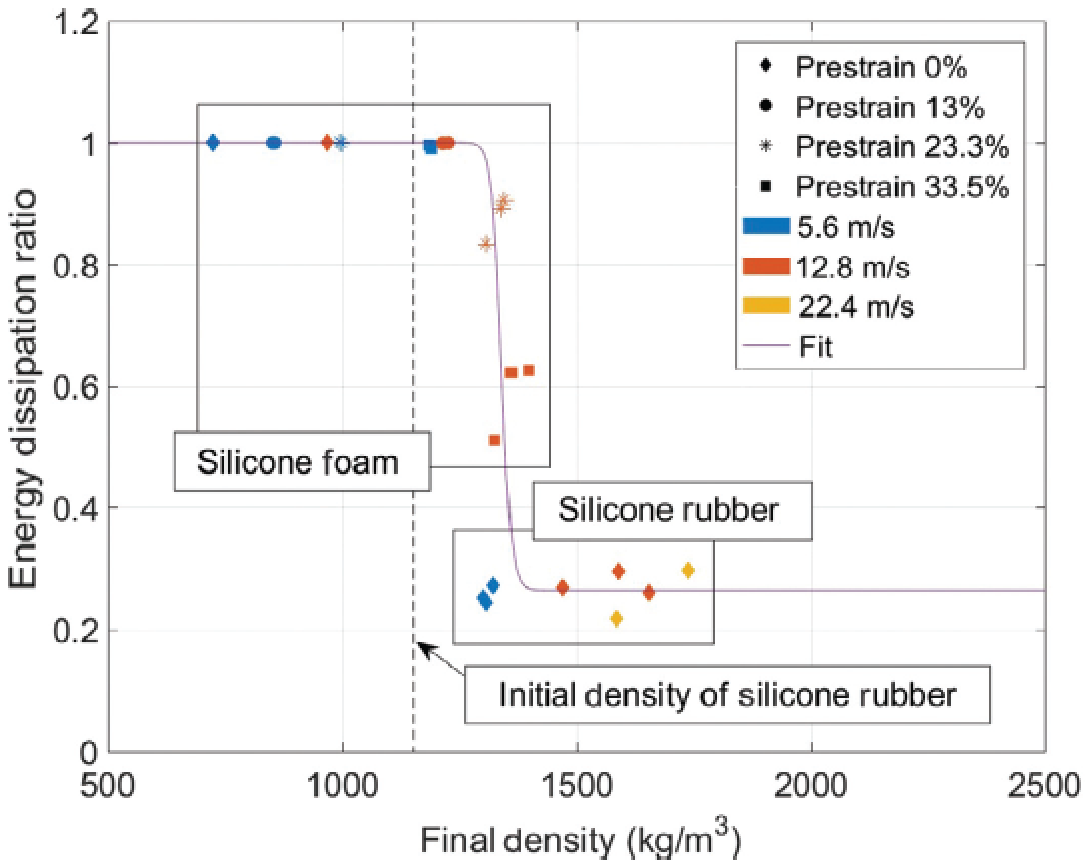
Frequency-dependent Energy Dissipation of Elastic-Plastic Foams





Energy Dissipation Characteristic of Confined Silicone Foam





Summary

Goal: maximize shock mitigation, optimize material and structural design

- Material properties need to be fully characterized
  - At different strain rates
  - At different temperatures
  - At different stress states
- Direct energy absorption and dissipation calculation from loading-unloading stress-strain curves
  - Dependent on strain, strain rate, temperature, stress state, etc.
- Structural response in terms of shock mitigation needs to be fully characterized
  - Impact crush response
  - Impact energy dissipation
    - In time domain
    - In frequency domain