U.S. Army Combat Capabilities Development Command – Armaments Center, Picatinny Arsenal, NJ
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Utilizing Hopkinson Bar for High-G, High-Frequency Mechanical Shock Tests

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Sandia National Laboratories

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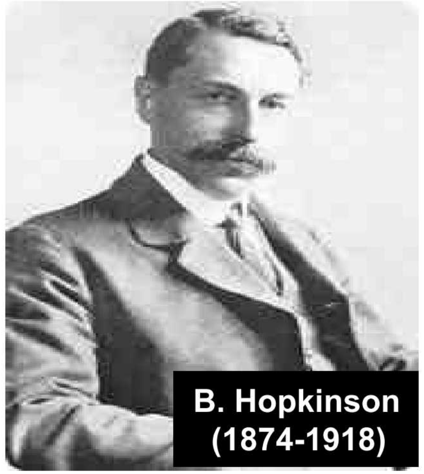
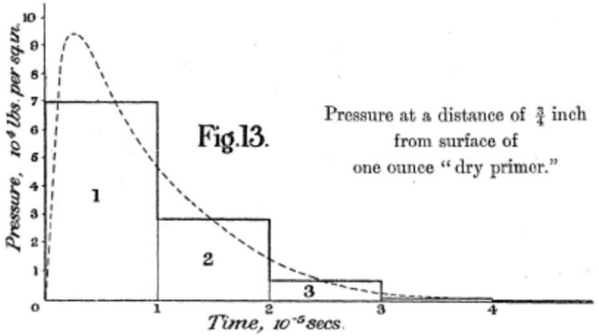
Hopkinson (Hoppy) Bar/Kolsky Bar

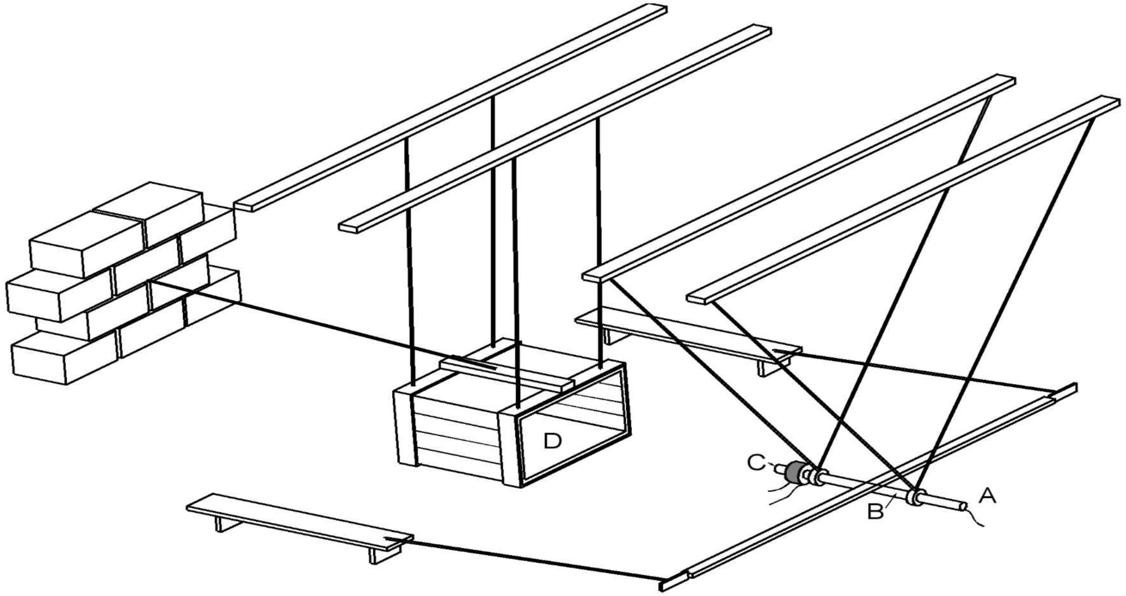


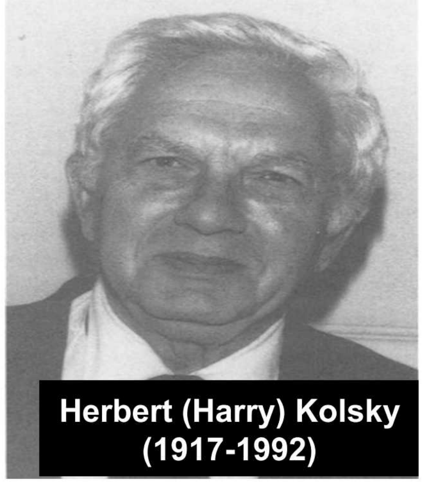
B. Hopkinson (1874-1918)

Hopkinson Bar (1914)

To measure pressure profile generated by explosives



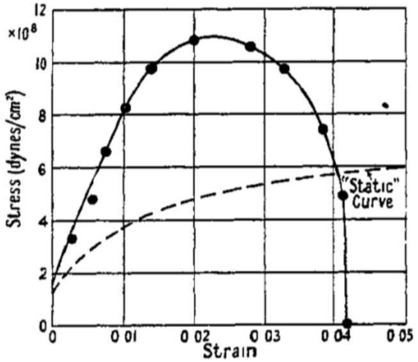


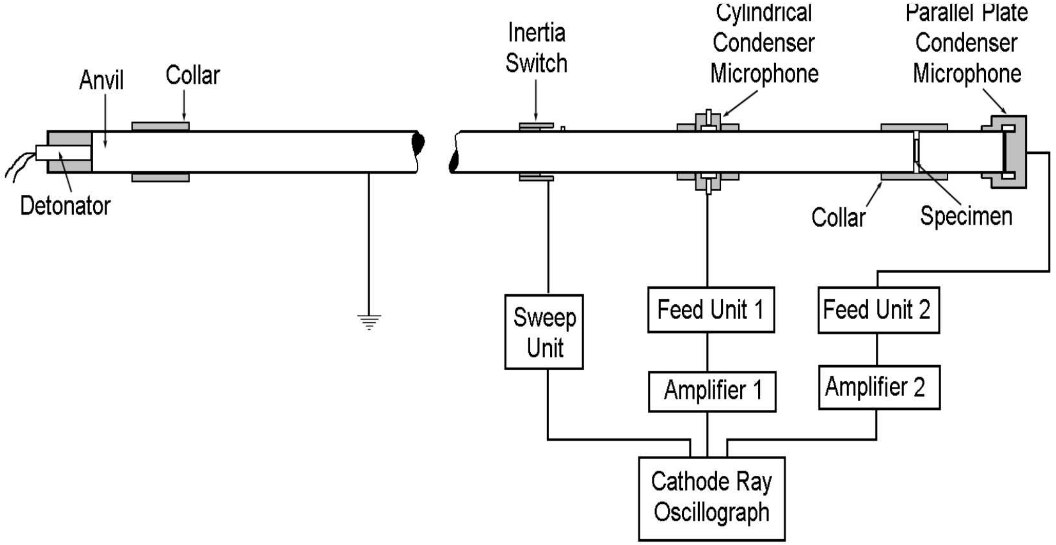


Herbert (Harry) Kolsky (1917-1992)

Kolsky Bar (1949)

To measure dynamic stress-strain curves of materials

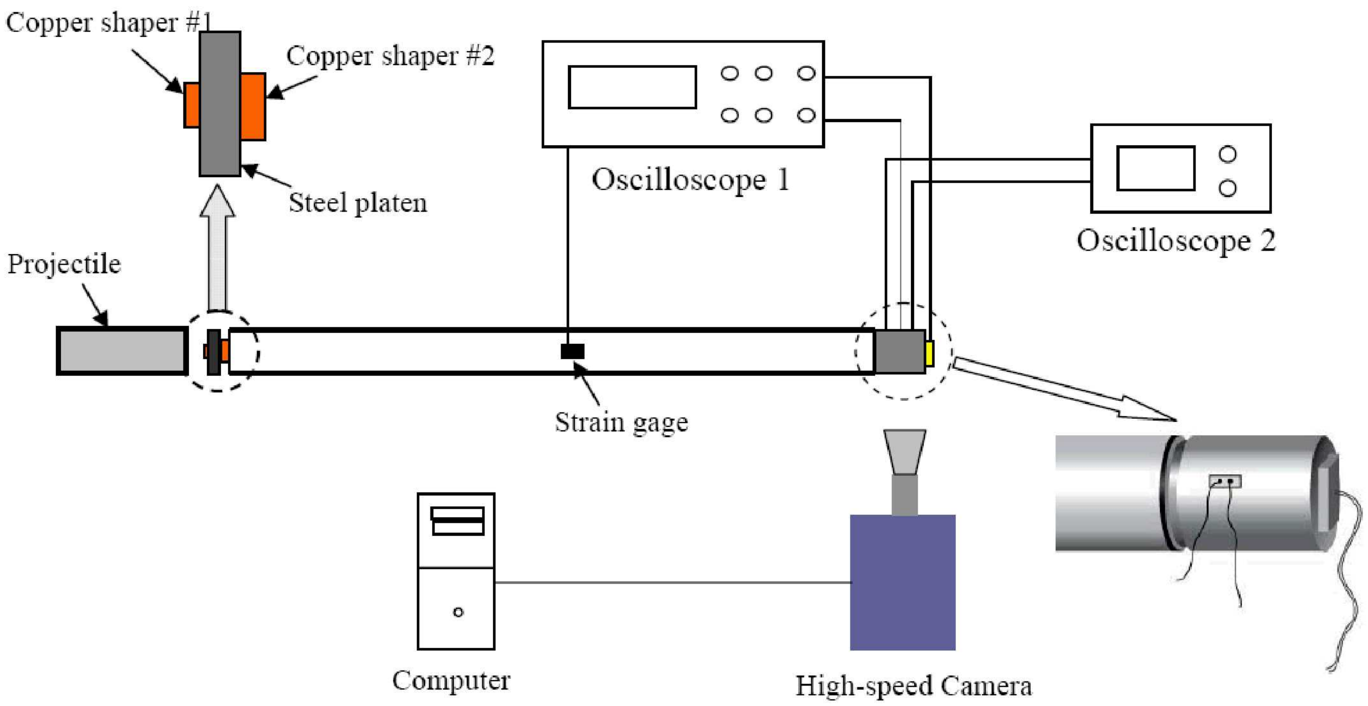


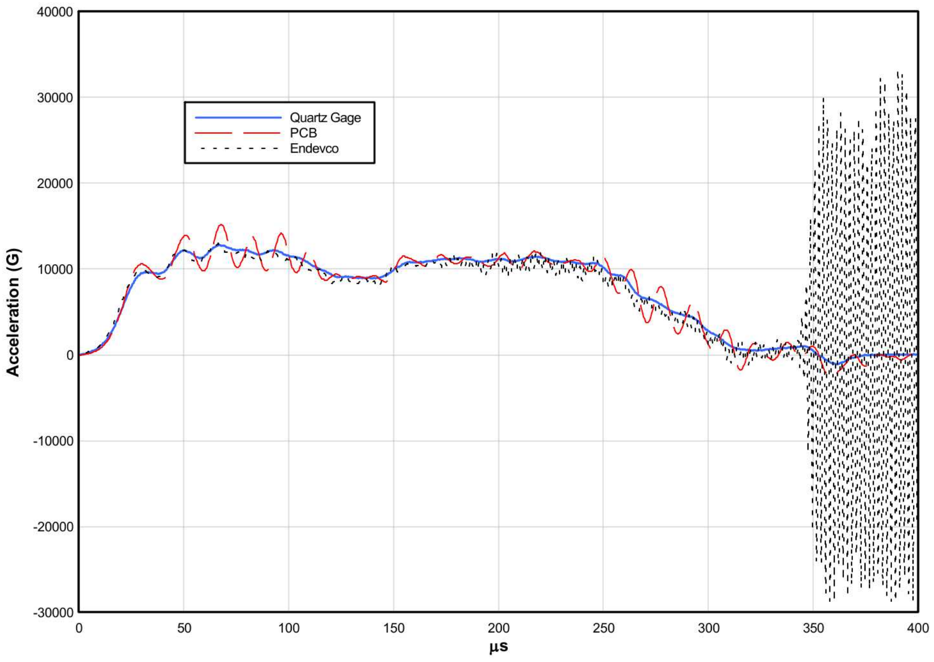


Hopkinson (Hoppy) Bar/Kolsky Bar/Split Hopkinson Bar

Hopkinson Bar ≠ Kolsky Bar = Split Hopkinson Bar

Hopkinson Bar (Actuator) – with auxiliary sensors (accelerometers) if needed

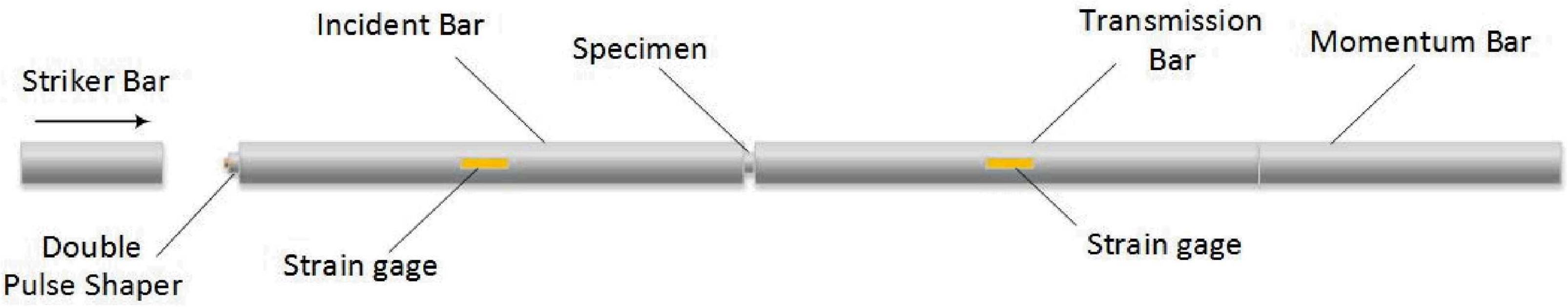


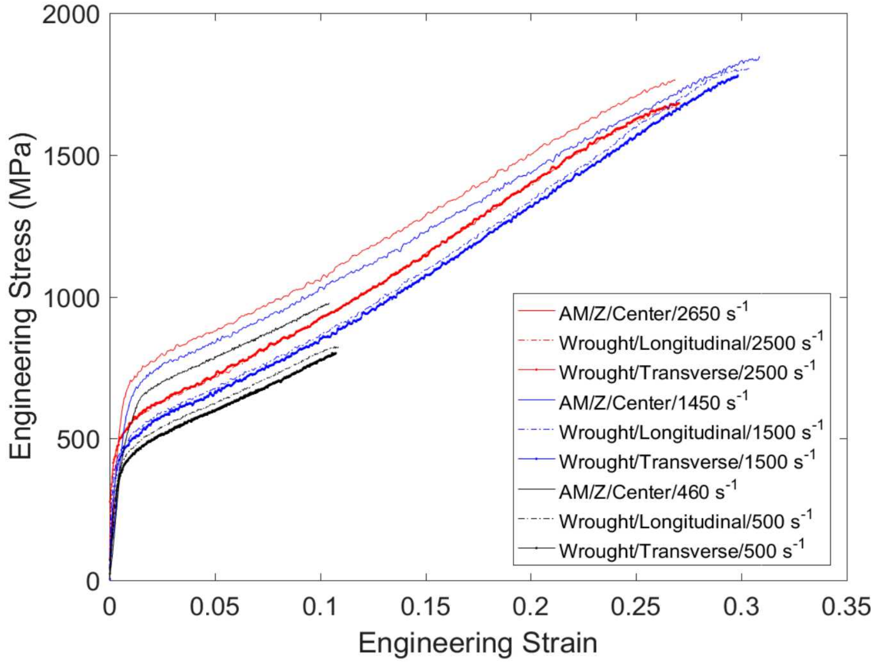


Hopkinson (Hoppy) Bar/Kolsky Bar/Split Hopkinson Bar

Hopkinson Bar ≠ Kolsky Bar = Split Hopkinson Bar

Kolsky Bar/Split Hopkinson Bar (Actuator & Sensor)





Currently, Kolsky bar/split Hopkinson bar is more commonly used than Hopkinson bar.

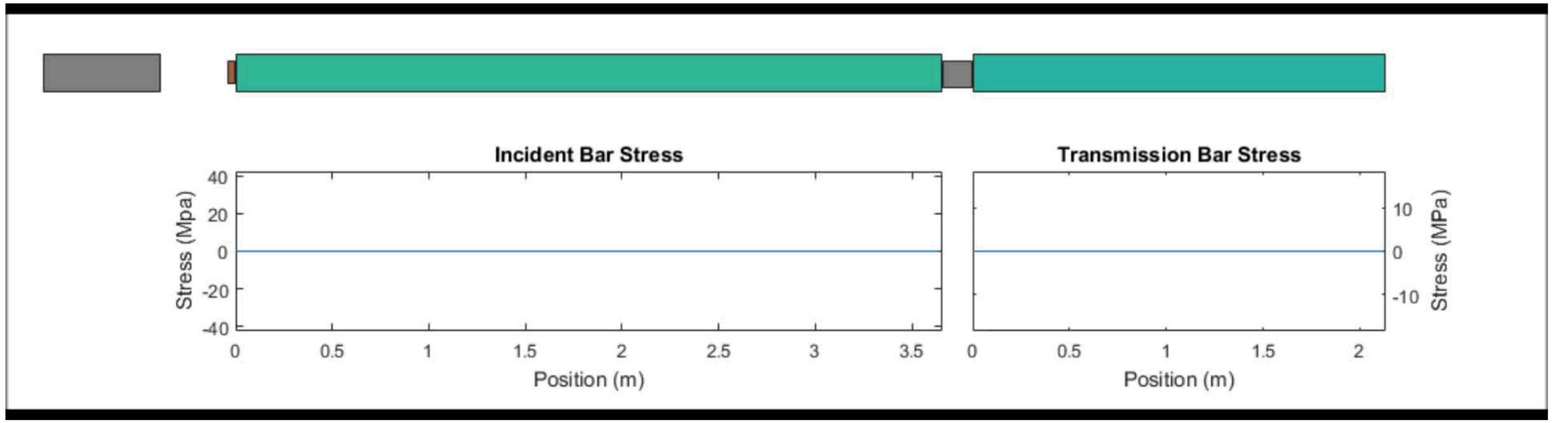
Hopkinson (Hoppy) Bar/Kolsky Bar/Split Hopkinson Bar

Similar setup but different languages

Split Hopkinson Bar/Kolsky Bar	**Hopkinson Bar**
➢ Stress/Force	➢ Acceleration
➢ Strain/Displacement	➢ Duration
➢ Strain rate/Velocity	➢ Frequency
➢ Stress-strain (or Force-displacement) curve	➢ Shock response spectrum (SRS)

Split Hopkinson (Kolsky) Bar

One-dimensional Elastic Stress Wave Propagation



Mass Conservation

$$V_1 = C_0\left(\varepsilon_i - \varepsilon_r\right)$$

$$V_2 = C_0 \varepsilon_t$$

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

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

Momentum Conservation

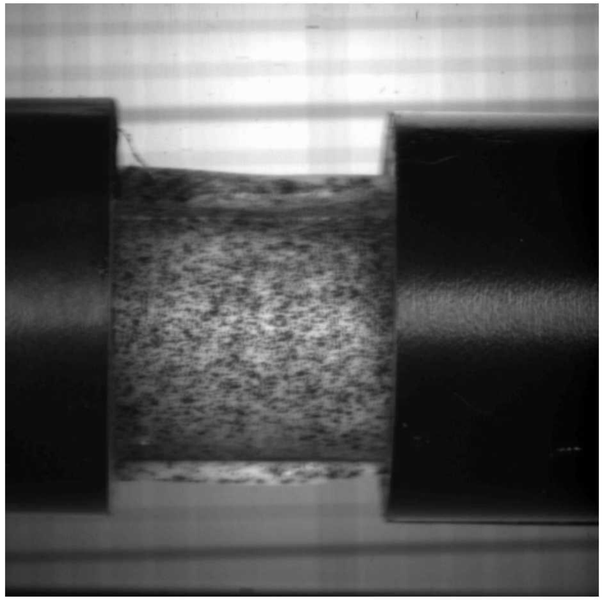
$$F_1 = E_0 A_0\left(\varepsilon_i + \varepsilon_r\right)$$

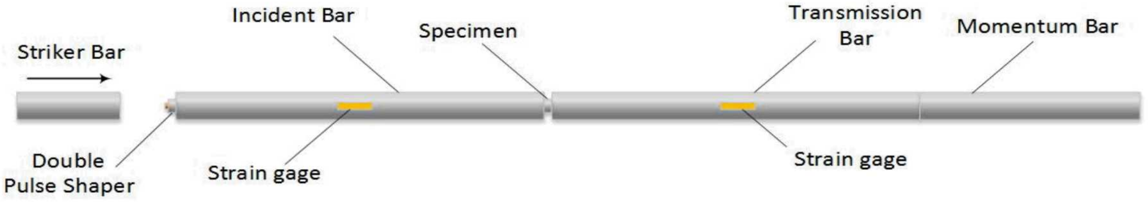
$$F_2 = E_0 A_0 \varepsilon_t$$

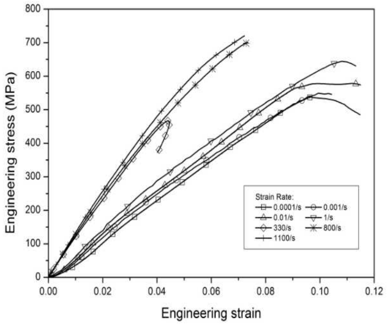
$$\sigma = \frac{F_1 + F_2}{2A_s} = \frac{E_0 A_0}{2A_s}\left(\varepsilon_i + \varepsilon_r + \varepsilon_t\right)$$

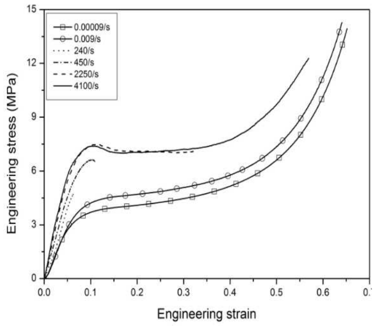
$$\boxed{\sigma \sim \varepsilon}$$

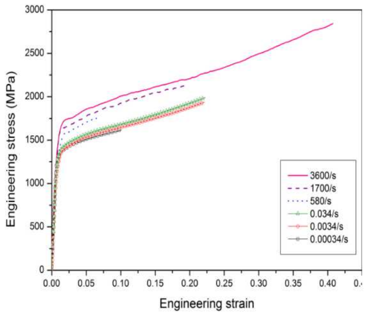
Split Hopkinson (Kolsky) Bar for Compression

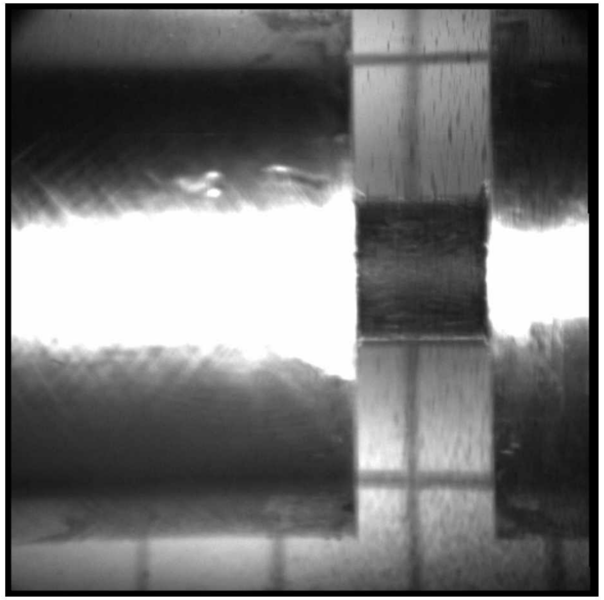


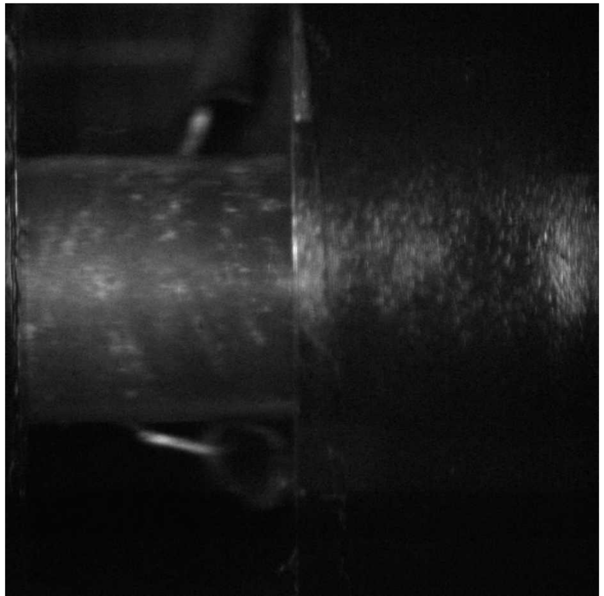


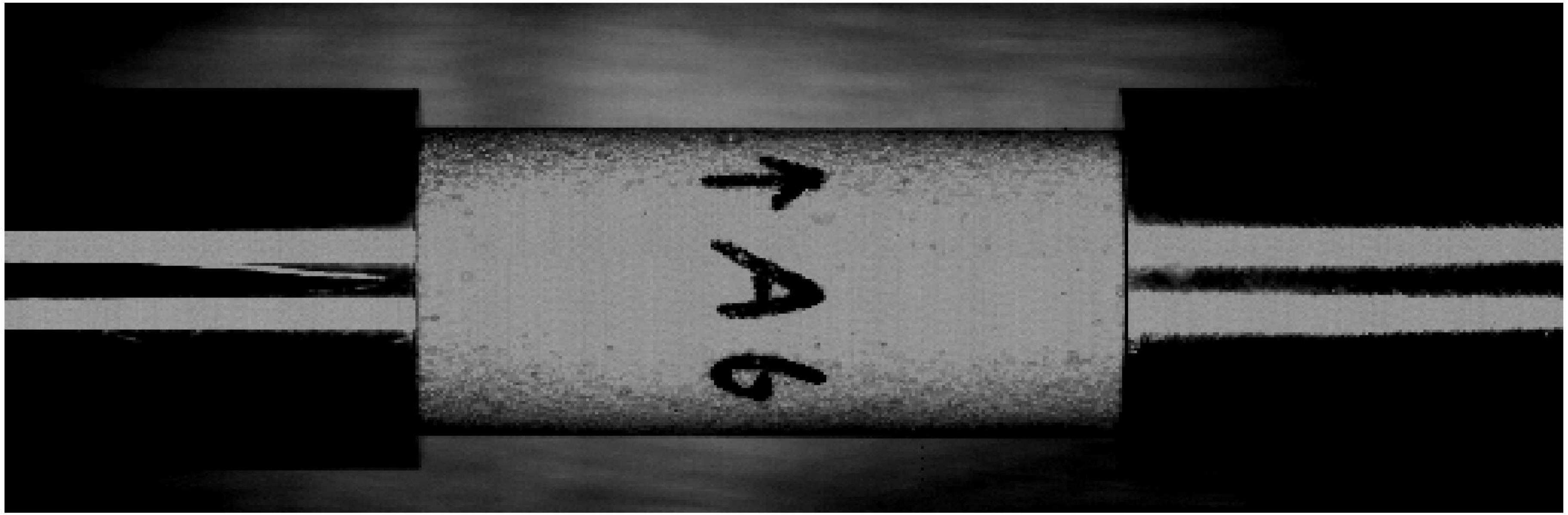




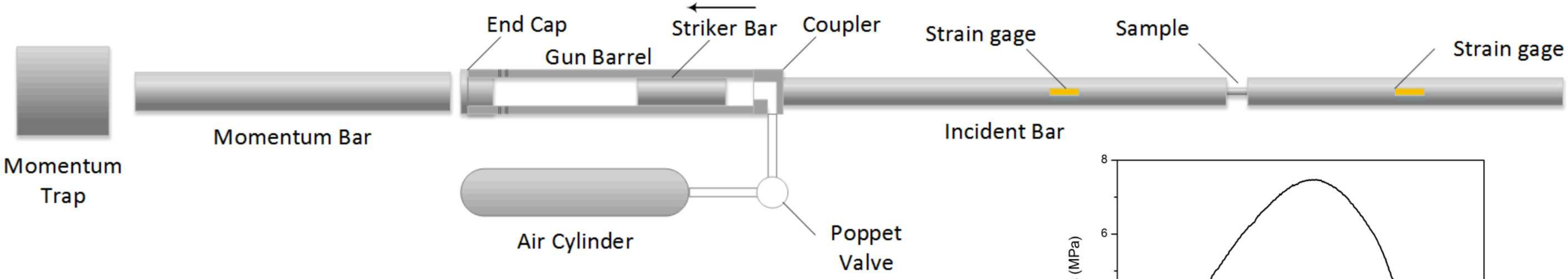


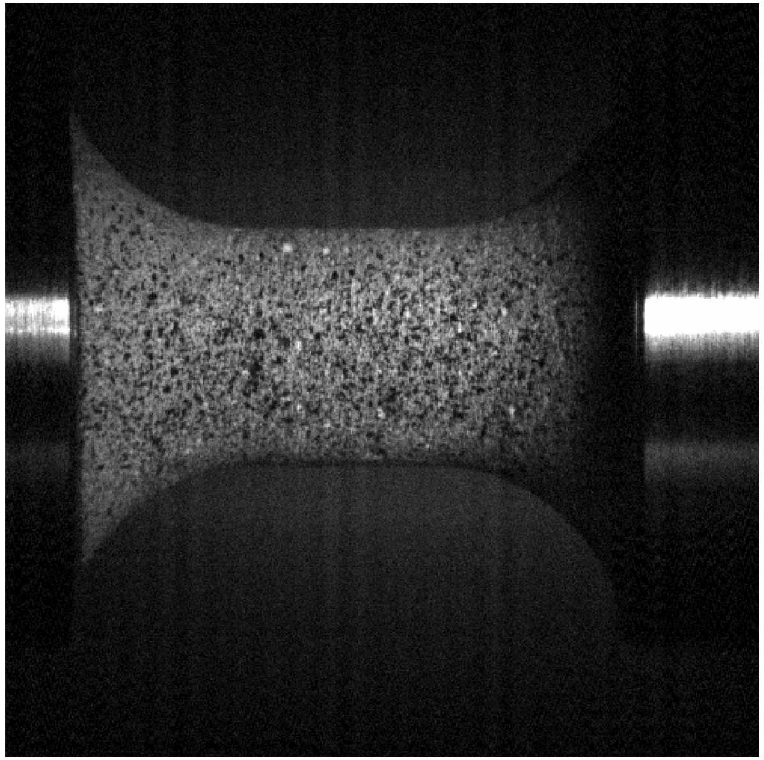


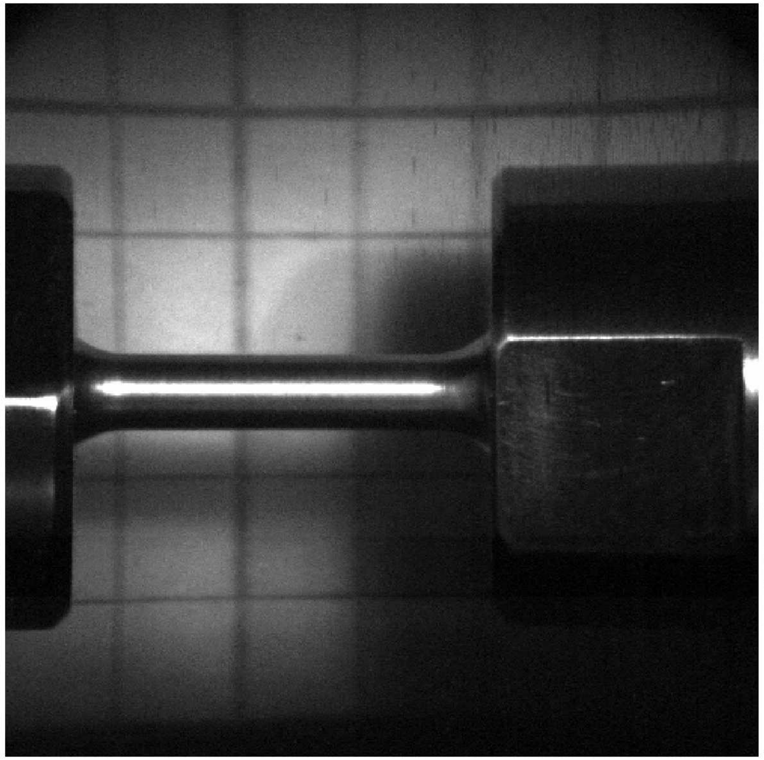


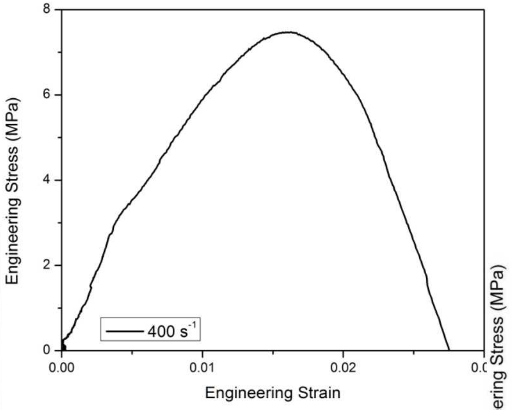


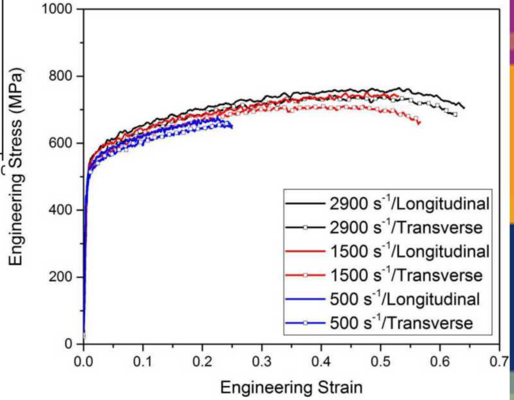
Split Hopkinson (Kolsky) Bar for Tension

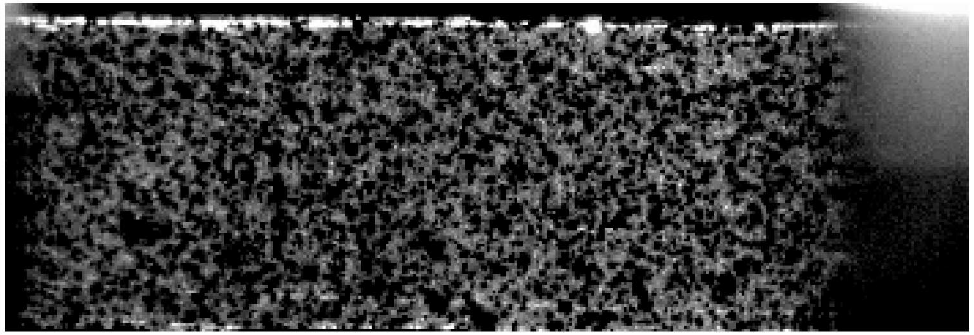




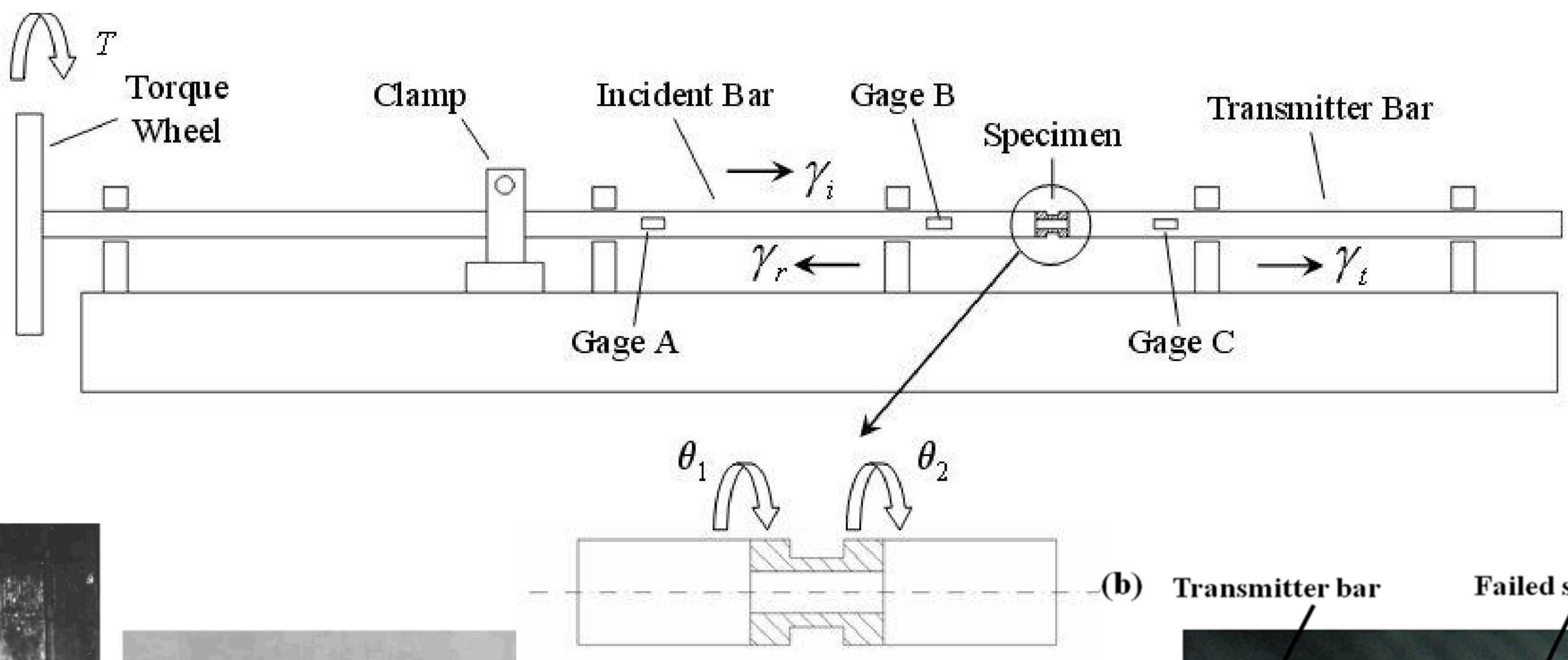


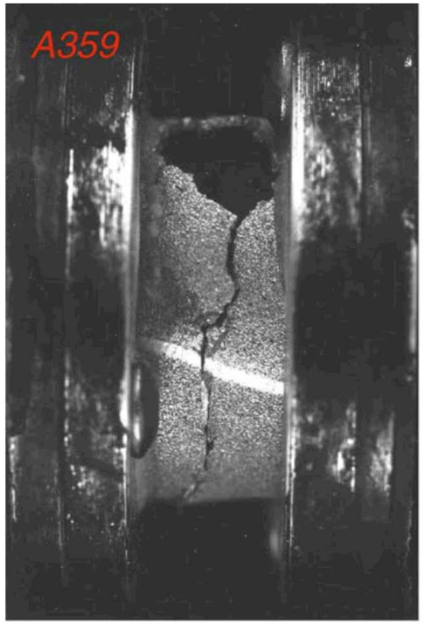






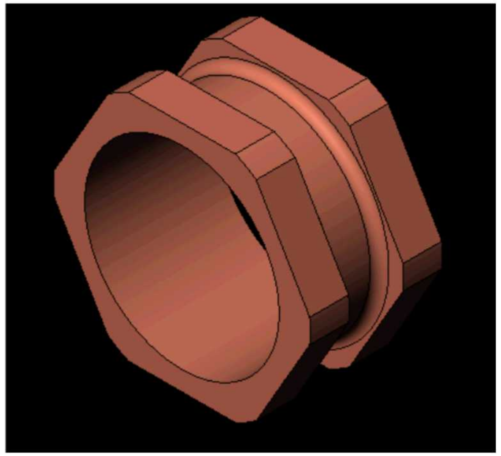
Split Hopkinson (Kolsky) Bar for Torsion

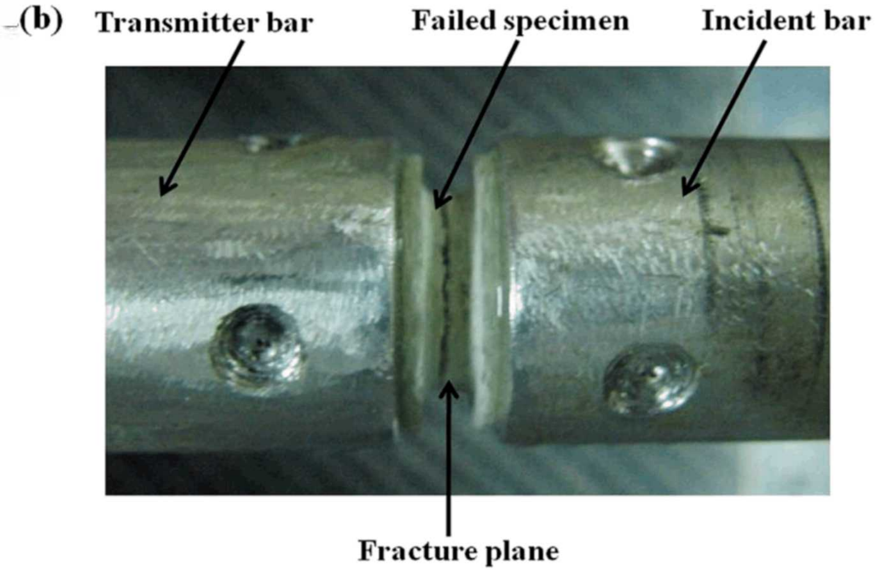




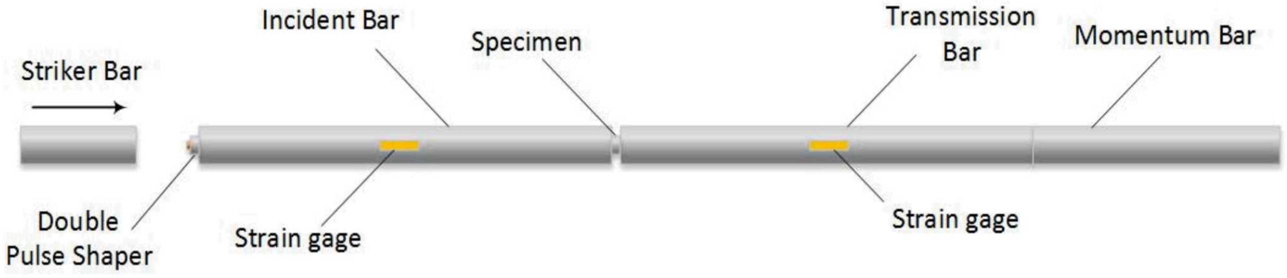
(a) Matrix Specimen

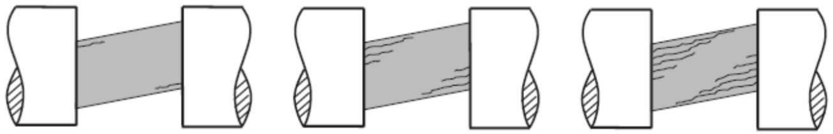
(b) Composite Specimen

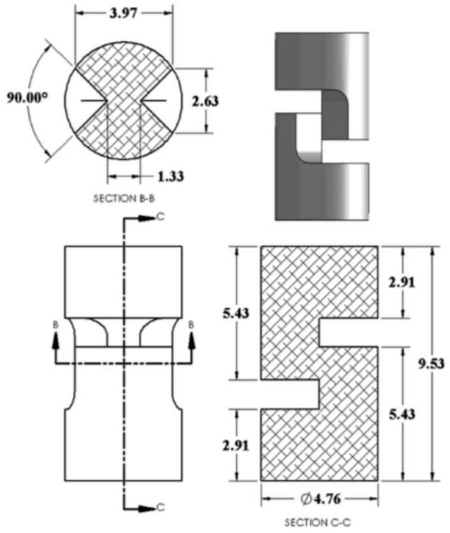


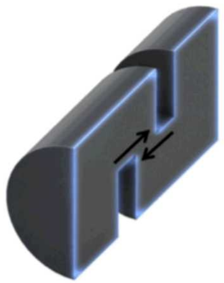


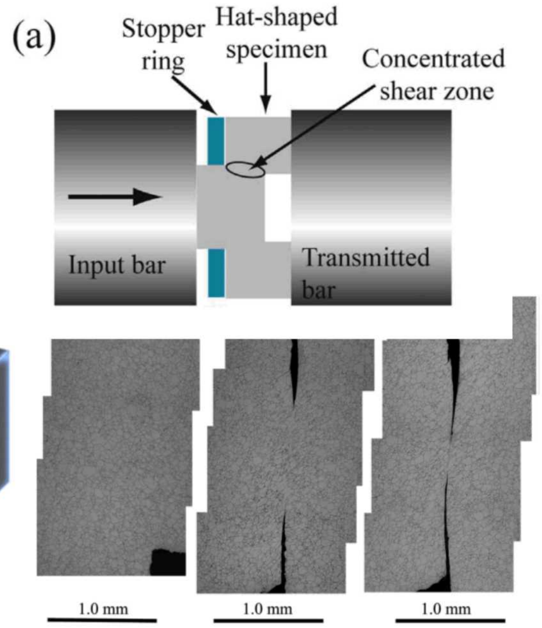
Split Hopkinson (Kolsky) Bar for Dynamic Shear, Compression/Shear, Tension/Shear

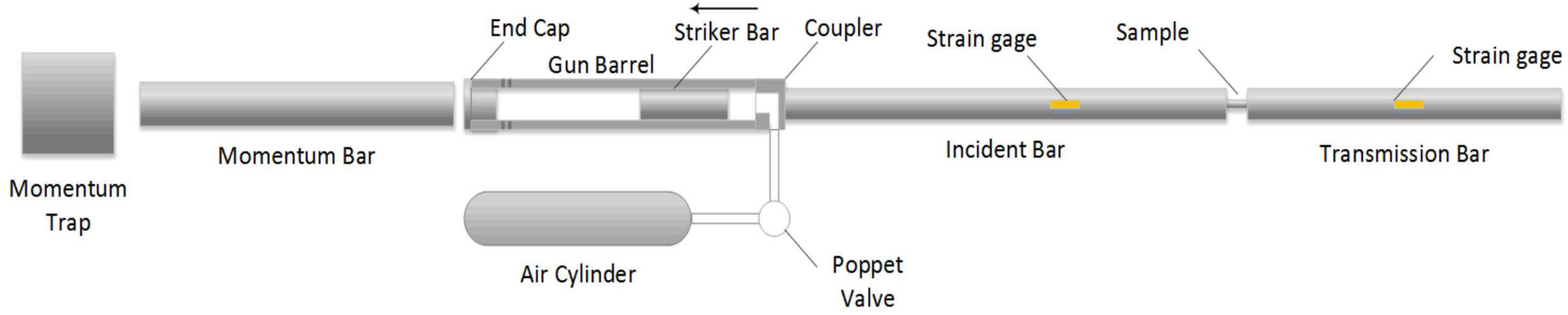


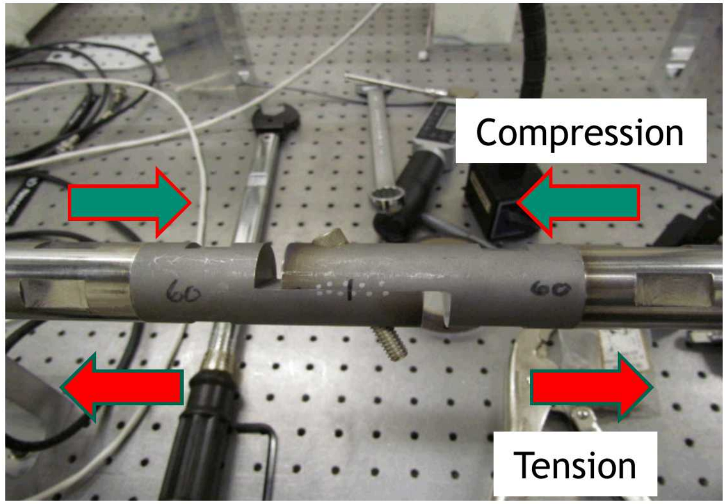




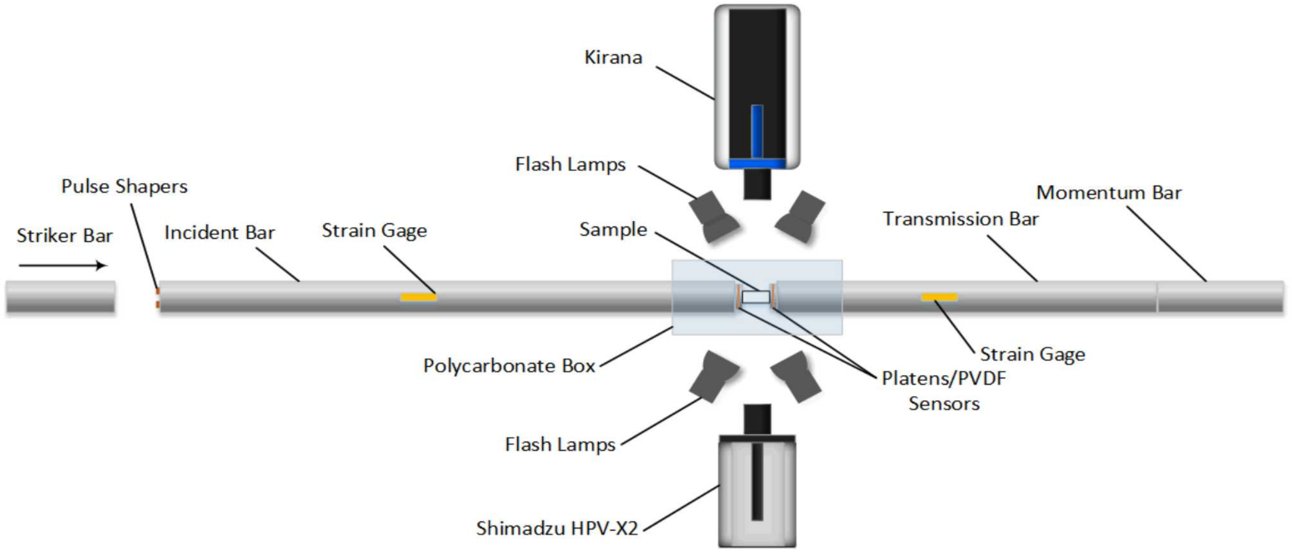


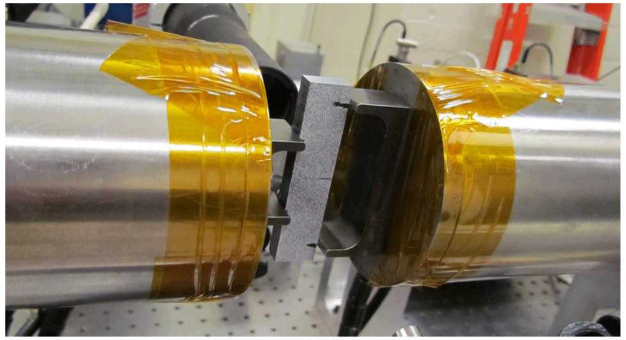


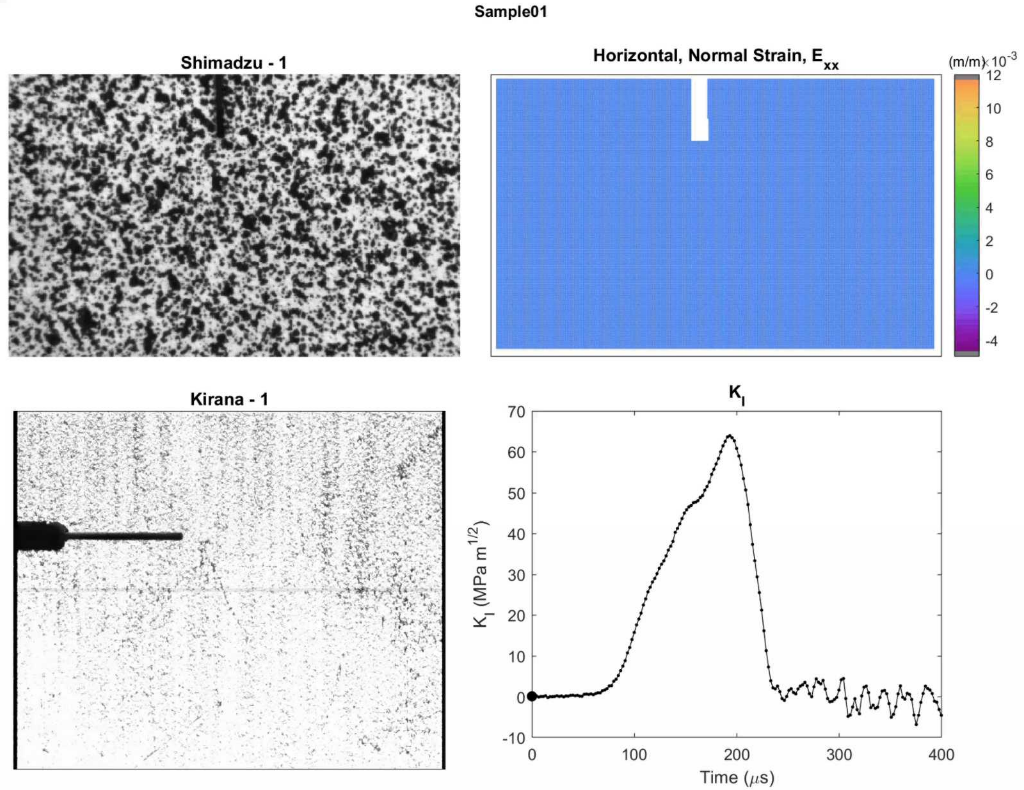


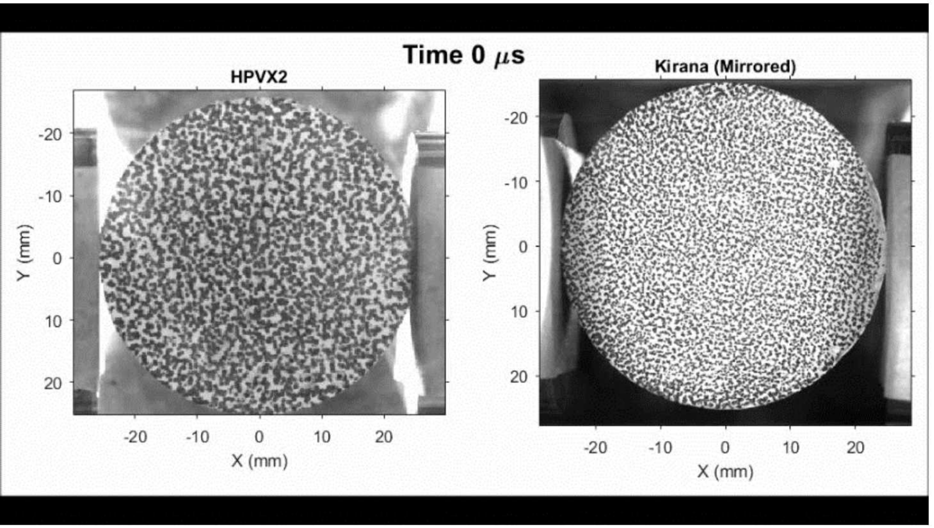


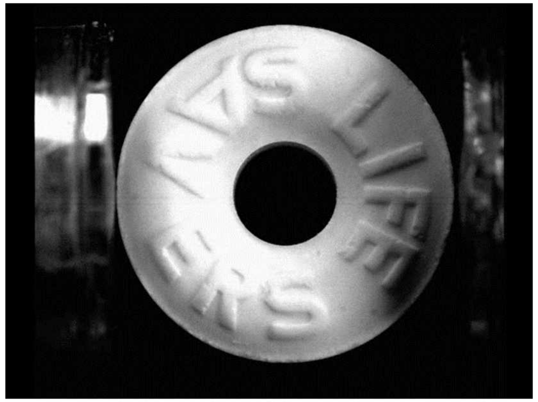
Split Hopkinson (Kolsky) Bar for Dynamic Fracture









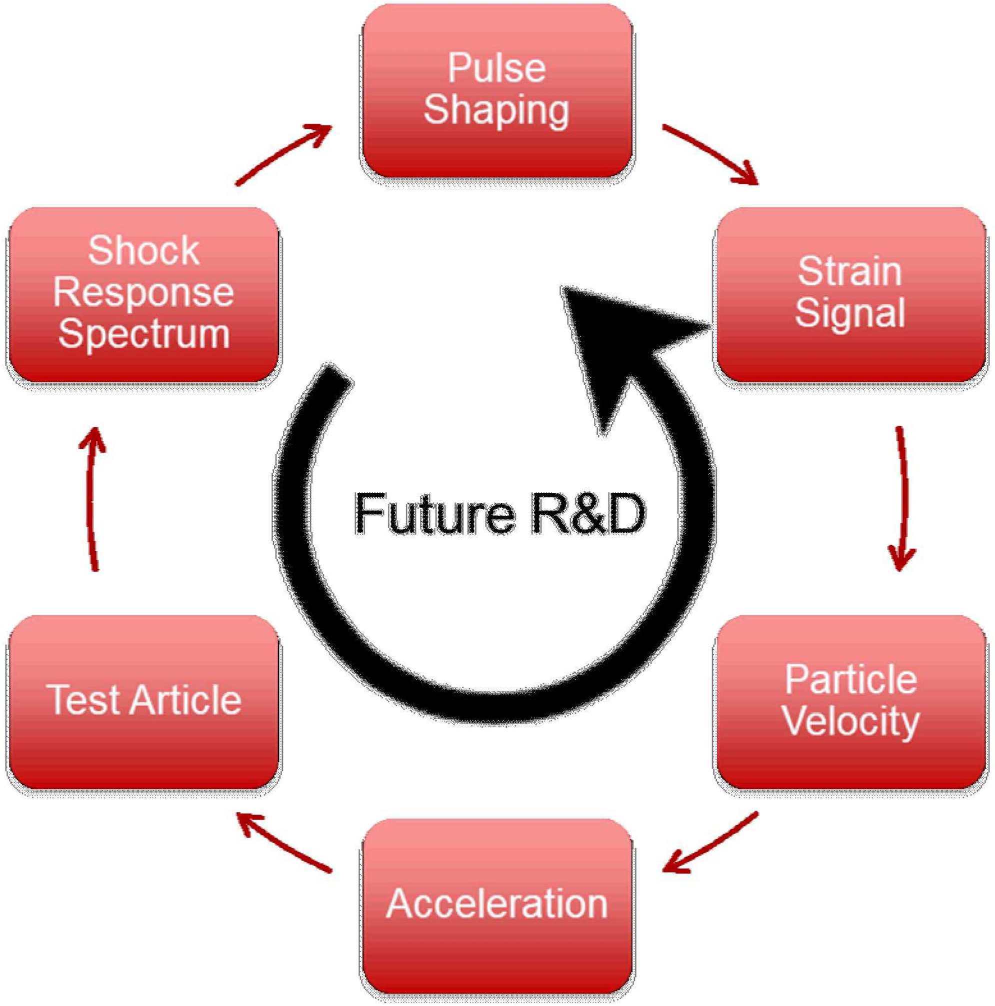


General Principles

- ***Send a high-acceleration, high-frequency shock wave to excite test articles***
- ***Test the components in terms of survivability, functionality, etc.***

Keys:

- **Acceleration (g-level)**
- **Duration**
- **Frequency**
- **Shock response spectrum (SRS)**



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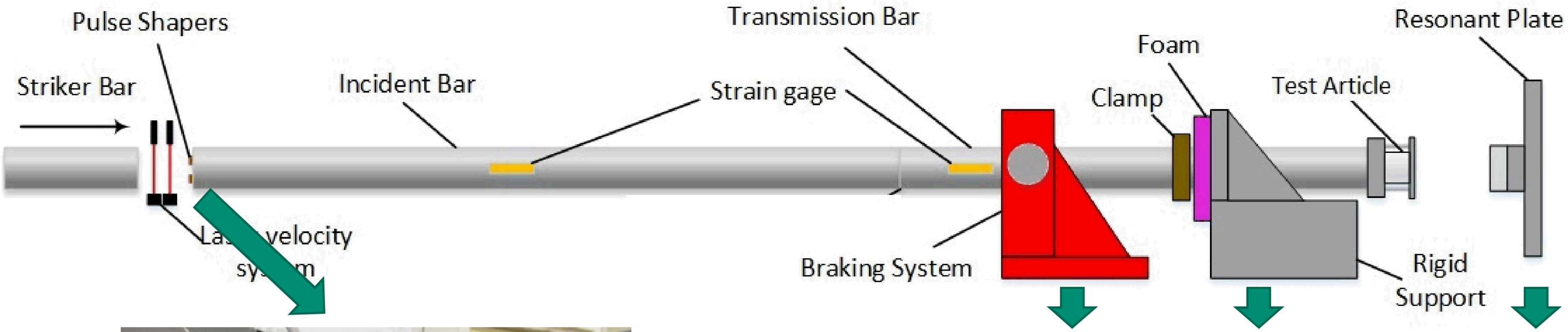
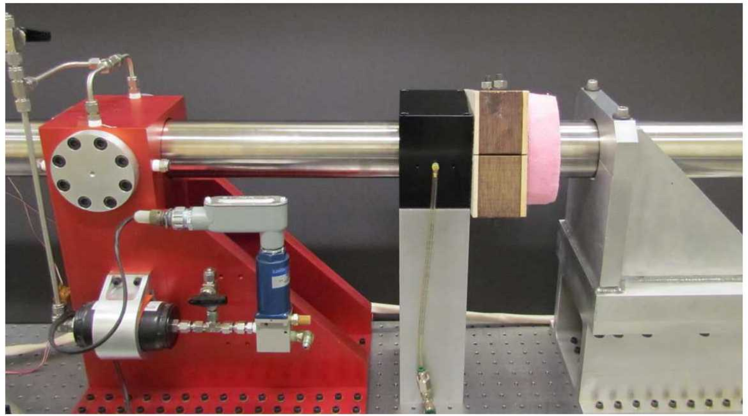
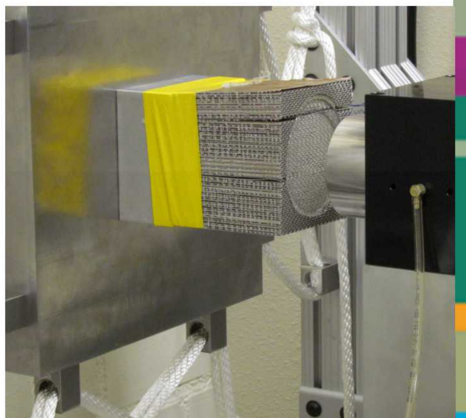
General Configuration

- ***Pulse shaping for desired pulses (g-level, frequency, duration, etc)***
- ***Bar stop mechanism (braking system, clamp, etc)***
    - ***Not to smash/crush the test article***

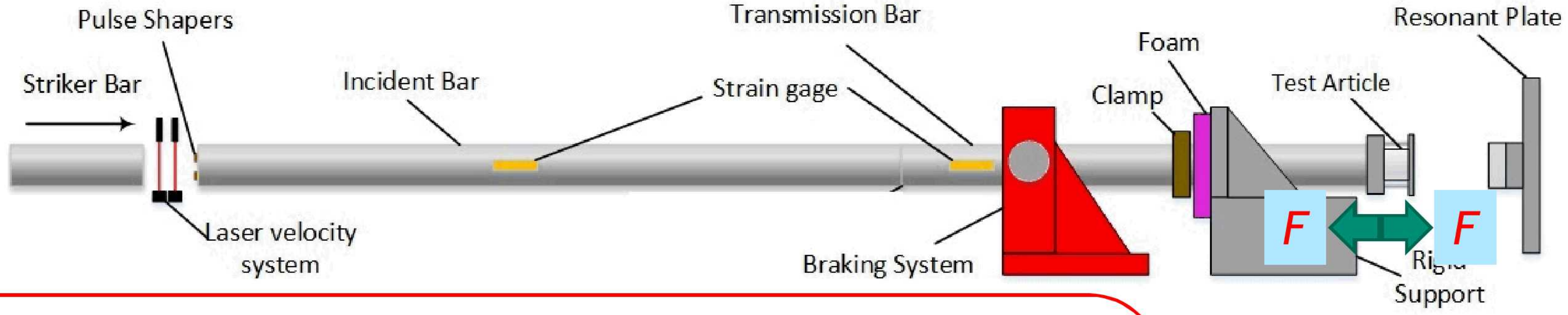






Hopkinson Bar Design for Mechanical Shock Tests

Design Considerations



- ***Bar Material***
  - ➢ Higher yield strength → ✓ Higher load capacity
    - ✓ Higher g-level
    - ✓ Larger mass
  - ➢ Higher elastic wave speed → ✓ Shorter rise time ✓ Higher frequency
- ***Bar Diameter***
  - ➢ Larger cross-sectional area → ✓ Larger size test article ✓ High load capacity
    - ✓ Higher g-level
    - ✓ Larger mass
  - **Trade Off**
  - ➢ Longer rise time → ✓ Lower frequency

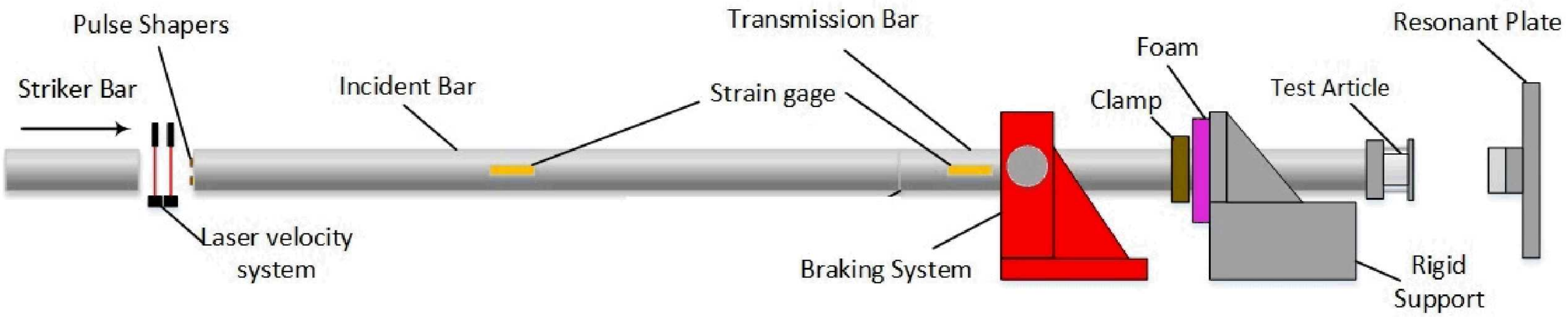
$$F = m \cdot a$$

$m \uparrow$ $a \uparrow$

$$F = \sigma \cdot A \uparrow$$

Hopkinson Bar Design for Mechanical Shock Tests

Design Considerations



- ***Bar Length***

  - Recommendation: at least 2 times of striker length for not messing up strain gage signal

  - "Natural frequency" due to wave propagation back and forth in the bar $f = \frac{C_0}{2L}$

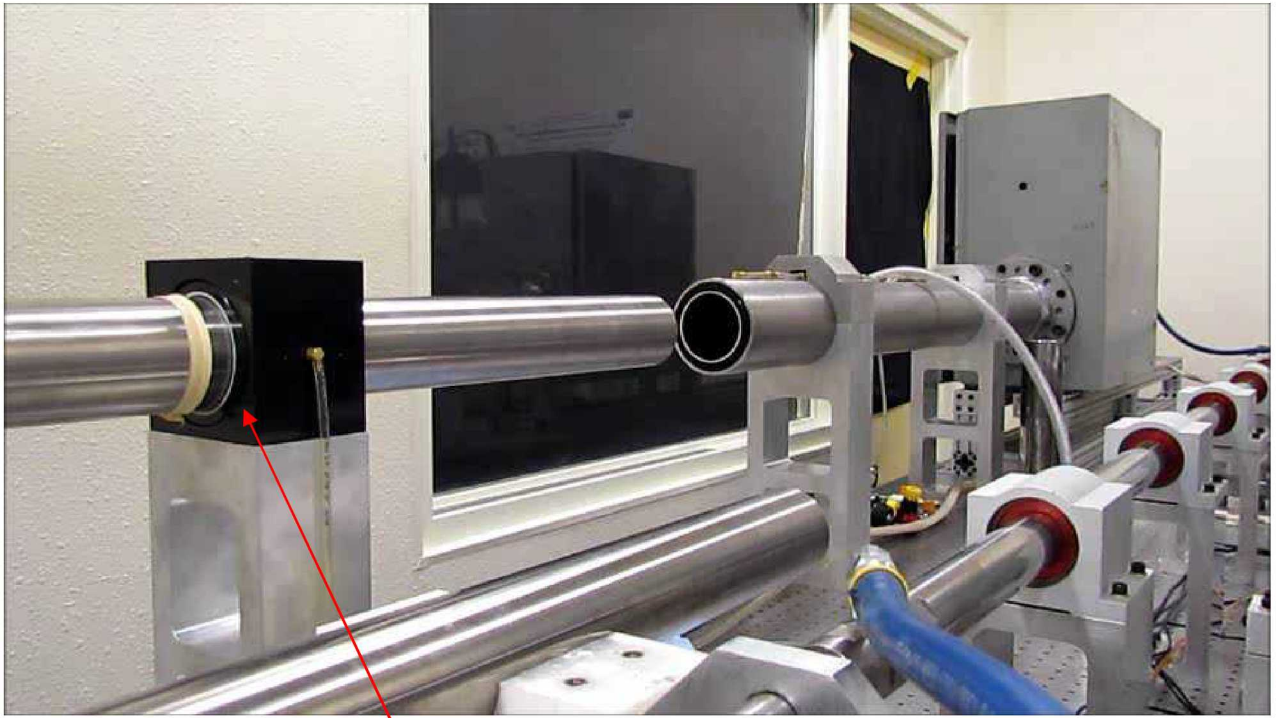
For a 12'-long bar, $f \sim 700 Hz$

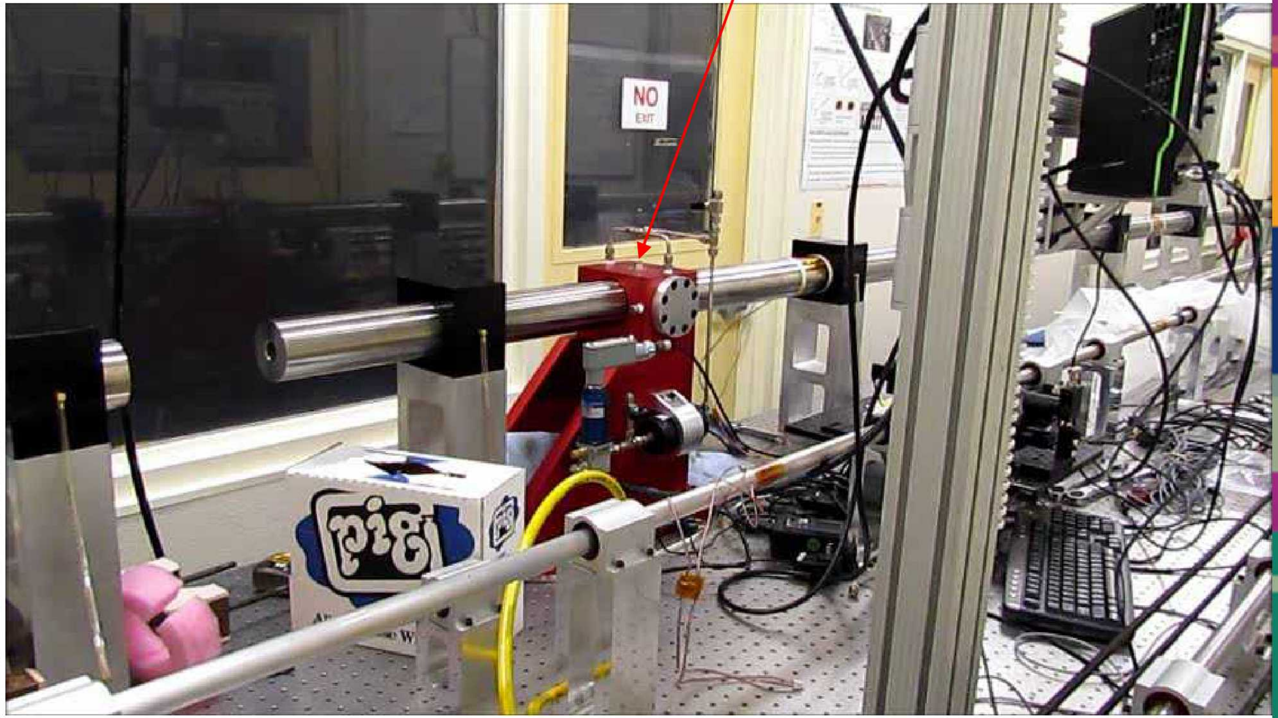
For general mechanical shock tests, a large-diameter, relatively long Hopkinson bar made of a high-strength alloy is preferred.

3”-Hopkinson Bar at Sandia National Laboratories

Diameter: 3”
Length: 12’ with additional 7’ and 5’ bars
Material: C300 maraging steel
Operation pressure: 60 psi

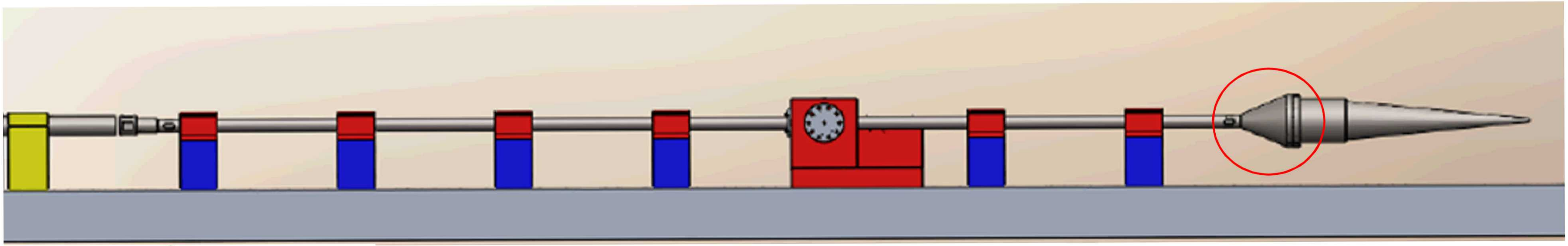
Computer-Controlled Braking System

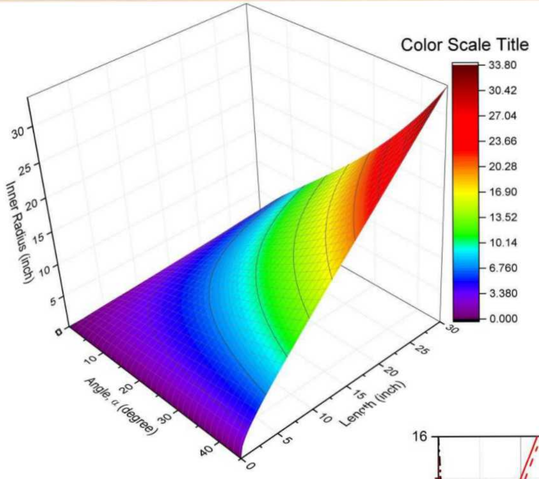


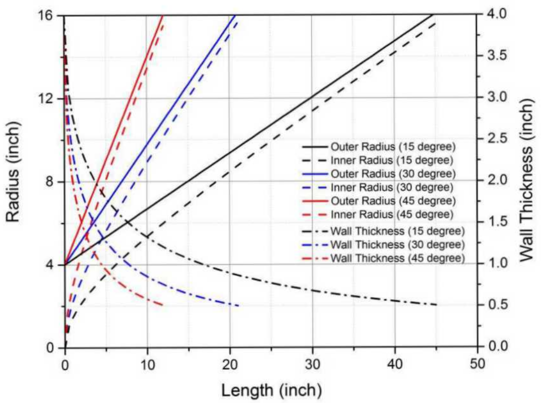


Air Bushing

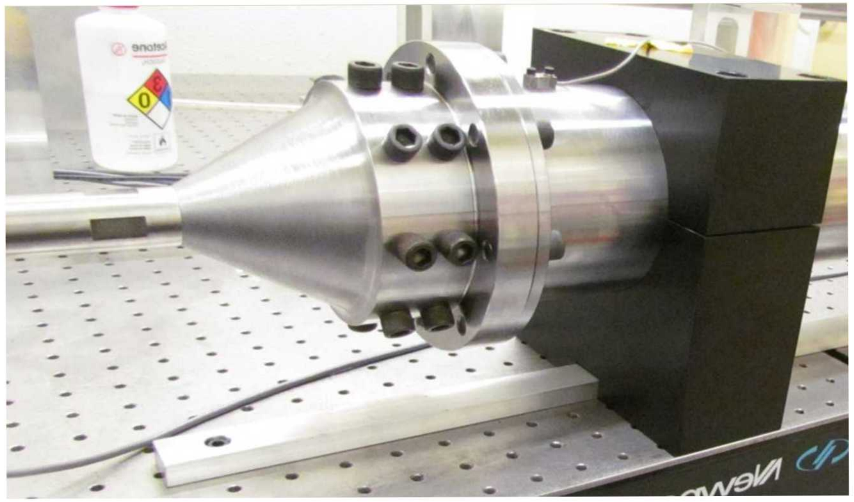
Alternative Design for Larger Test Articles

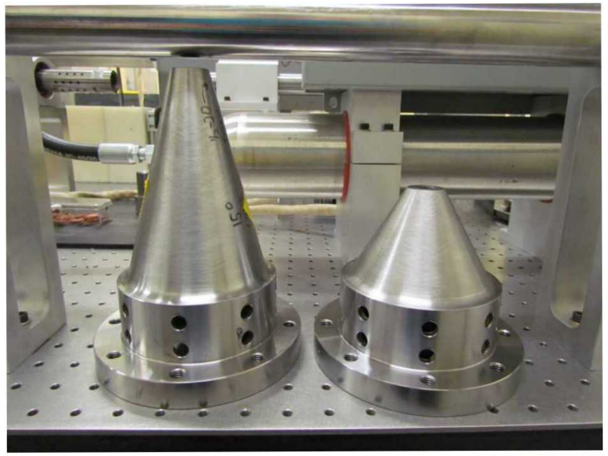


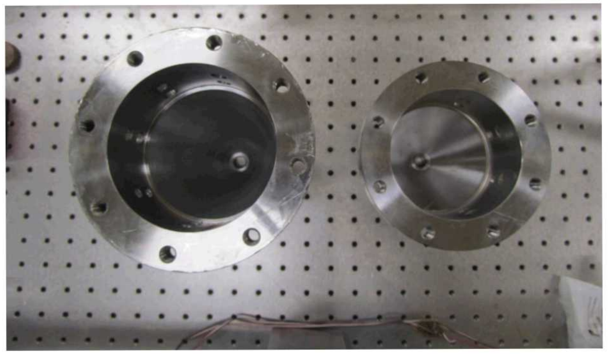




Mechanical Impedance Matched Adapting Cone

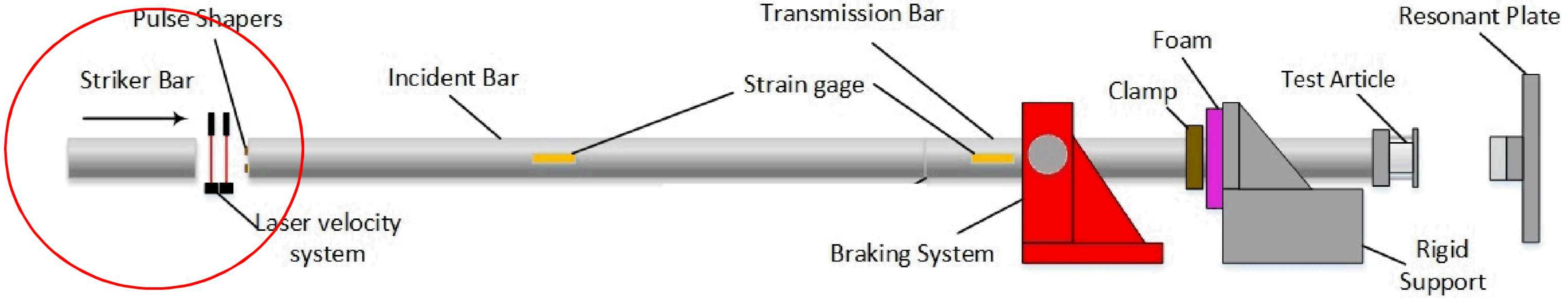


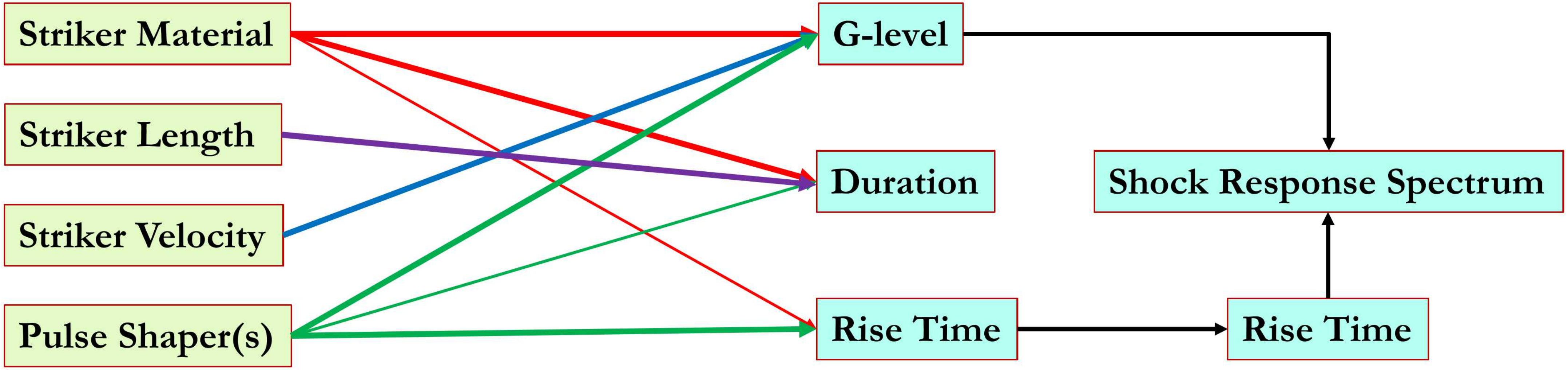




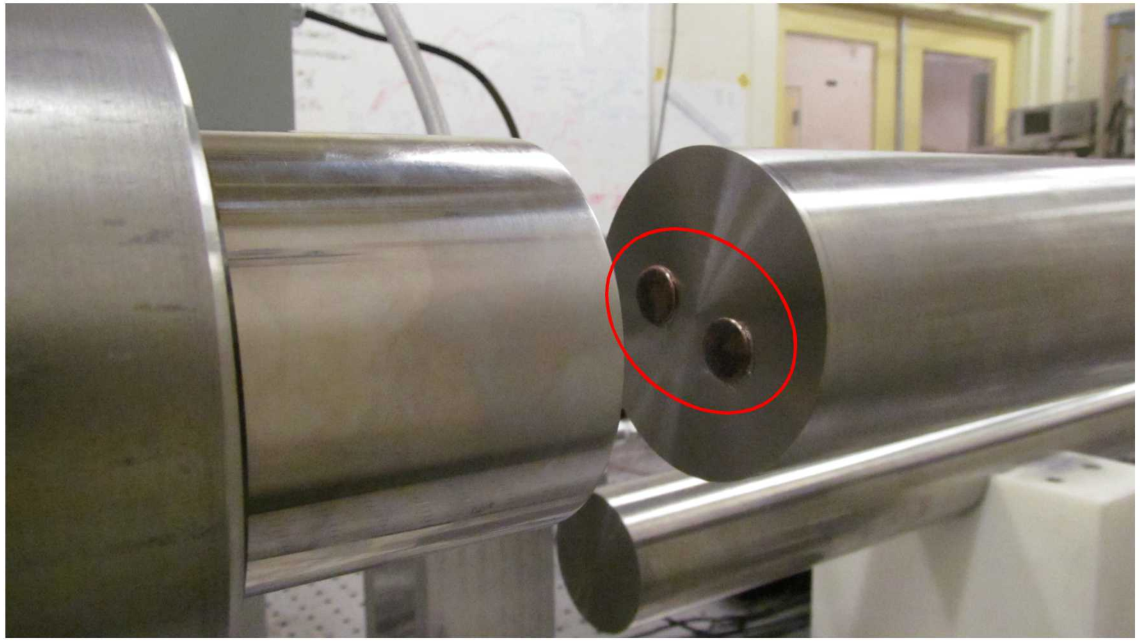
Hopkinson Bar Operation for Mechanical Shock Tests

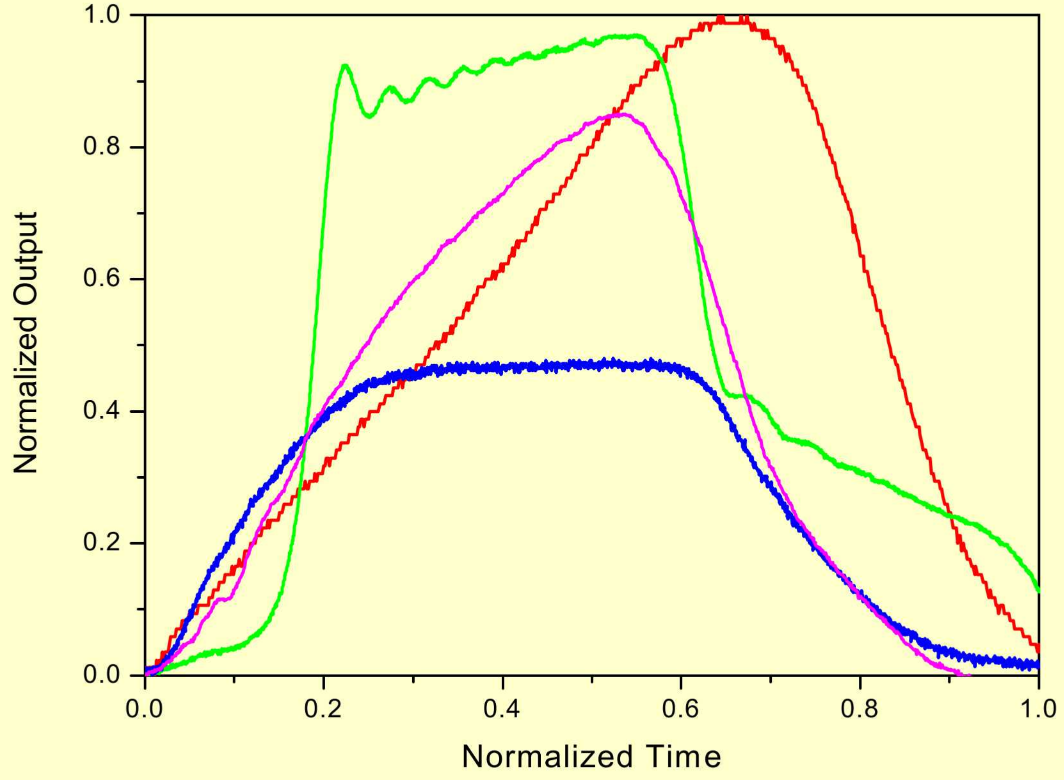
Test Design (Which Controls What?)





Pulse Shaping





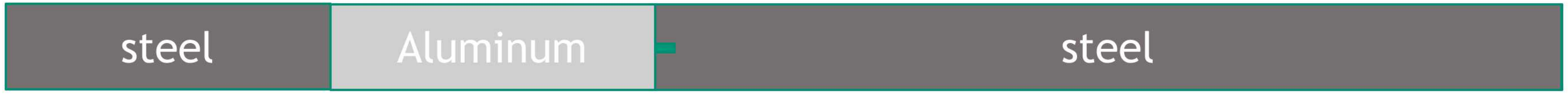
Pulse Shaper(s)

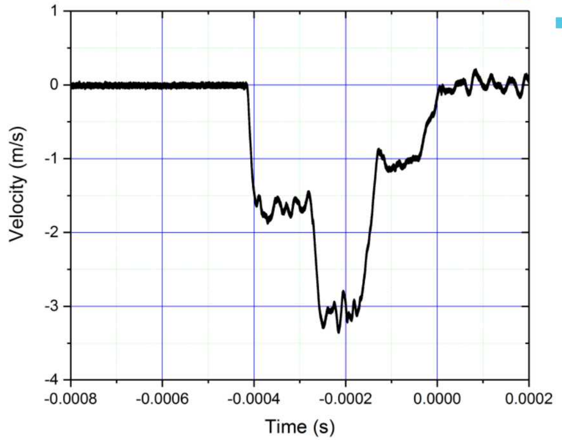
- **Material**
- **Diameter**
- **Thickness**

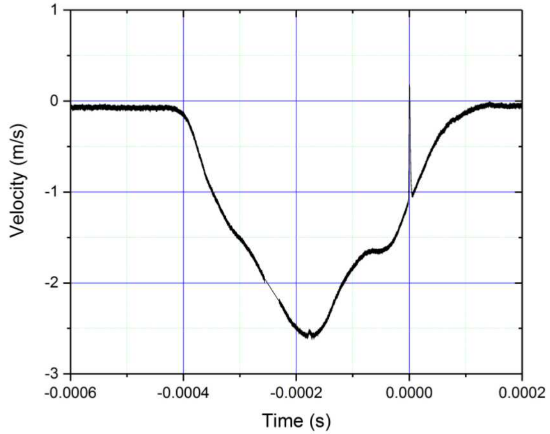
Pulse shaping design also depends on impact velocity and duration.

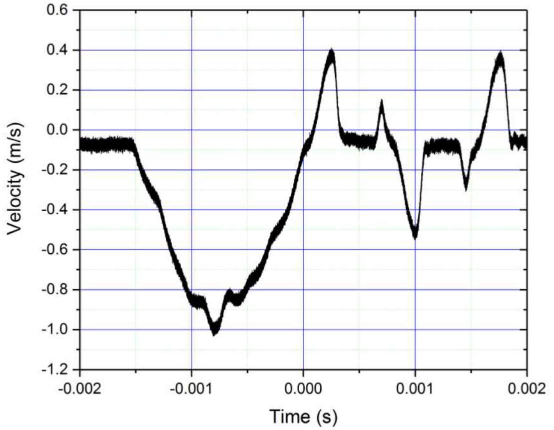
Special Pulse Shaping Design Examples

By changing striker material



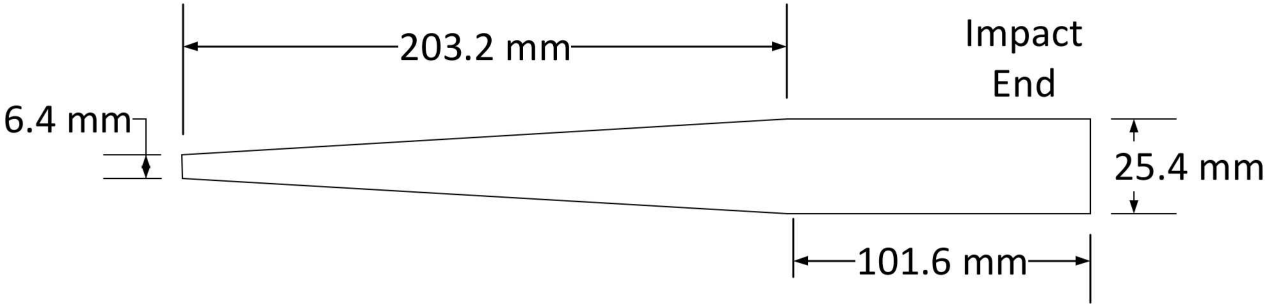


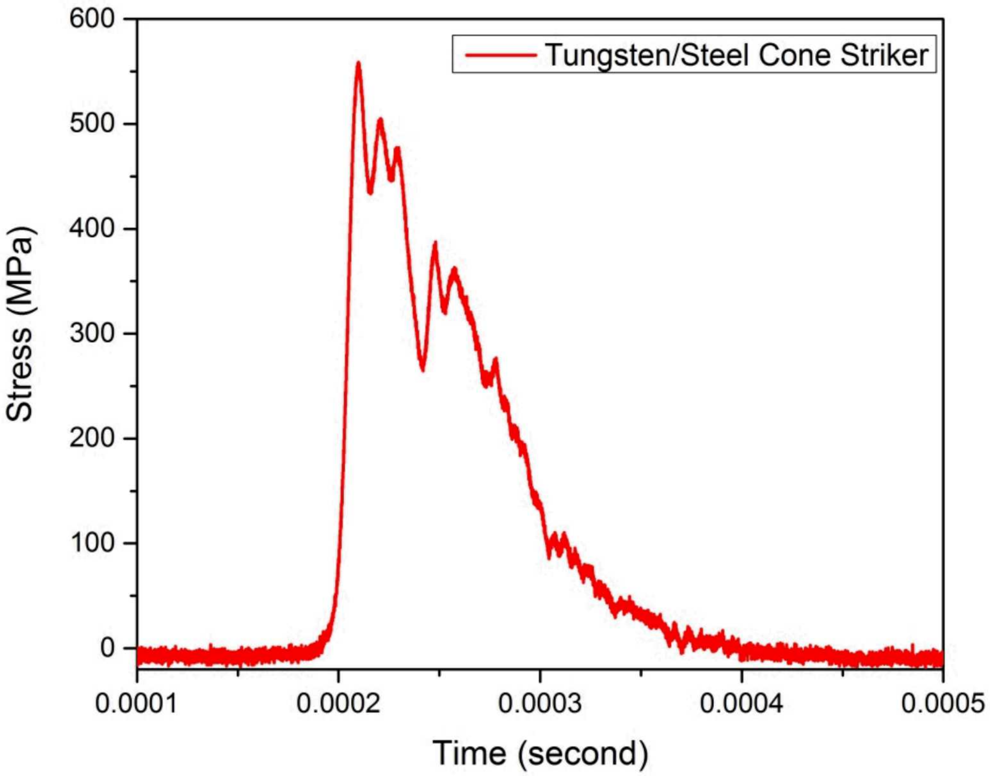




Special Pulse Shaping Design

By changing striker shape (and material)





Hopkinson Bar Limitations for Mechanical Shock Tests

Striker impact velocity

$$V < \frac{2 \cdot \sigma_y}{\rho_0 \cdot C_0} = \frac{2 \cdot \sigma_y}{\sqrt{\rho_0 \cdot E_0}}$$

(striker is made of the same material as the bar and had the same diameter)

For maraging C300 steel,

$$\sigma_y = 300ksi \approx 2.1GPa$$

$$\rho_0 = 8000\, kg/m^3$$

$$E_0 = 189.6GPa$$

$$\Rightarrow \quad V < 107.8\, m/s$$

Rise Time for Velocity

$$\Delta t \approx \frac{2.5 \cdot D_{bar}}{C_0} = \frac{2.5 \cdot D_{bar}}{\sqrt{E_0/\rho_0}}$$

For 1”-diameter maraging C300 steel bar,

$$D_{bar} = 1" = 25.4mm$$

$$\rho_0 = 8000\, kg/m^3$$

$$E_0 = 189.6GPa$$

$$\Rightarrow \quad \Delta t \approx 13 \mu s$$

Hopkinson Bar Limitations for Mechanical Shock Tests

Acceleration

$$a = \frac{V}{\Delta t}$$

For 1"-diameter maraging C300 steel bar,

$$V < 107.8\, m/s$$

$$\Delta t \approx 13 \mu s$$

$$a < 8{,}300{,}000\, m/s^2 = 846{,}000 g$$

A more conservative estimate: $a < 400{,}000 g$

Frequency for Velocity

$$f_V = \frac{1}{\Delta t}$$

For 1"-diameter maraging C300 steel bar,

$$f_V < 65 kHz$$

Frequency for Acceleration

$$F\left[a(t)\right] = F\left[\frac{dV(t)}{dt}\right] = i\omega \cdot V(\omega)$$

The frequency would be much higher for accelerations.

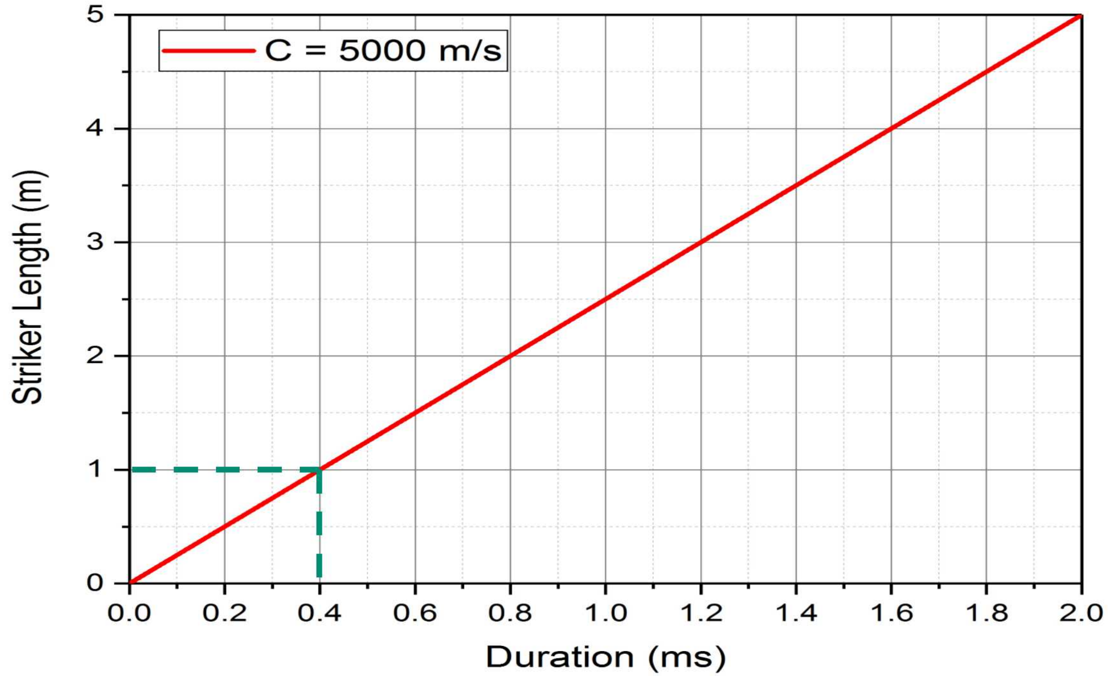
Hopkinson Bar Limitations for Mechanical Shock Tests

Duration of Loading

$$T = \frac{2 \cdot L_s}{C_0} = \frac{2 \cdot L_s}{\sqrt{E_0 / \rho_0}}$$

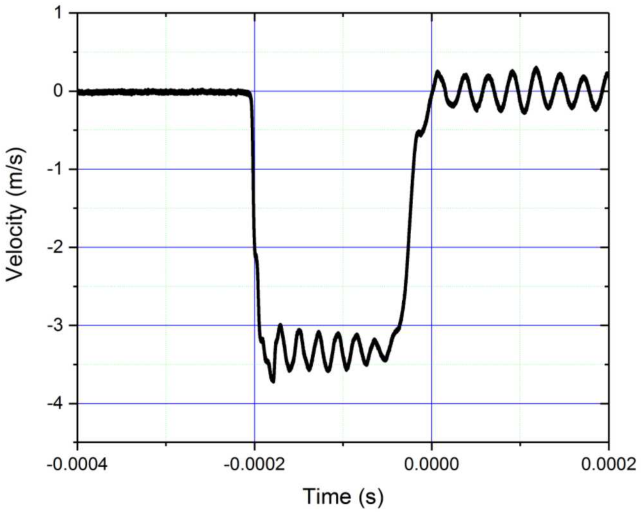
For 1-m-long maraging C300 striker,

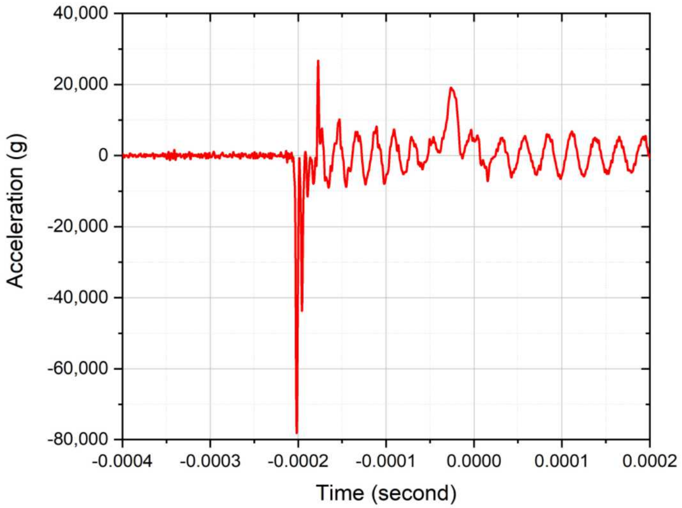
$$T \approx 0.4ms$$



This duration is for velocity pulse. For acceleration, the duration will be much shorter.

For a certain striker, pulse shaper(s) may further extend the duration of loading.





Hopkinson Bar Limitations for Mechanical Shock Tests

Acceleration

$$a \approx 400,000g$$

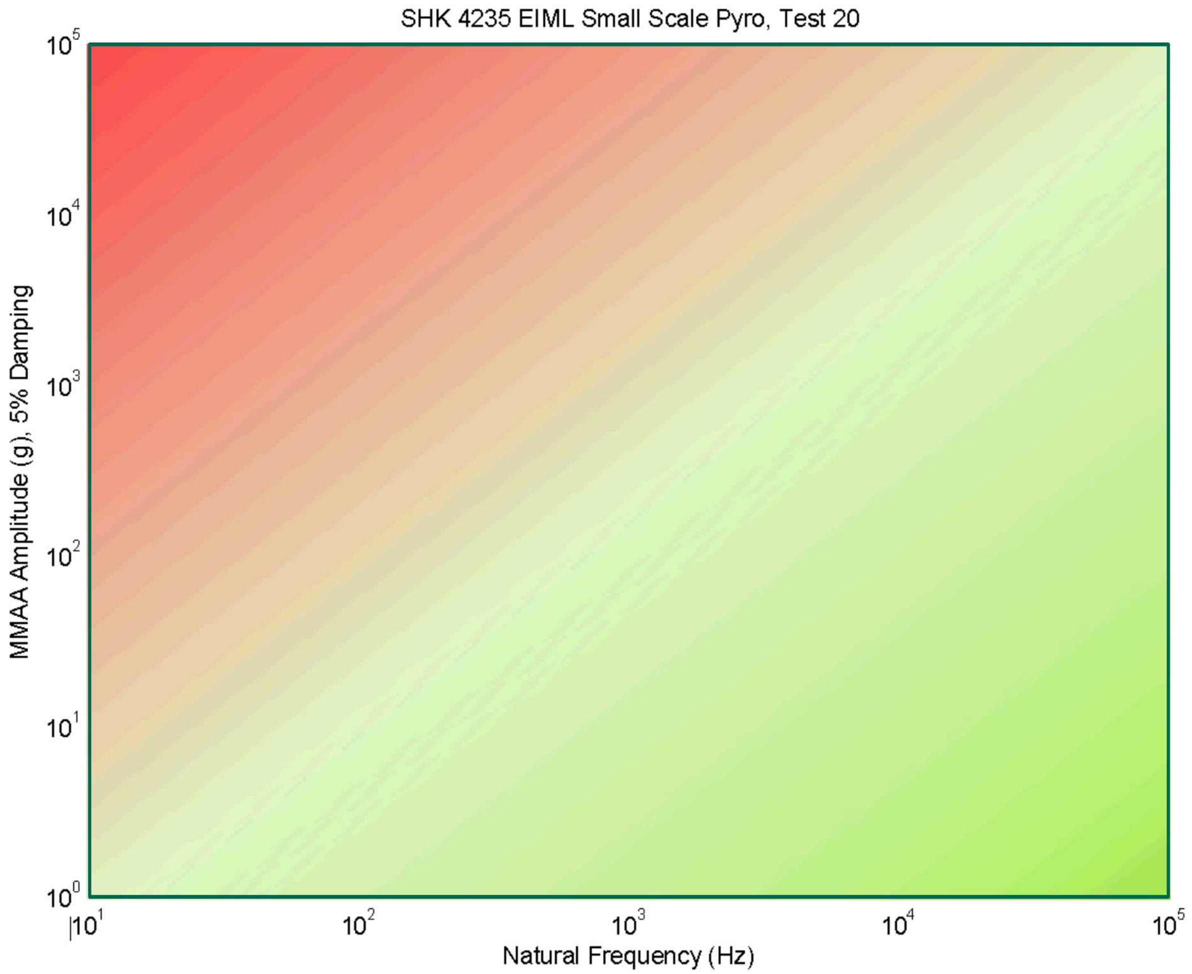
Frequency

$$f \approx 100,000Hz$$

Duration of Loading

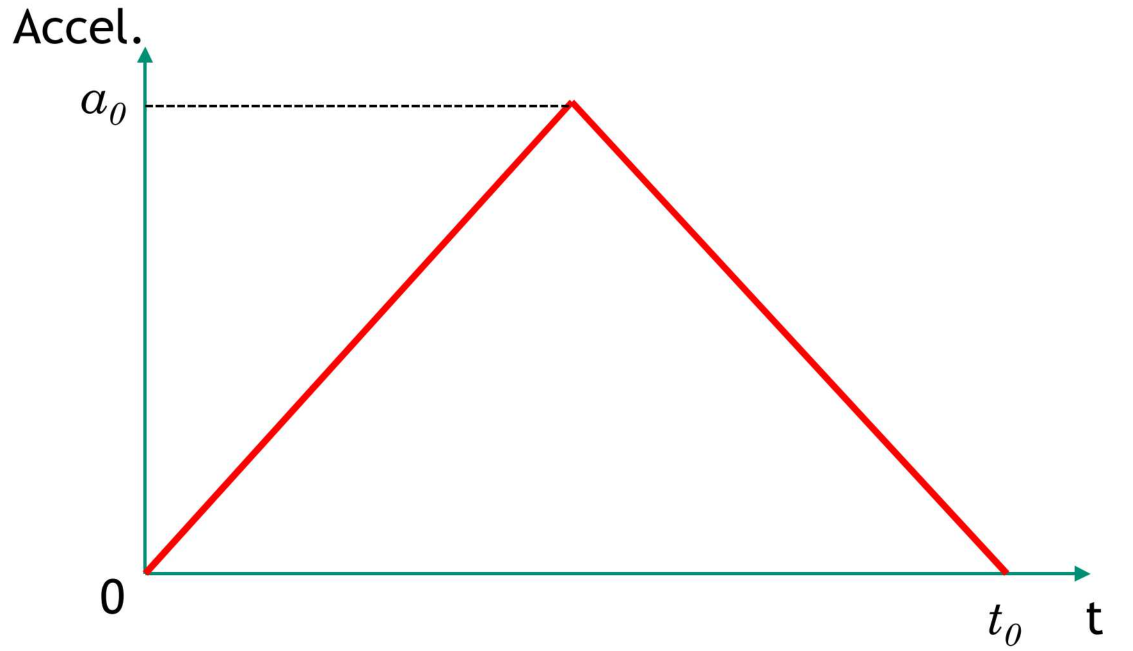
$$T \sim 0.4ms$$

Can we do all of them simultaneously in a single test?

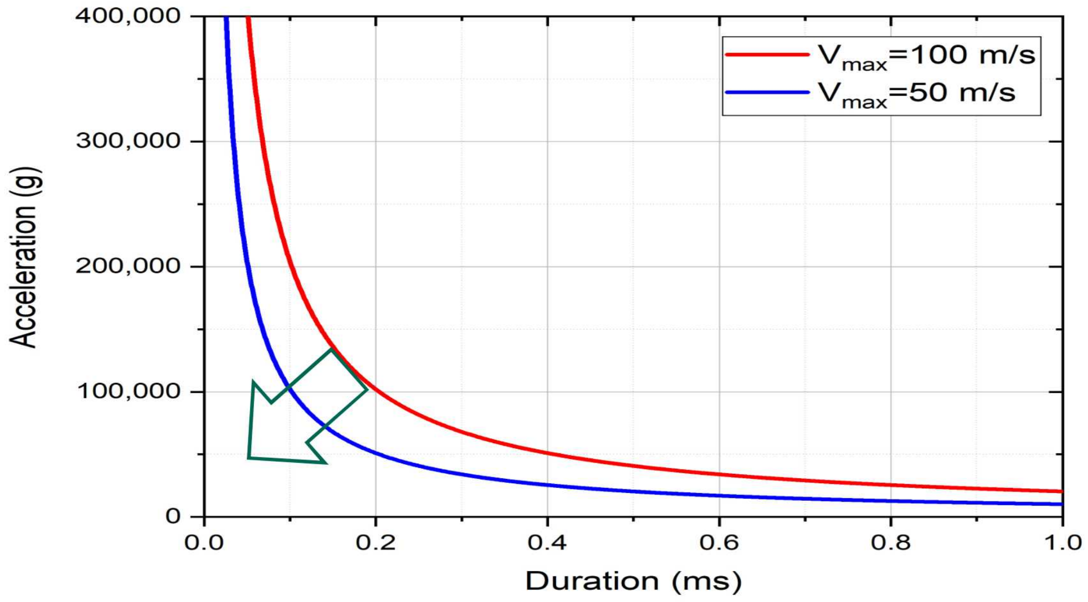


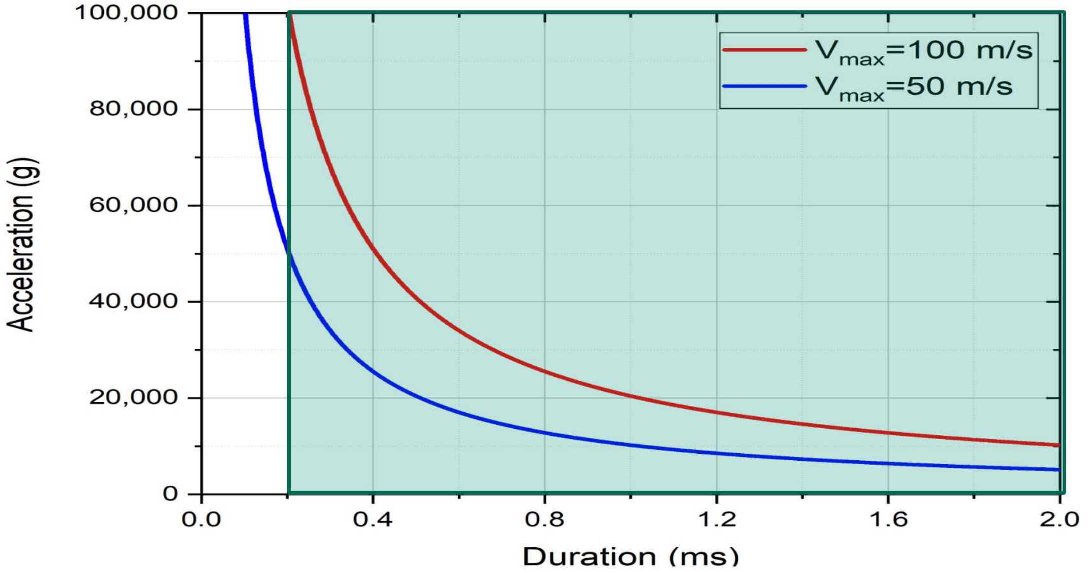
A Very Tricky Problem

For a triangular mechanical shock pulse with a peak of a_0 and a loading duration of t_0.



$$V = \int_0^{t_0} a(t)dt = \frac{1}{2}a_0 t_0 < V_{max}$$

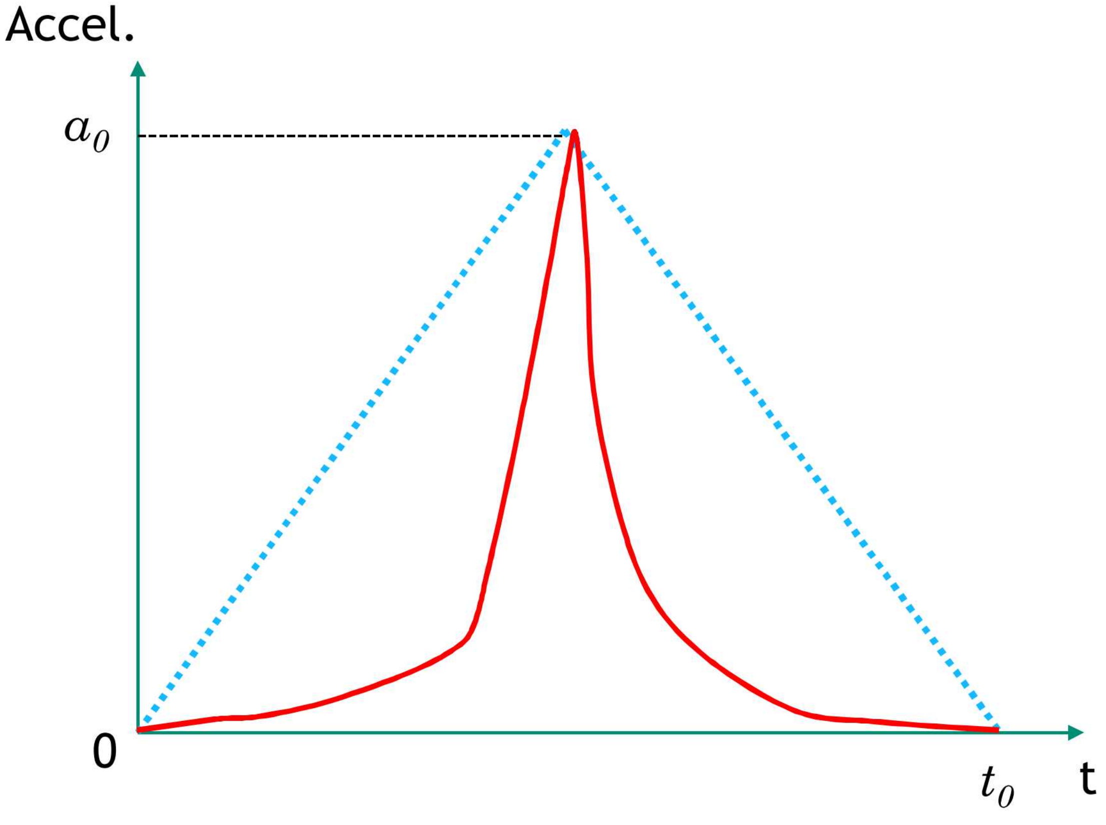


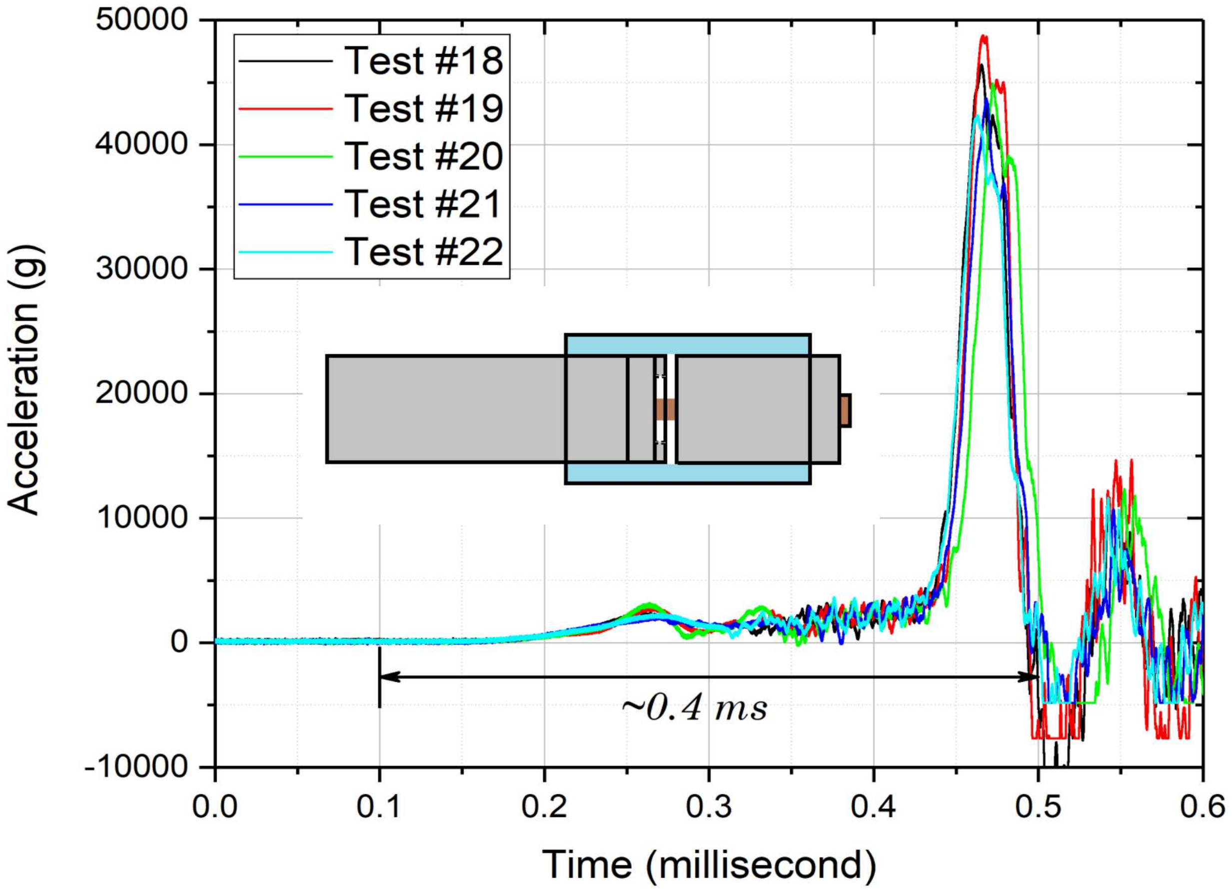


Solutions for Long-Duration Pulse

Near-term Solution

$$V = \int_0^{t_0} a(t)dt = \frac{1}{2}a_0 t_0 < V_{\max}$$

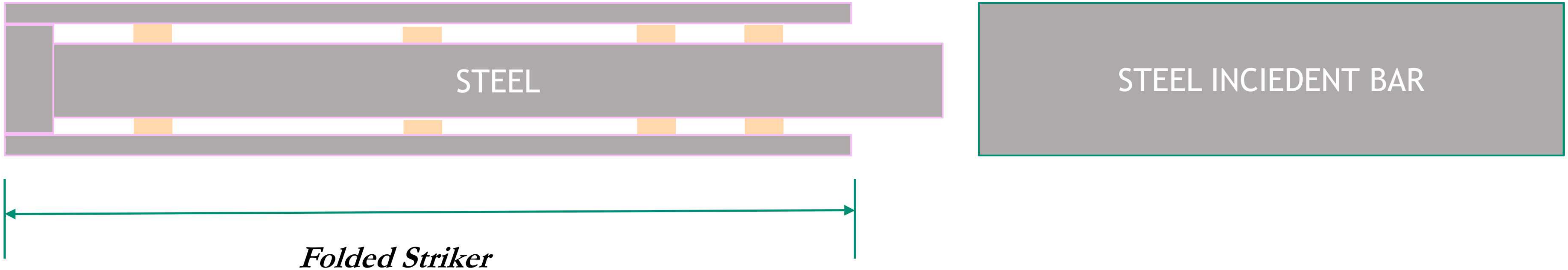




Very unique pulse shaping design

Solutions for Long-Duration Pulse

Near-term Solution

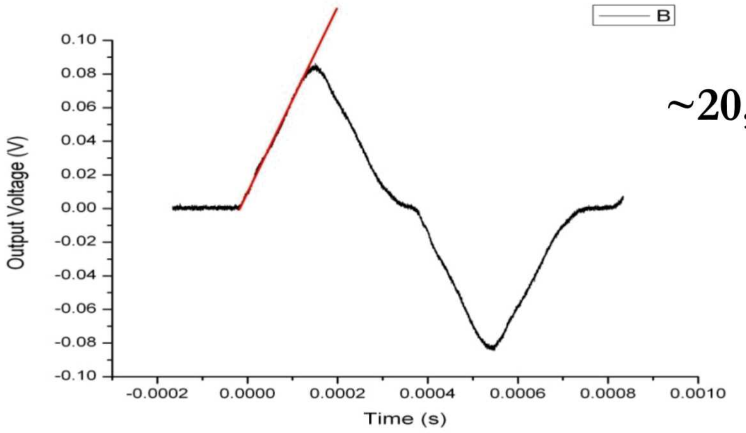


Folded Striker

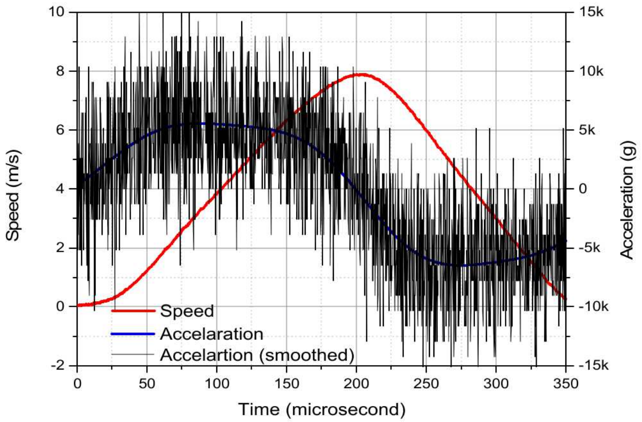
Long-term Solution

A large-diameter, long gas gun/Hopkinson bar system.

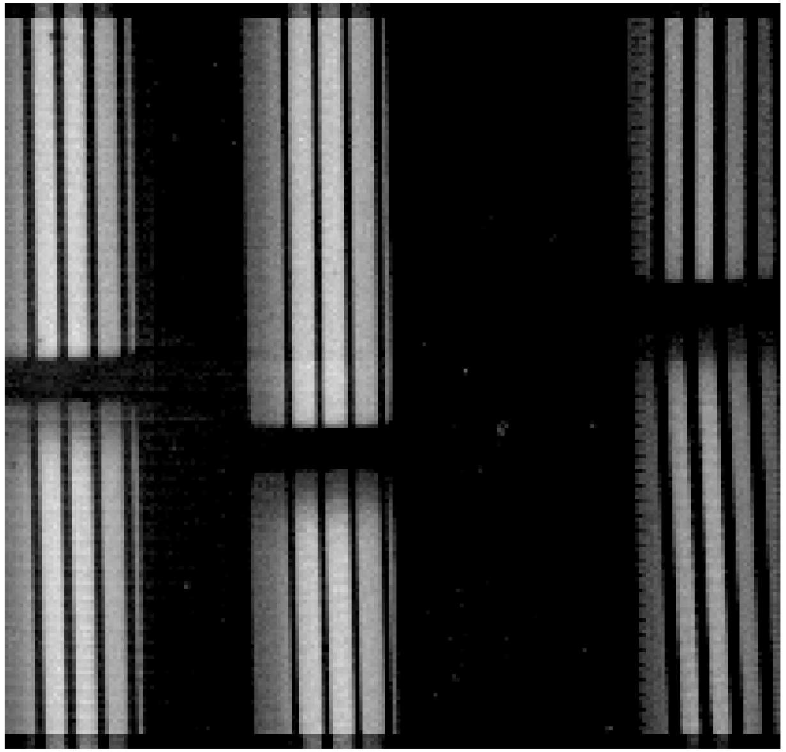
Examples – High-G Shock Tests of Microelectronic Devices with a Hopkinson Bar



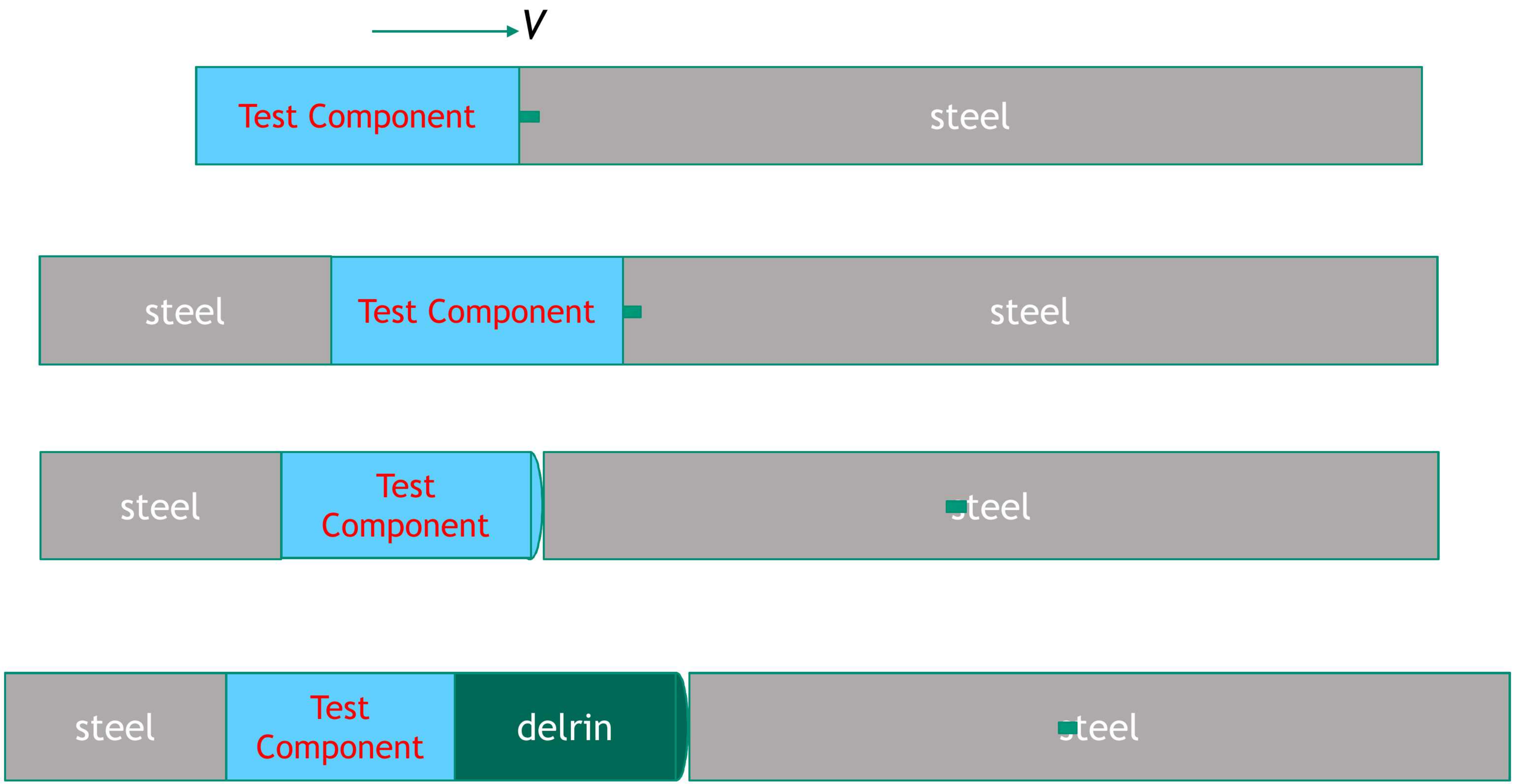
~20,000 g



~6,000 g

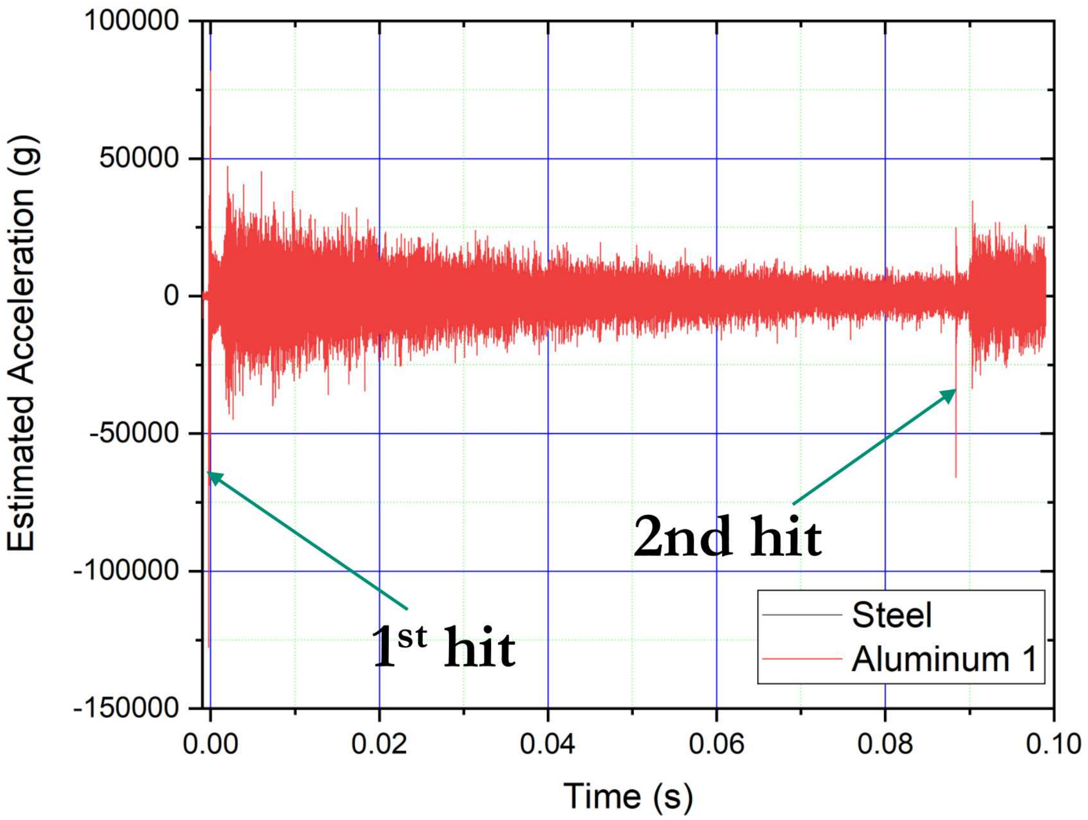


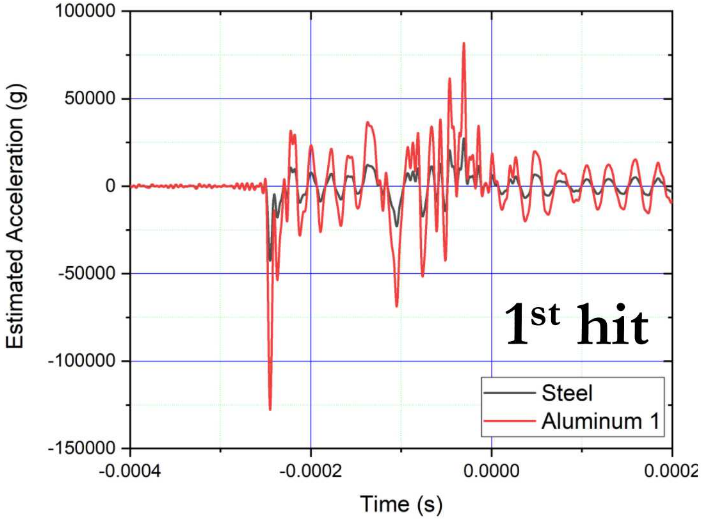
Other Options - Reverse Impact

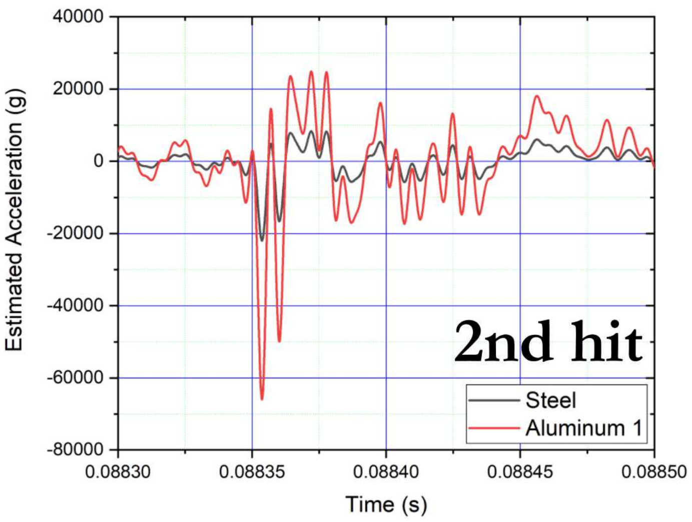


Multiple Hits

The impedance of the test component is lower than that of the pressure bar.







Summary

- **Hopkinson bar is demonstrated to be an effective and efficient tool for high-g, high-frequency mechanical shock tests**
  - ***Duration is the most challenge***

- **Experimental design for high-g, high-frequency mechanical shock tests with Hopkinson bars is case by case, depending on the test unit and requirements**
  - ***Pulse shaping is the most challenge***

- **Hopkinson bar can be extended for more specific tests**
  - ***Reverse impact***
  - ***Multiple hits***
  - ***Environmental temperatures***

Experimental ***I***mpact ***M***echanics ***L***aboratory (***EIML***) at Sandia

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