Constitutive relation development through the FIRE test

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Overview

- Fully Instrumented Ring Expansion (FIRE)
- Motivation & Background
- Equipment Development
  - Velocimetry
  - Actuators
- Experimental Results
- Future Work
- Conclusions

Motivation

- High rate deformation is difficult to characterize, yet constitutive properties in this regime are valuable
- Traditional high rate tensile testing is limited by the Von Karman velocity:

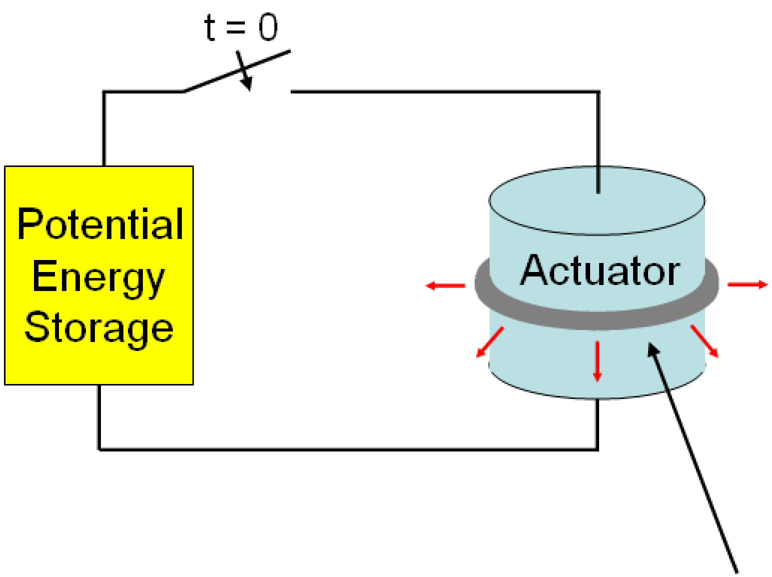
$$v_{VK} = \sqrt{\frac{\partial \sigma / \partial \varepsilon}{\rho}}$$

  - SHPB limited to $\dot{\varepsilon}$ = ~1000 s^{-1} in tension
- Compression tests are possible at high rate, but can't account for T-C asymmetry
  - Additional correction factors needed as well

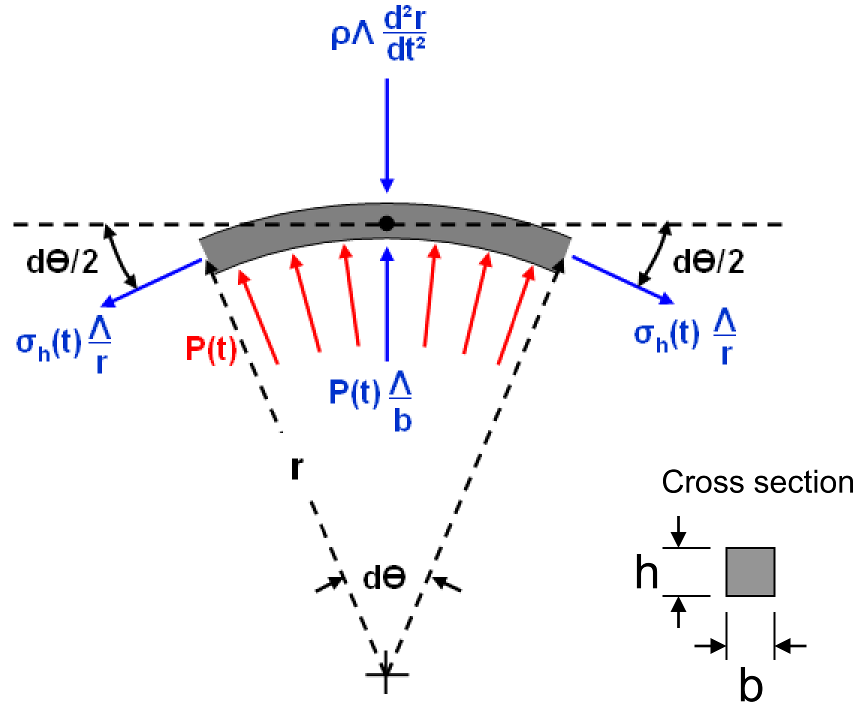
Motivation

- Ring expansion testing has been shown to be unaffected by the Von Karman velocity, due to geometric factor
  - 2D as opposed to 1D loading
  - Strain produced by a uniform velocity gradient
- Simple uniaxial tension – provided by symmetry
  - Caveat: thin rings, where thickness < ~10*(radius)
  - More complicated analytical analyses and/or FEA can potentially deal with 2D effects in thick rings (future)
- Potential application in many materials systems
  - Not just good conductors

Background



Ring sample



Ring segment

$$\Lambda = bhrd\theta$$

↓

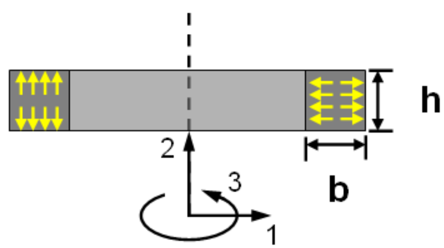
$$\rho\Lambda\frac{d^2r}{dt^2} = P(t)\frac{\Lambda}{b} - \sigma_h(t)\frac{\Lambda}{r}$$

→ For P(t)≈ 0 →

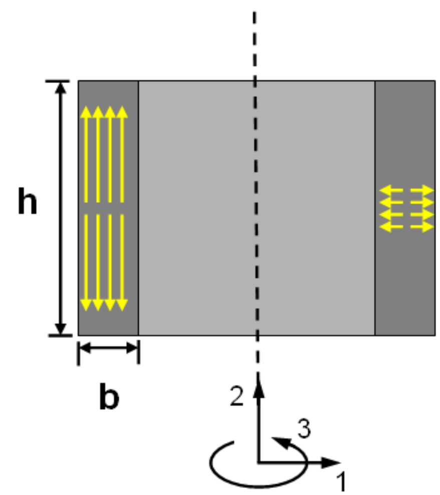
$$\boxed{\sigma_h(t) = -r\rho\frac{d^2r}{dt^2}}$$

Background

- Stress state can be varied from plane stress to plane strain with choice of sample cross section aspect ratio
  - Due to inertial constraint in the axial direction



Plane stress: $\varepsilon_1 = \varepsilon_2 = -\varepsilon_3/2$



Plane strain: $\varepsilon_2 = 0$, $\varepsilon_1 = -\varepsilon_3$

Background

- Photon Doppler Velocimetry (PDV) has provided accurate measurements that are simple to acquire and analyze

Beat frequency from recombined reference and Doppler shifted light:

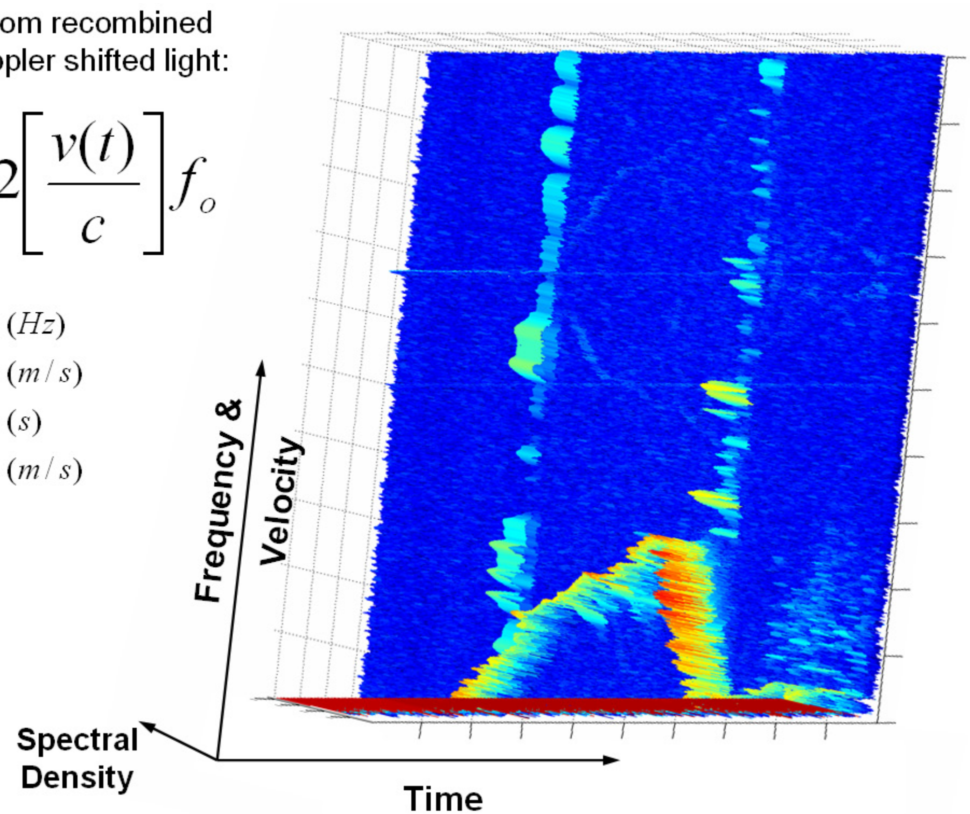
$$f_{beat}(t) = 2\left[\frac{v(t)}{c}\right] f_o$$

$f = frequency \quad (Hz)$

$v = velocity \quad (m/s)$

$t = time \quad (s)$

$c = 2.998 * 10^8 \quad (m/s)$



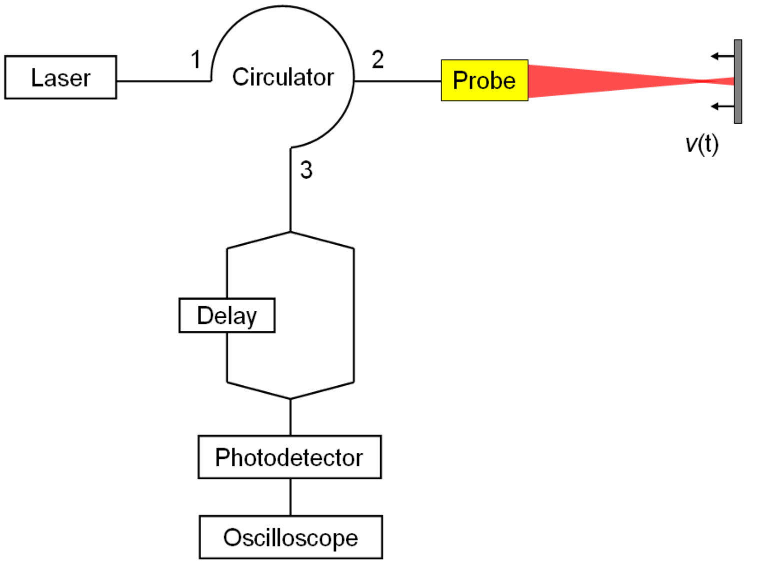
MatLab command: "spectrogram" - `spectrogram(pdvdat,t,(t/2),f,fs);`

Velocimetry

- OSU's PDV system consists of:
  - 1 watt Er fiber laser: λ = 1550 nm
    - Stable, tunable, 3 kHz line width
  - 1 GHz digital storage oscilloscope
  - 1.5 GHz photodetectors
  - Various optical components and probes
- Measurement specifications:
  - 0 to 1 km/sec
  - 1 ns temporal resolution
  - 1 µm spatial resolution

Velocimetry

- Recently discussed Photon Doppler Accelerometer (PDA)
  - Measuring acceleration directly avoids issues that arise when differentiating high speed signals
- Proof of concept has been demonstrated
  - Simple additions to PDV system are all that is needed
  - Laser sources are stable enough to avoid phase noise over the periods of interest for t_{delay}



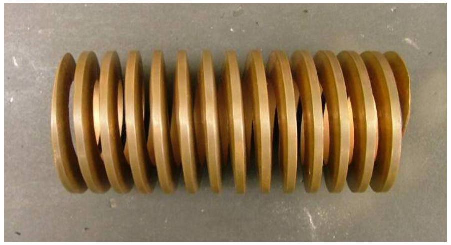
Probe must be a non-back reflecting type for PDA (specify as -60 dB return loss)

Actuators

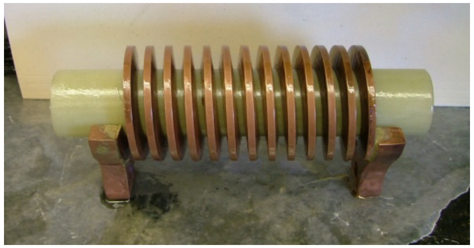
- Electro-Magnetic (EM)
  - Improvements in construction technique have produced highly accurate, robust actuators
    - Repeatable use energy limit > 10 kJ
  - CNC machined coils from billet C18150
  - Spectra fiber filament winding adds strength

Example: Tube Compression Actuator

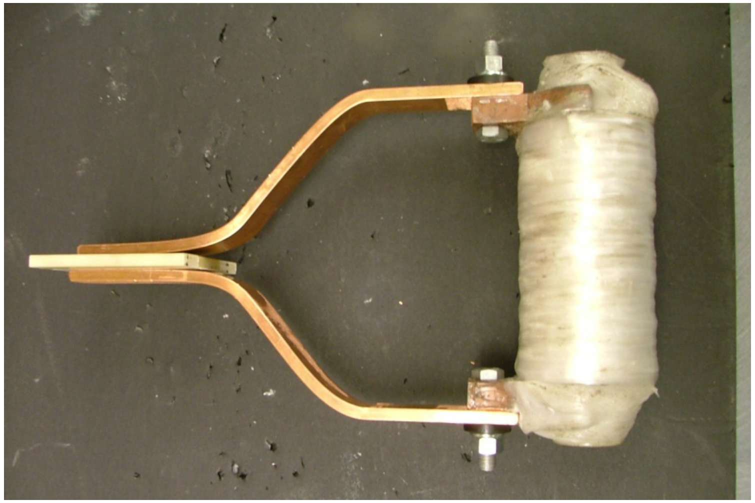
Machined coil



Brazing and coating



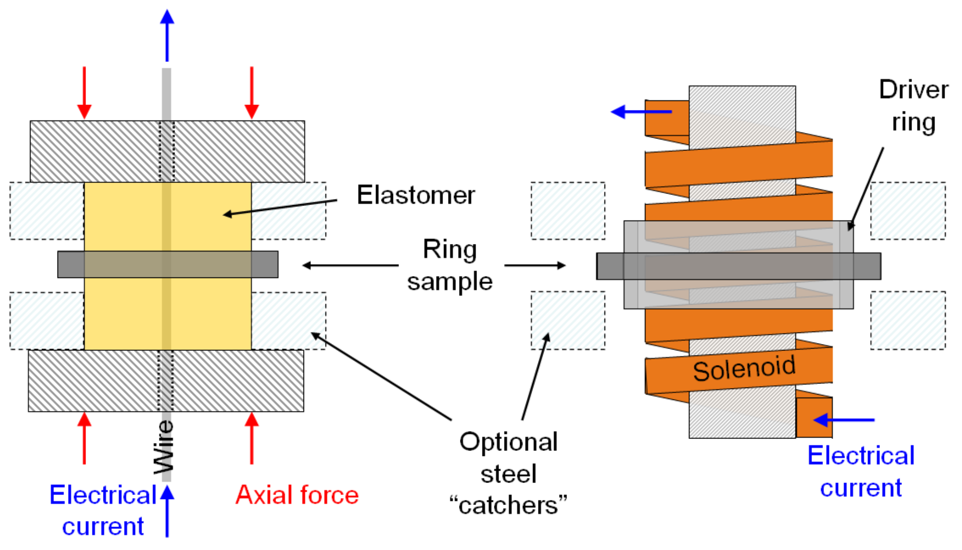
Filament winding



Actuators

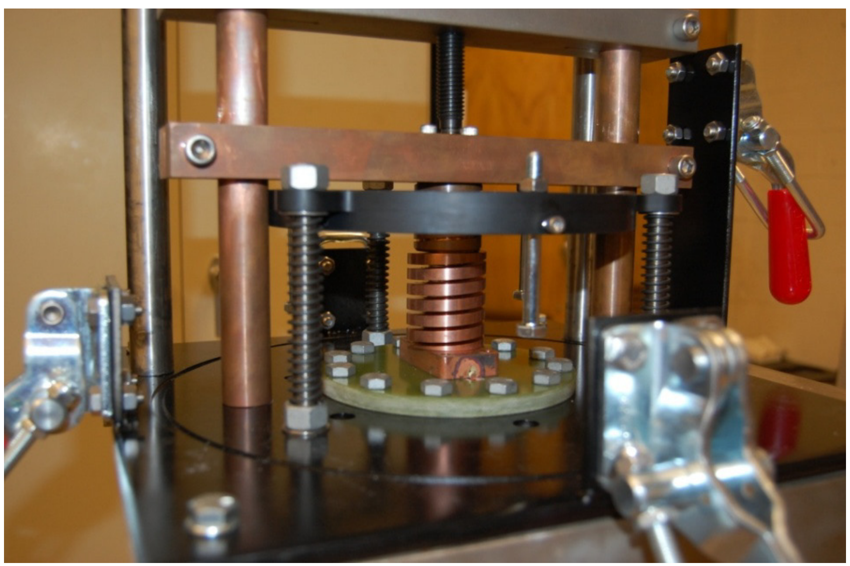
- Exploding Wire (EW)
  - Disposable – no energy limitation
  - Have had good luck with polyurethane as pressure transfer medium
  - 0.060” diameter Al welding wire works well
  - Optional radial steel constraint rings provide a pressure history that is much closer to an ideal delta function

EW vs. EM actuator

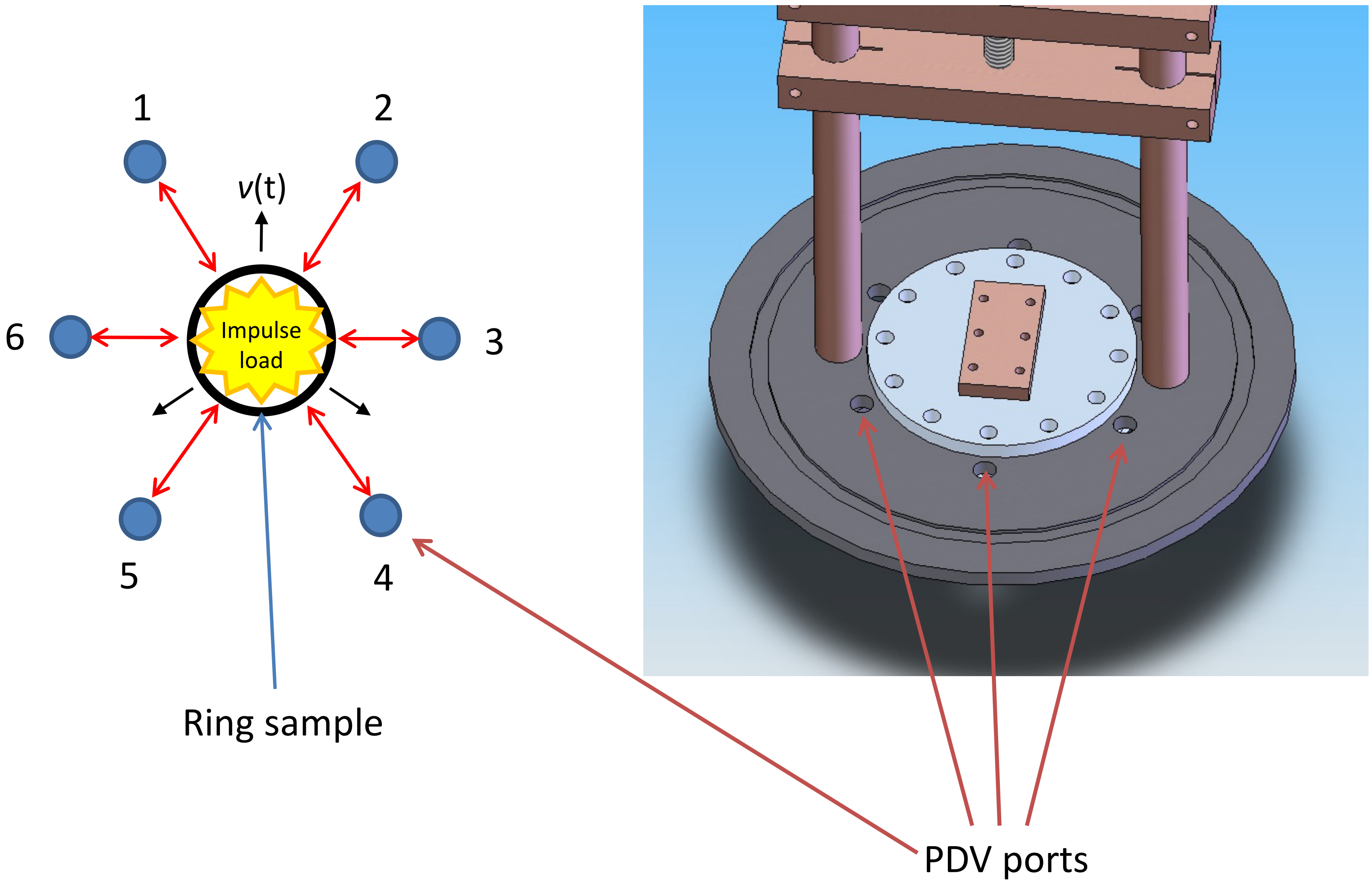


The FIRE System

- Fully Instrumented Ring Expansion (FIRE)
  - Combines up to 6 channels of velocimetry and ability to precisely measure current & voltage from power supply
  - Interchangeable EW and EM actuators
  - Machine tool accuracy

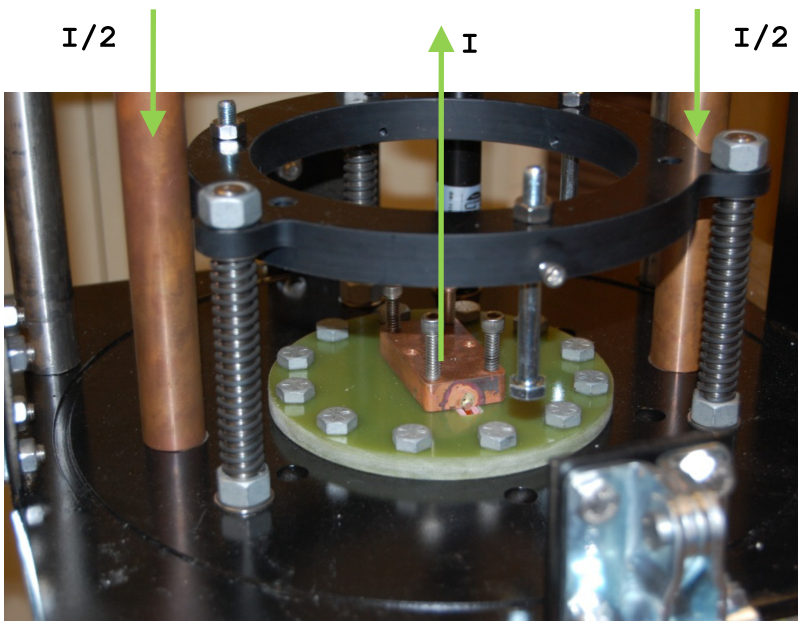


The FIRE System



The FIRE System

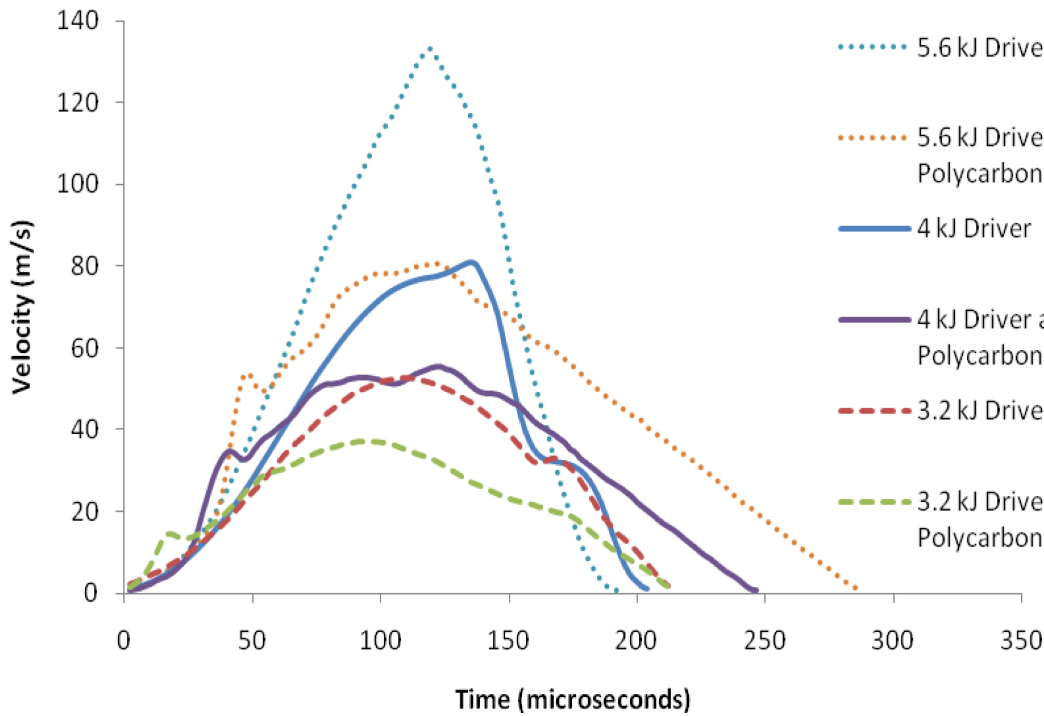
Symmetric current path:

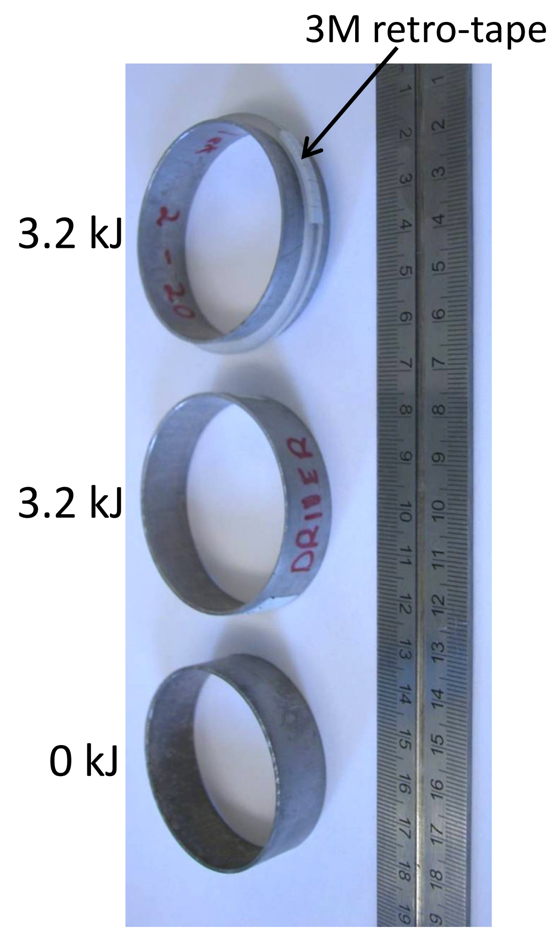


- PDV support ring is located in a plane via 3 threaded posts
- Can independently or simultaneously adjust all 6 PDV channels for axial height
  - Useful on long tube samples

Experimental Results

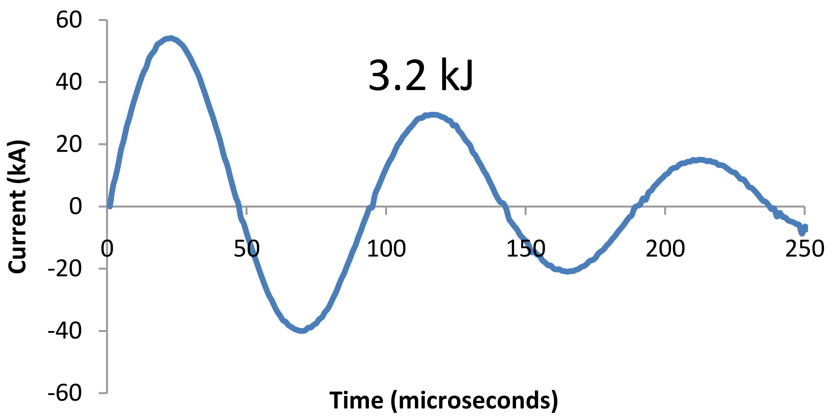
- Indirect expansion of polycarbonate rings
  - 2” inside diameter, 0.12” wall thickness extruded polycarbonate tube
    - 0.12” sample height
- Summary of 6 shots
- Compare bare driver to composite driver/sample

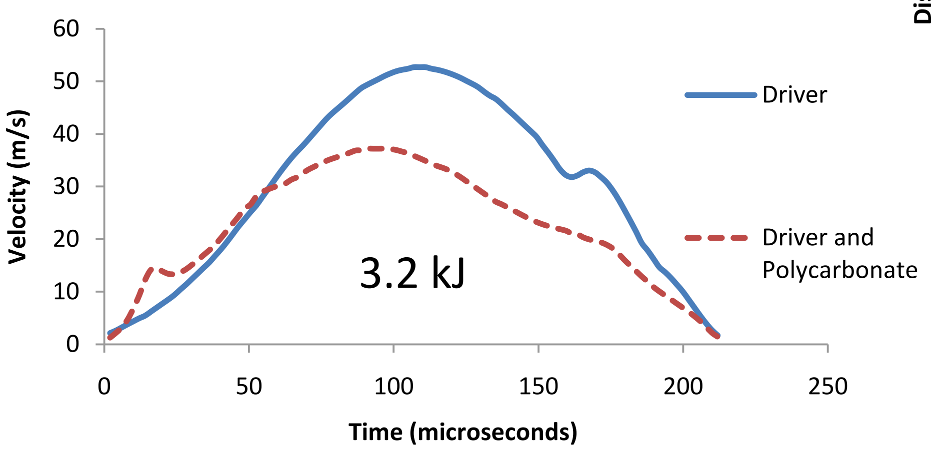


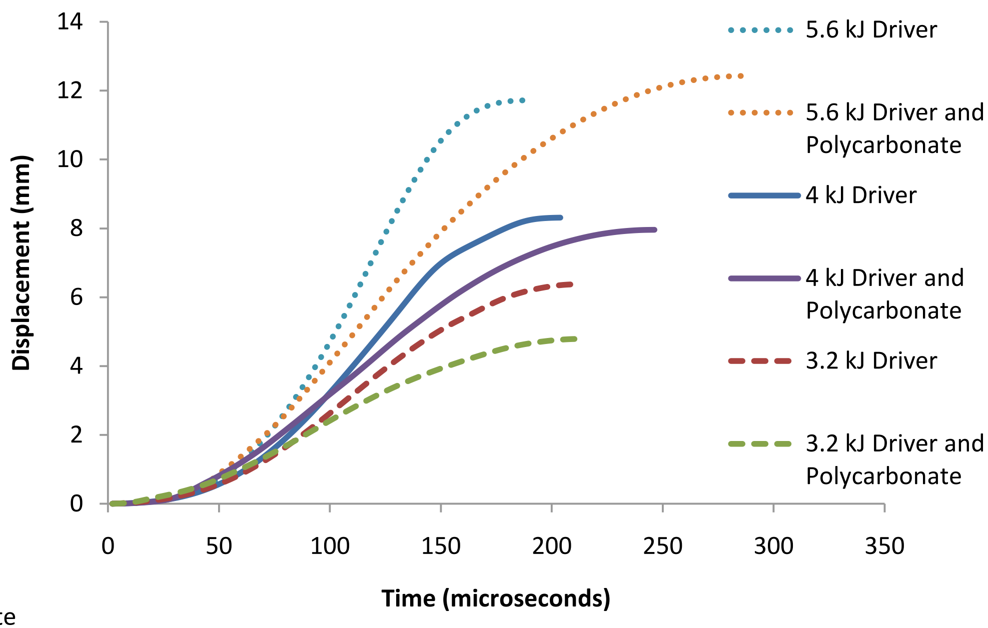


Experimental Results

- Indirect EM expansion of polycarbonate rings
- Data is from 10 cm focal length, -15 dB PDV probes

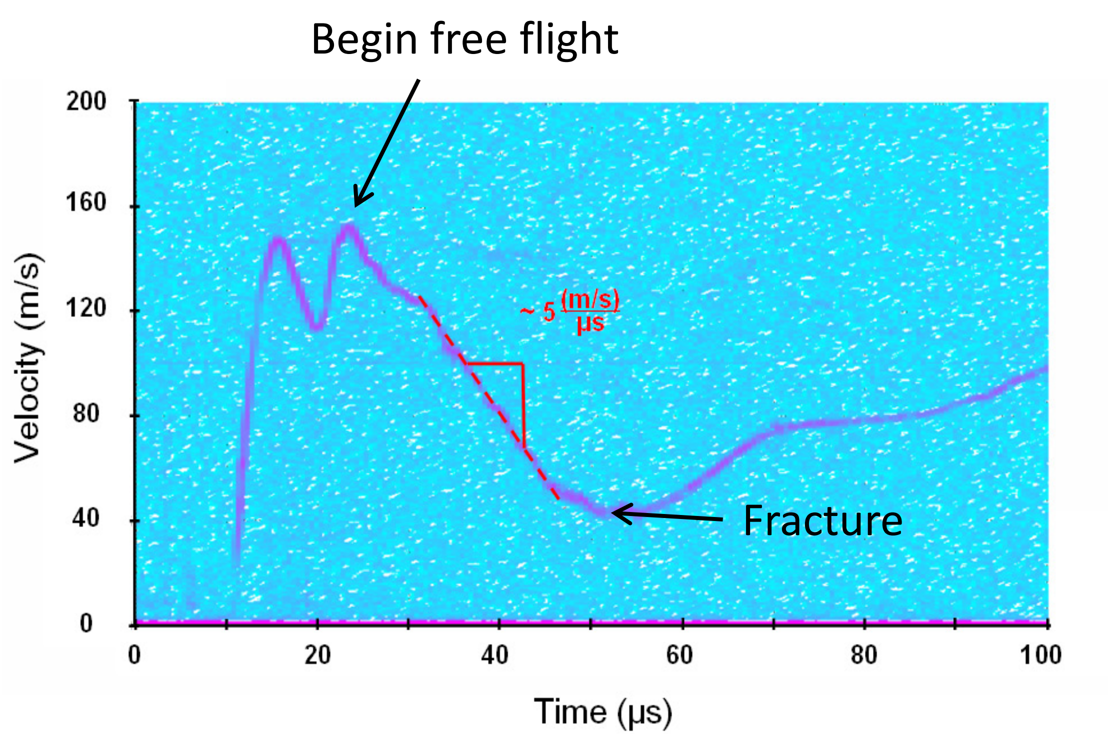






Experimental Results

- EW expansion of AISI 4130
  - 1.027” inside diameter, 0.049” wall thickness seamless DOM tube
    - 0.375” sample height
  - 1” long, 1” outside diameter extruded urethane actuator body
    - Durometer rating: 80 Shore A
  - 6.4 kJ shot energy



30 cm focal length, -15 dB probes were used in this experiment

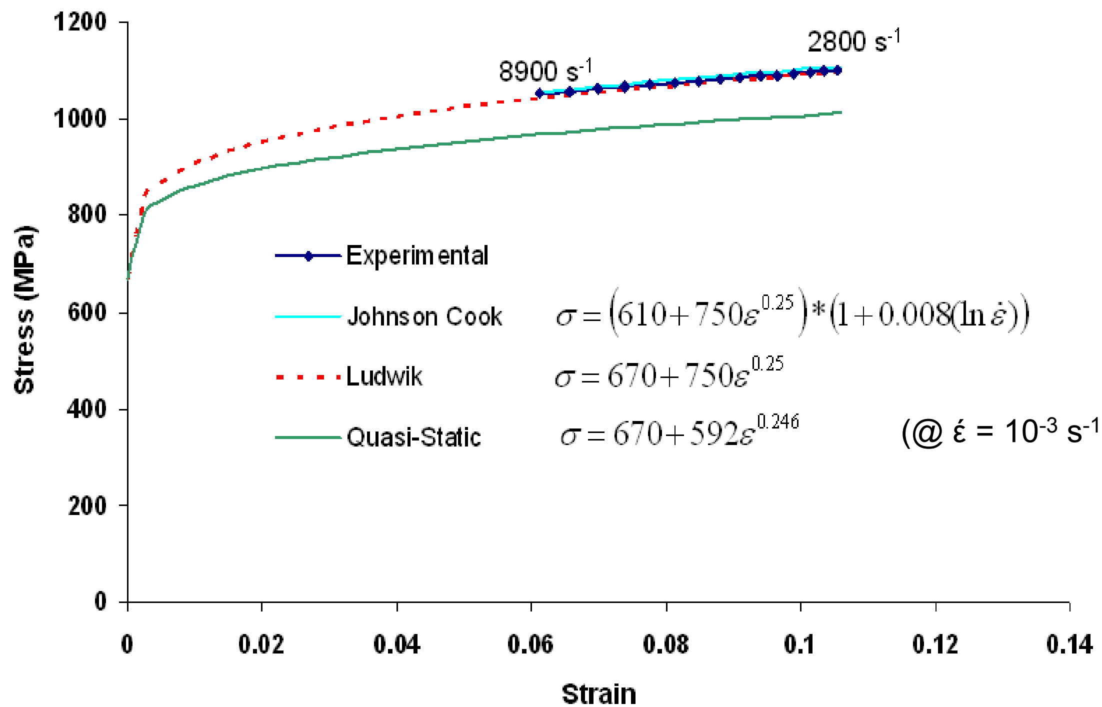
Peak strain rate ~12000 s^{-1}

Experimental Results

- EW expansion of AISI 4130 HSLA steel
  - Track displacement and strain rate of region shown above
  - Use freely expanding ring analysis
  - Fit constitutive model of choice to data

$$\sigma_h(t) = -r\rho \frac{d^2 r}{dt^2}$$

-5×10^6 m/s^2



Quasi-static data adapted from *Park, L., et al,* **Materials Science and Engineering A**, Vol. 527, pp. 645-651, 2010.

Future Work

- Elevated temperature testing is a priority
  - Can use ceramic fiber or graphite tape to thermally isolate samples from actuator
    - Initially heating will be accomplished by radiant and/or convective transfer
    - Later revision will likely incorporate induction heating
  - Thermocouple probes and/or infrared thermal detector will be added
- Geometries other than the simple ring and expansion actuator
  - Notched rings for fracture toughness
  - Compressive variant – already demonstrated, needs adaptation to FIRE system
    - Collapse of tubes filled with a compressible media
  - Shear variant – addition of tool steel ring with shearing edge

Conclusions

- Ring expansion offers rapid assessment of tensile properties in ductile materials
- Constitutive parameters can be extracted
  - This is easiest for the freely expanding ring
- High speed velocimetry is an indispensable tool in the FIRE system arsenal
  - PDV is becoming well established
  - PDA is promising

Comments?