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Dynamic Mechanical Response of Brain Tissues

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Brett Sanborn
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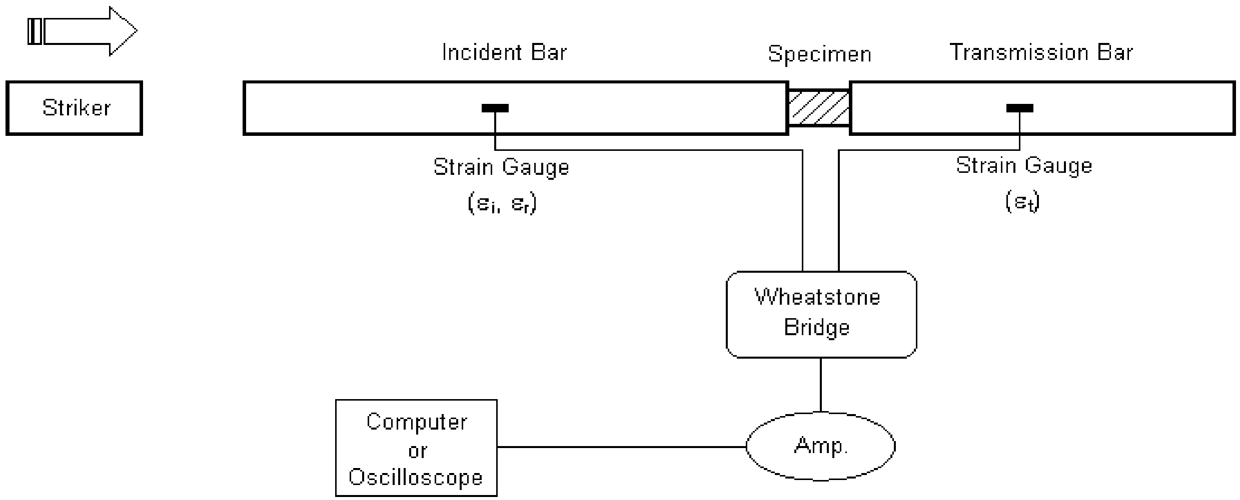
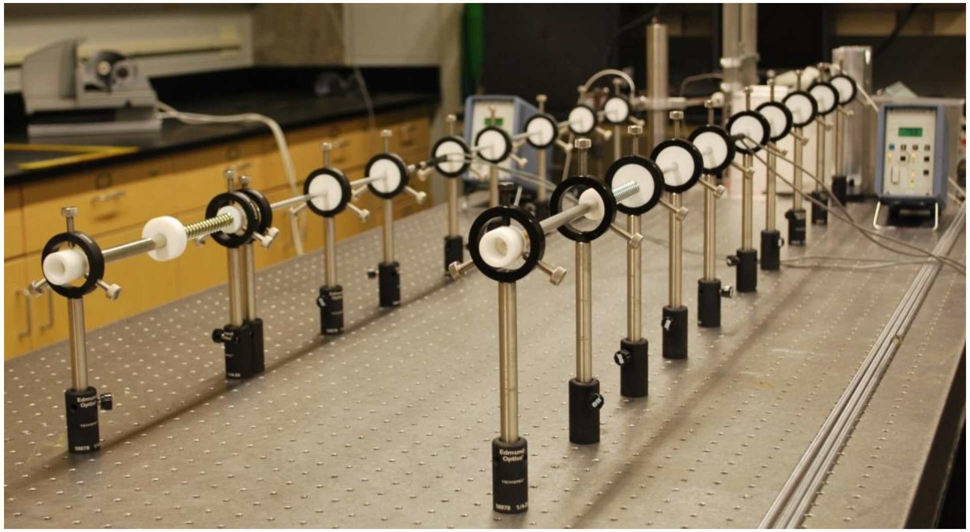
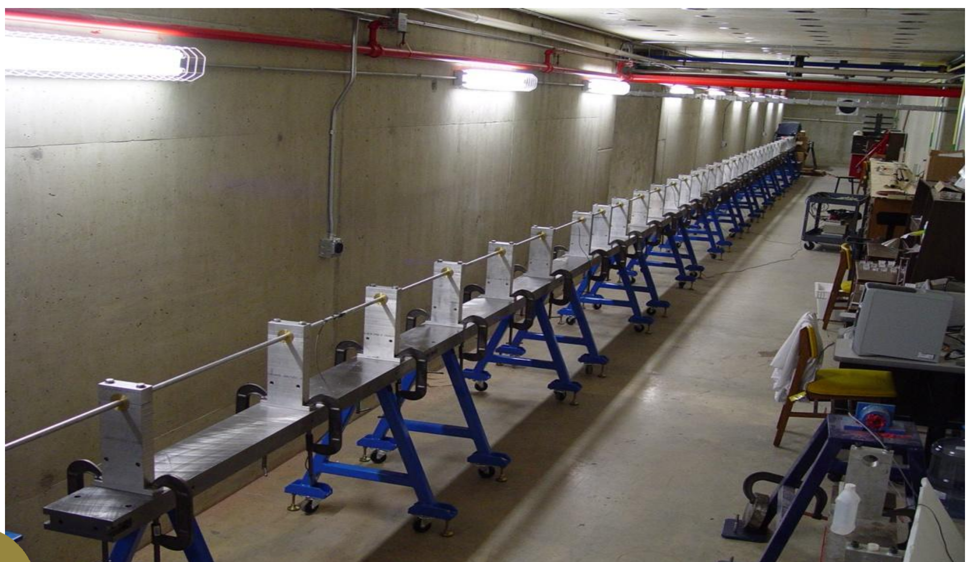
Kolsky Bar



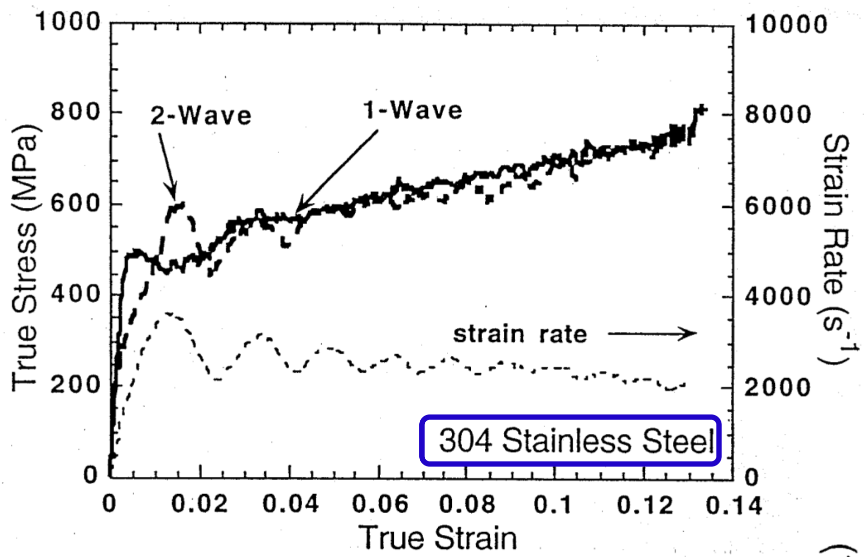
Lindholm, 1964

Some of the Kolsky Bars at Purdue



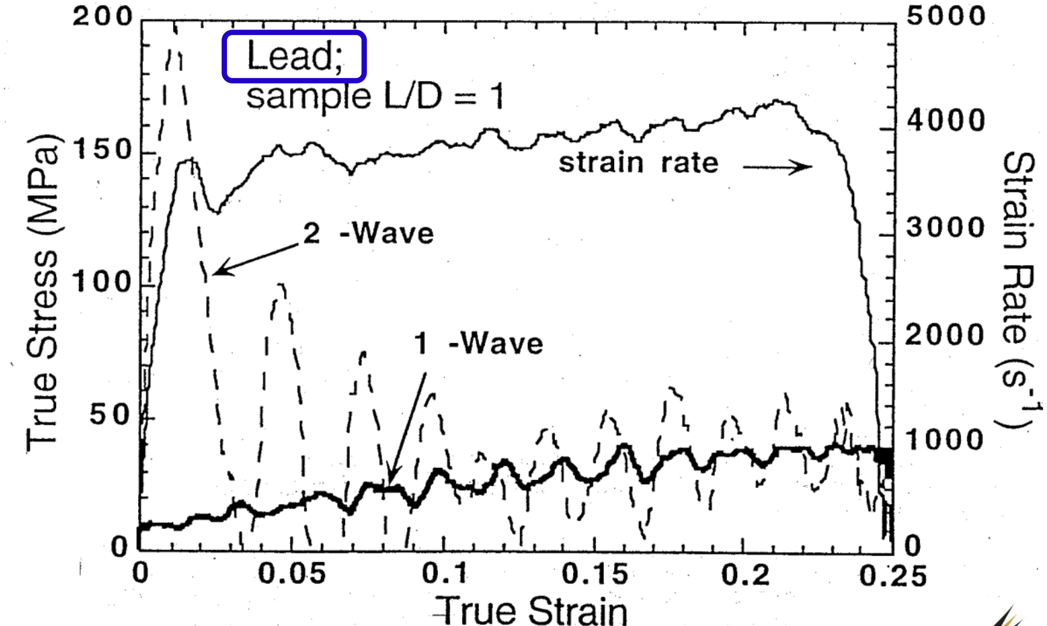


Non-Uniform Loading on Soft Specimens



After Gray, 2000

Note: **Lead is harder than most soft tissues.**



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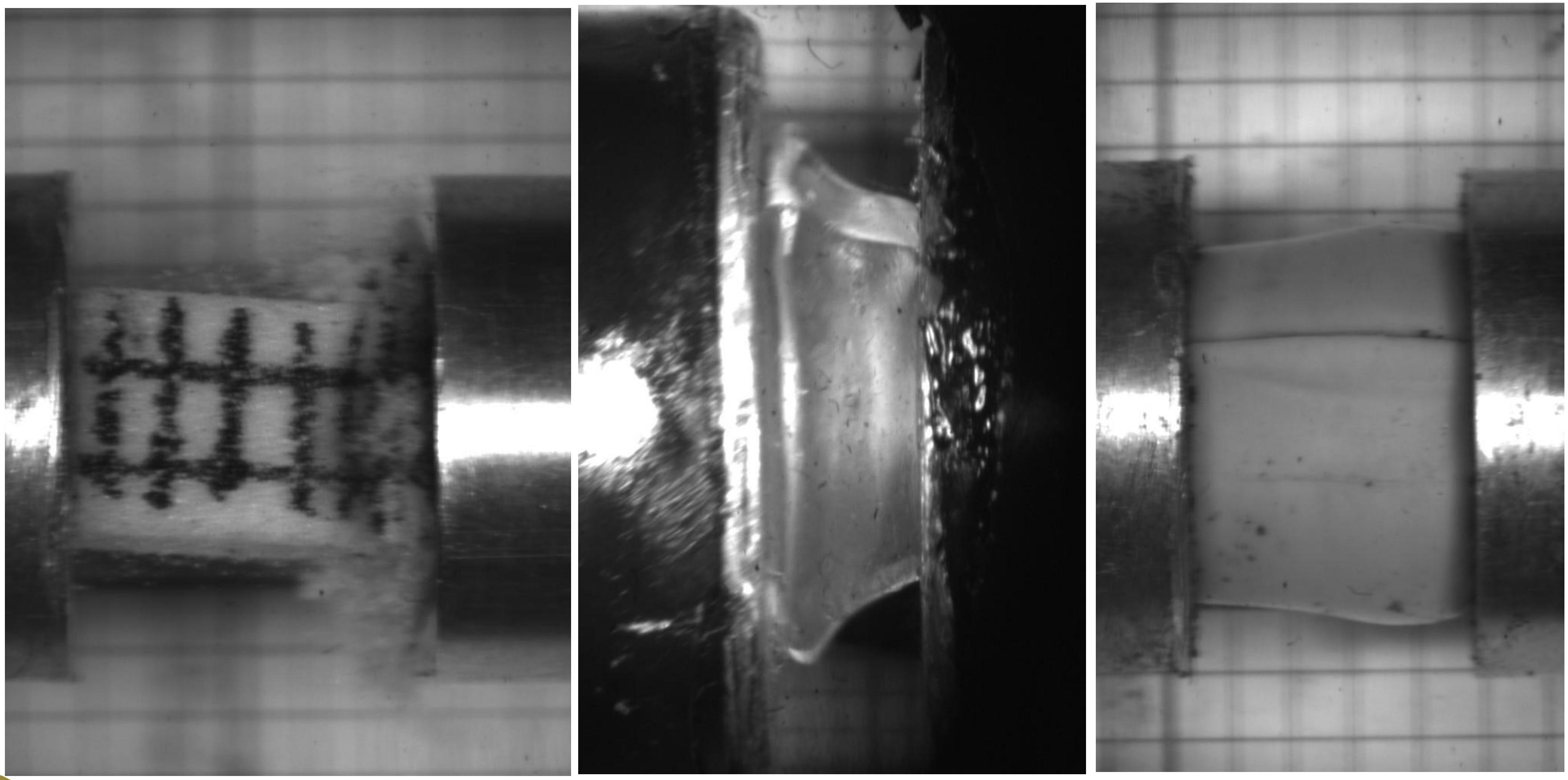
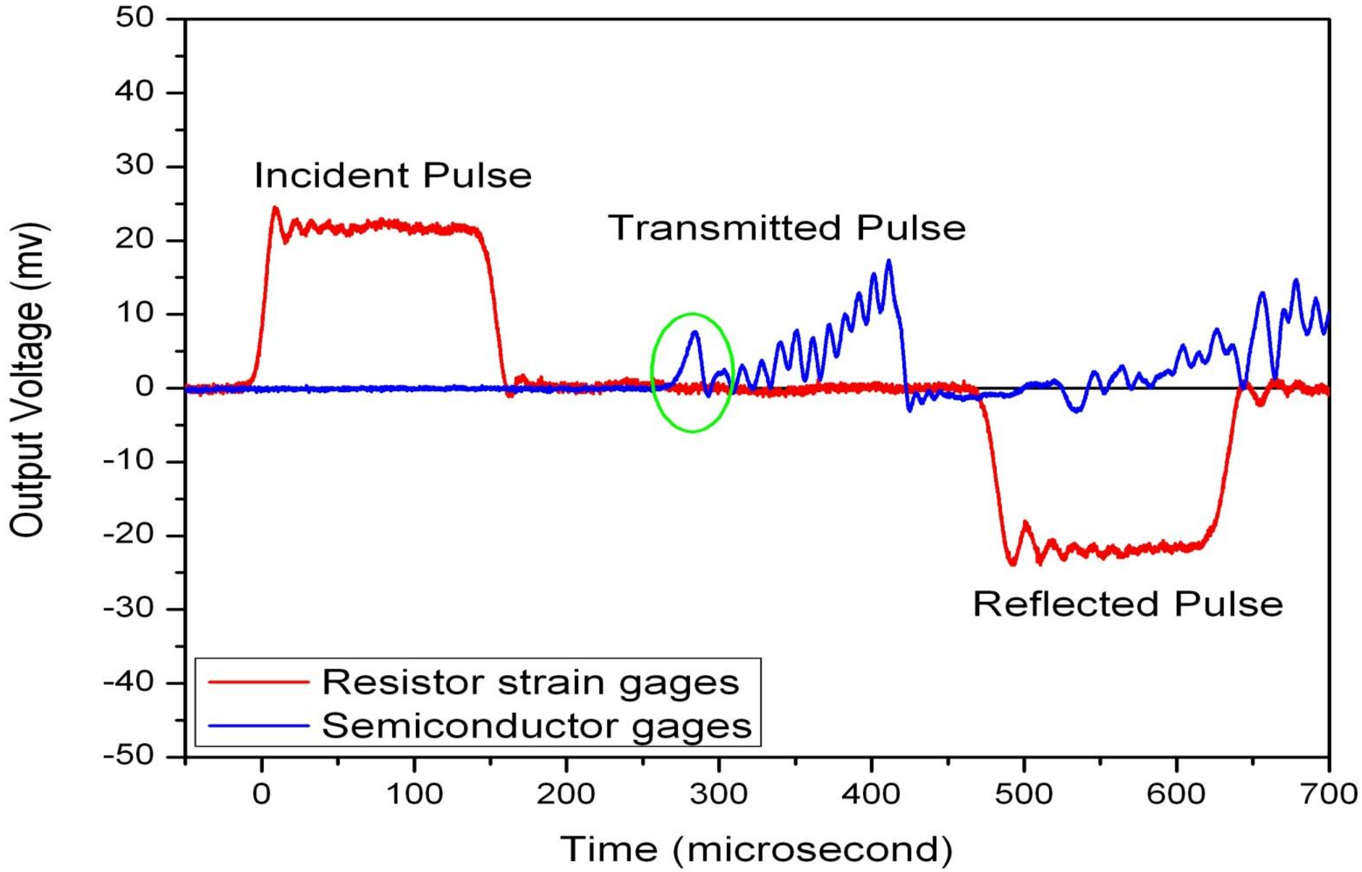
Non-homogeneous Deformation

- Uniform deformation along specimen thickness
- Related to dynamic stress equilibrium in most cases

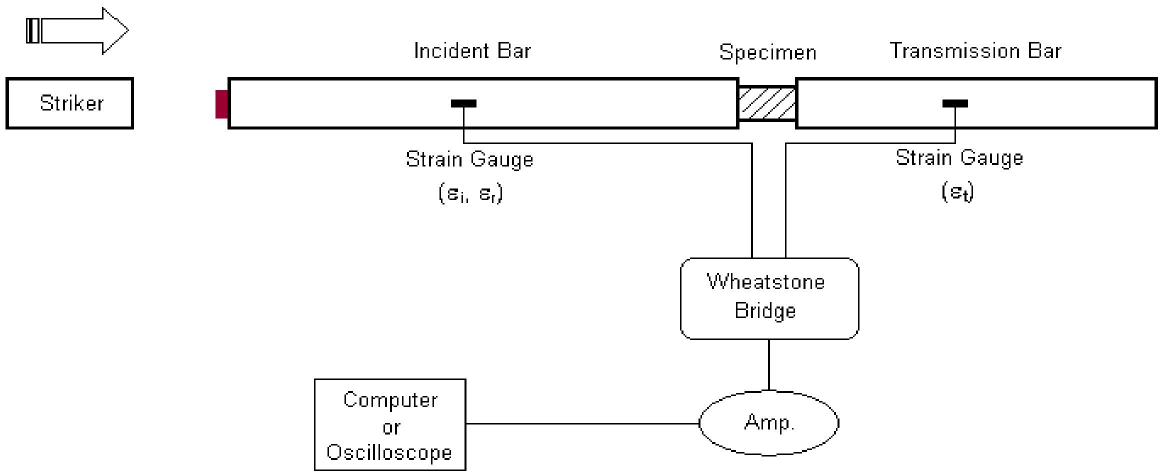


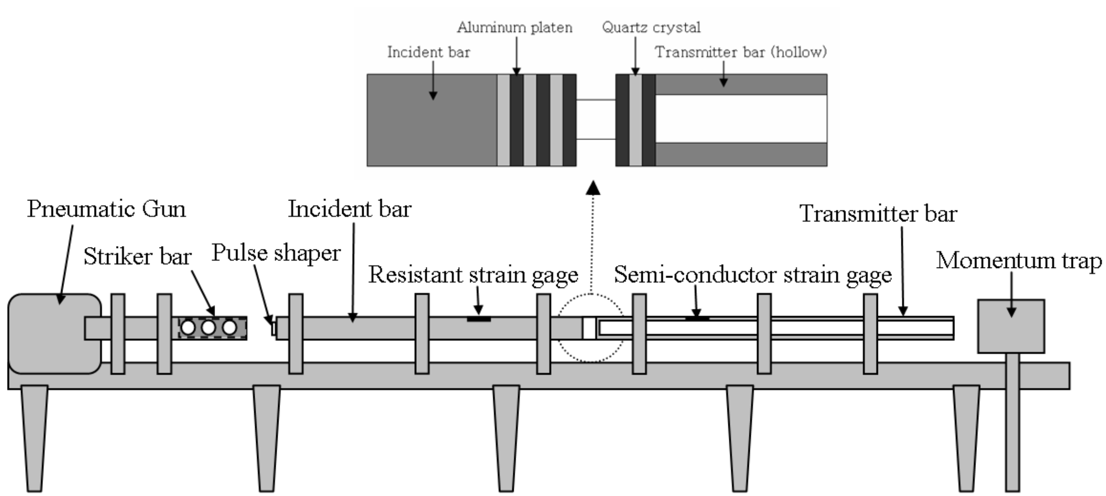
Two-dimensional Effects in the Specimen

– **Friction effect**
– **Radial inertia in specimen**

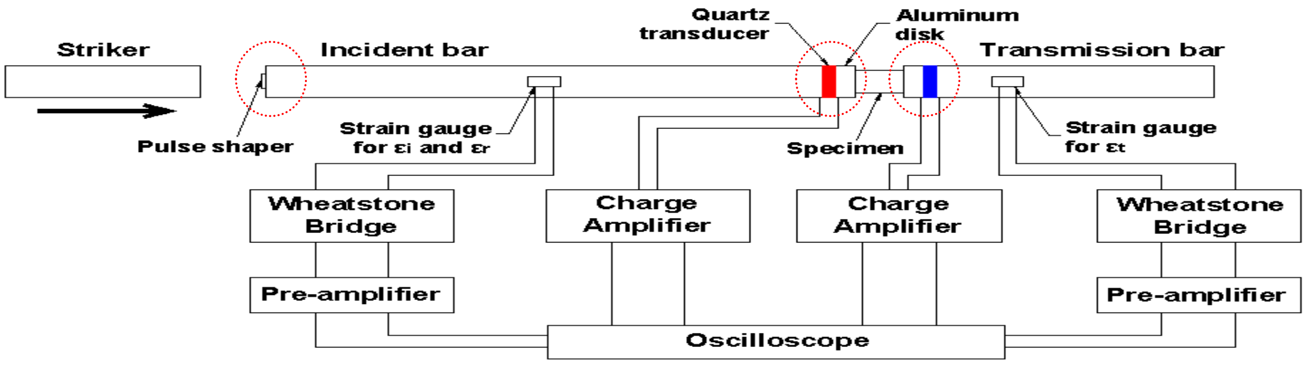


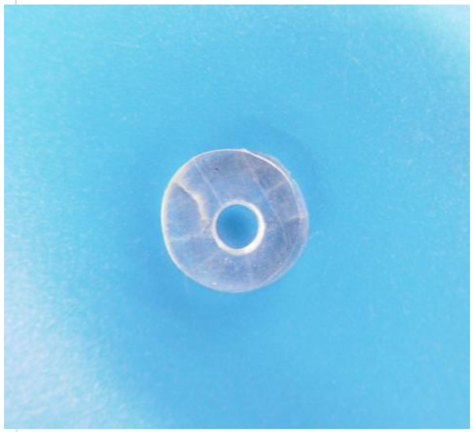
Dynamic Characterization of Soft Materials

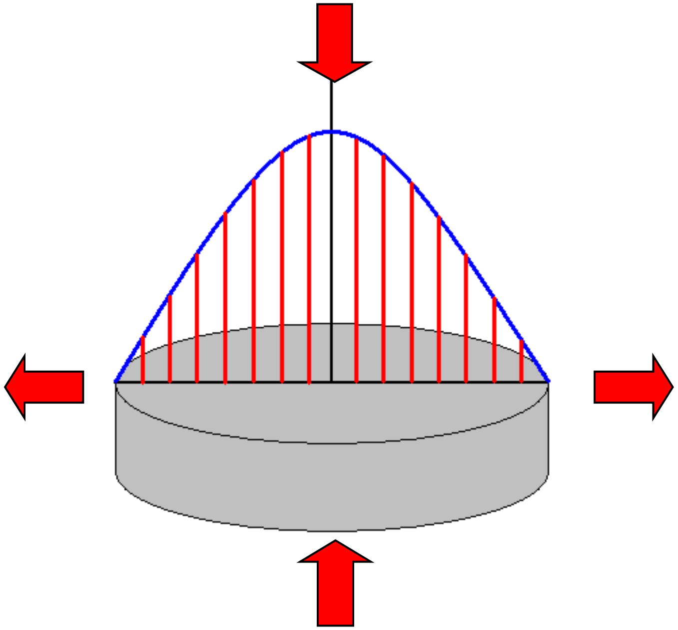


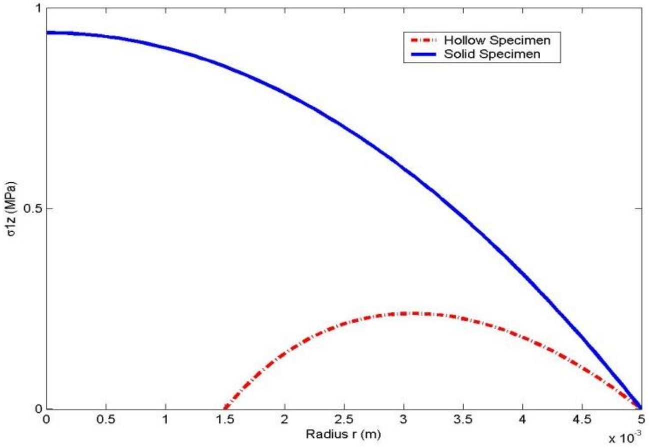


Modified Kolsky Bar for Soft Materials

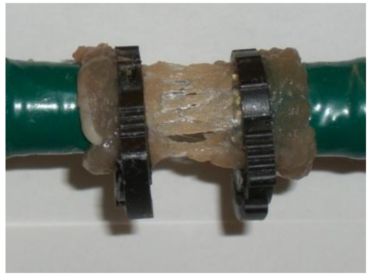




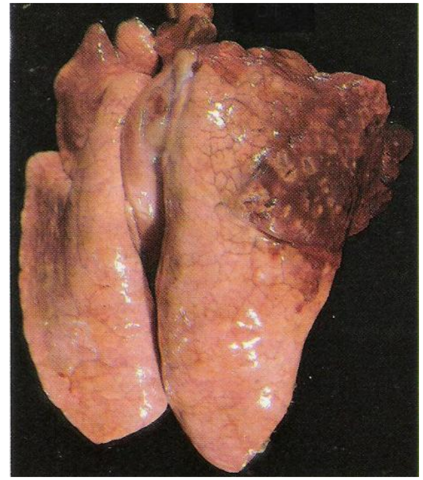
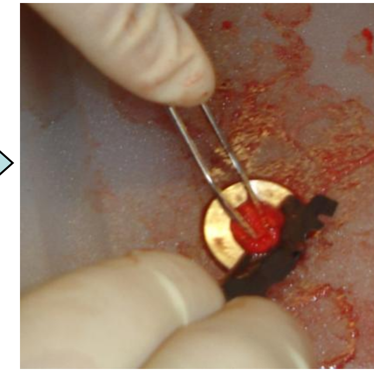




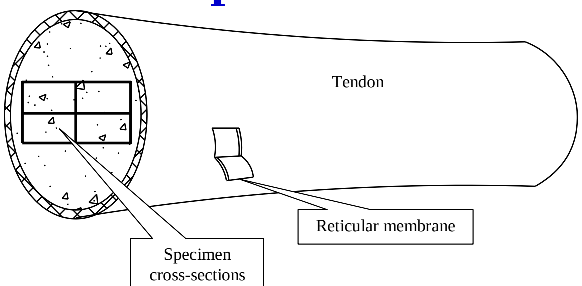
Some Tissues Dynamically Characterized

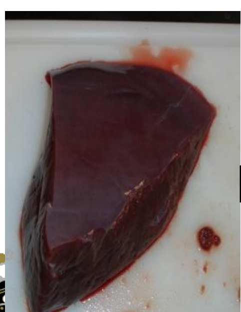
Muscles under compression and tension

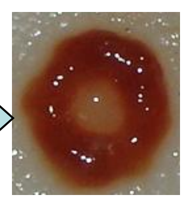



Lungs



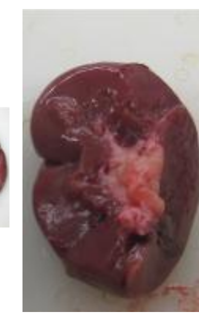
Tendons under tension





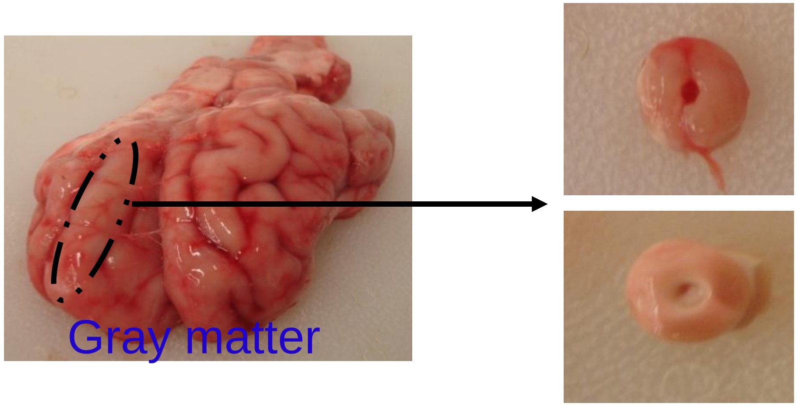
Livers

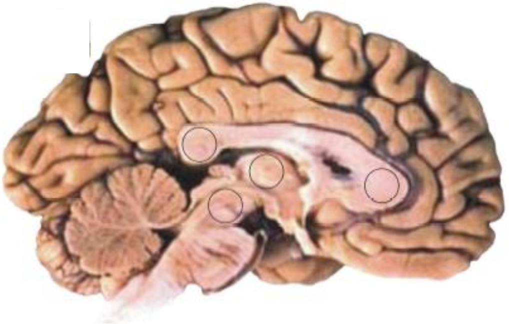
Skin

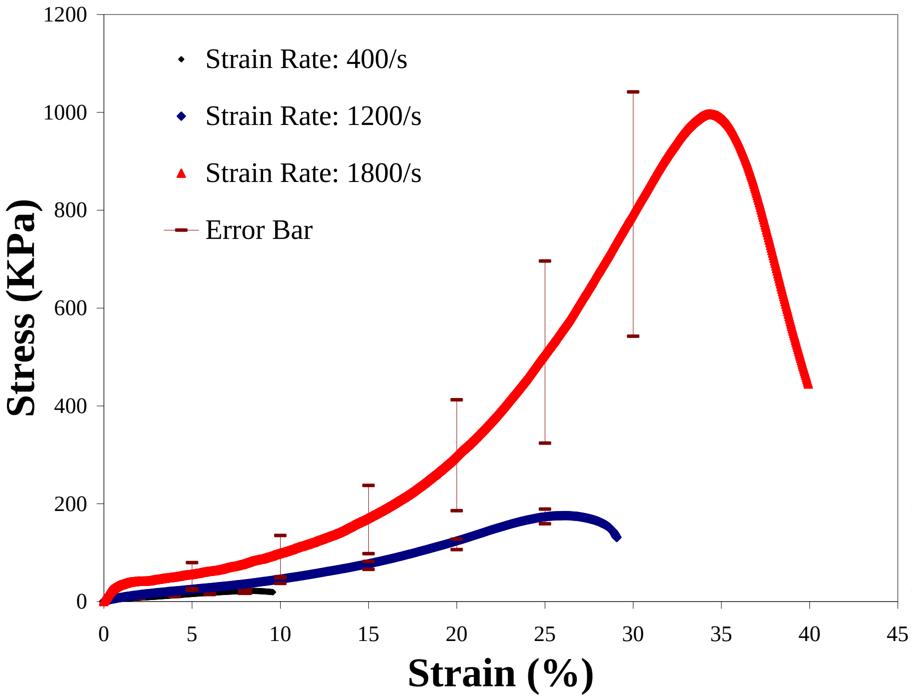
Kidneys

Dynamic Properties of Gray and White Matters



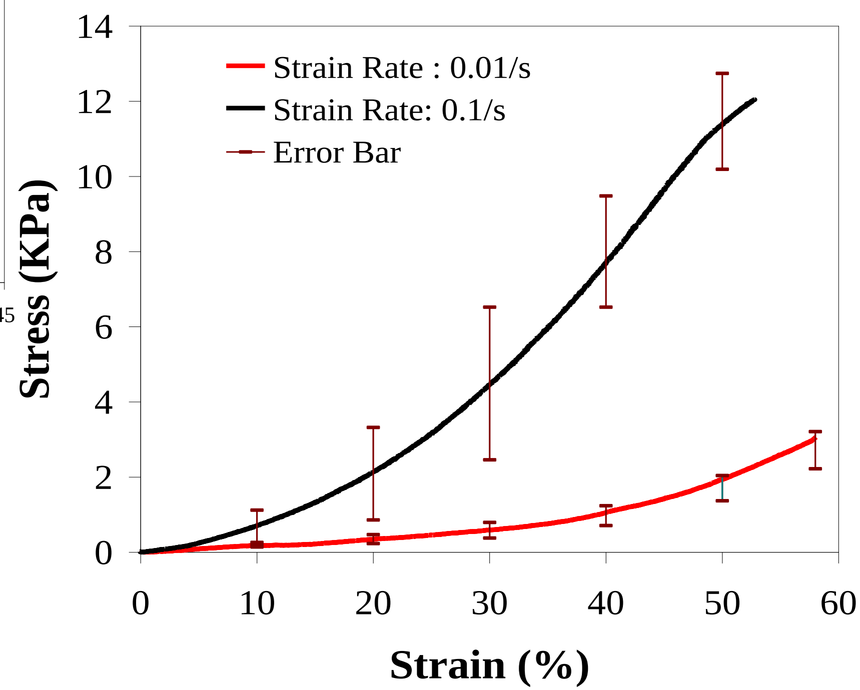


Scatter in Response of Bovine Gray Matter

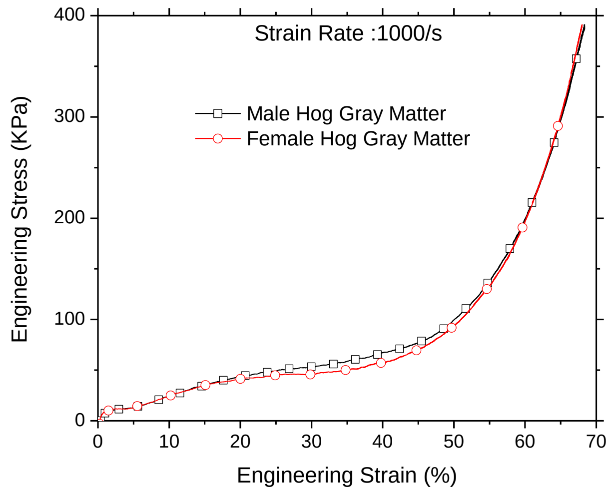


High-rate Results

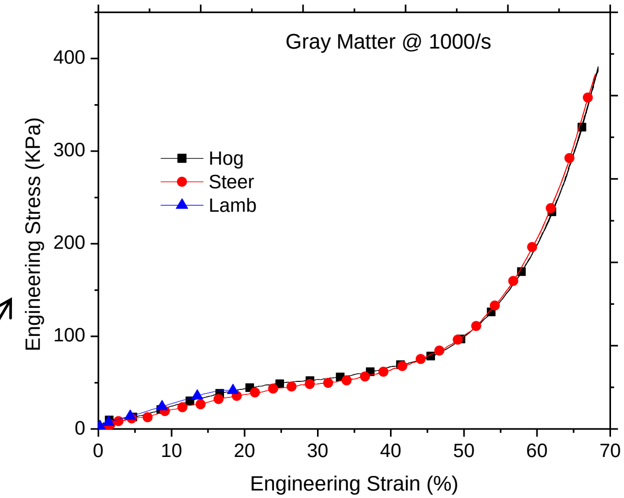
Low rates



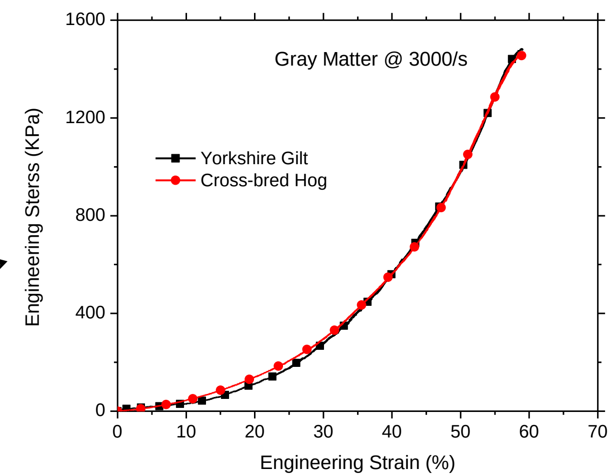
Brain Tissues from Different Animals



Male/Female



Pig/Cow/Lamb



Purebred/Crossbred

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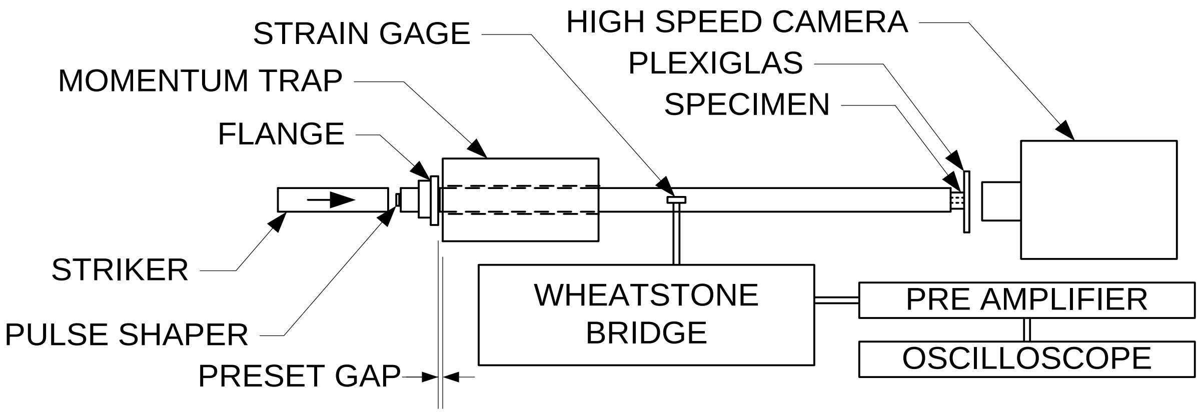
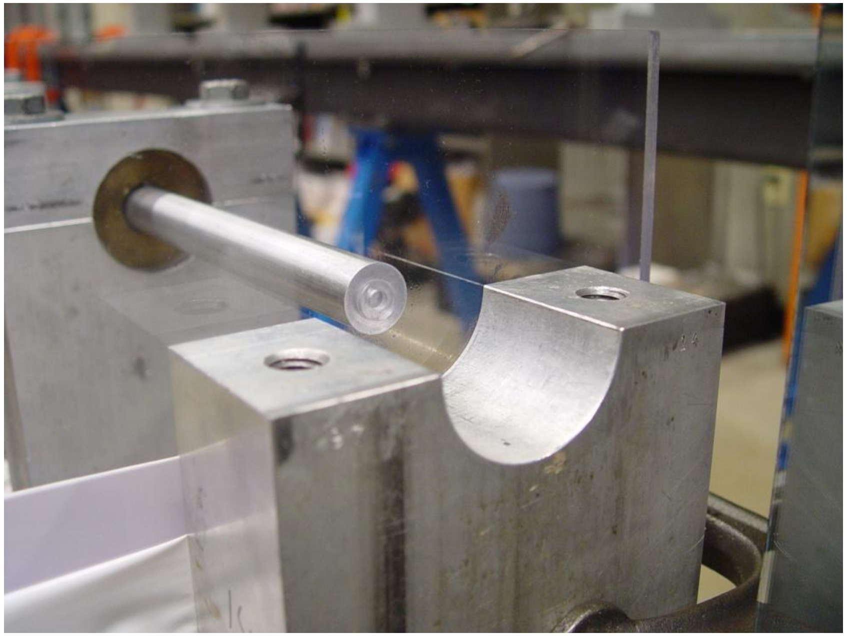
Brain Tissue Lateral Deformation





Specimen dimension:

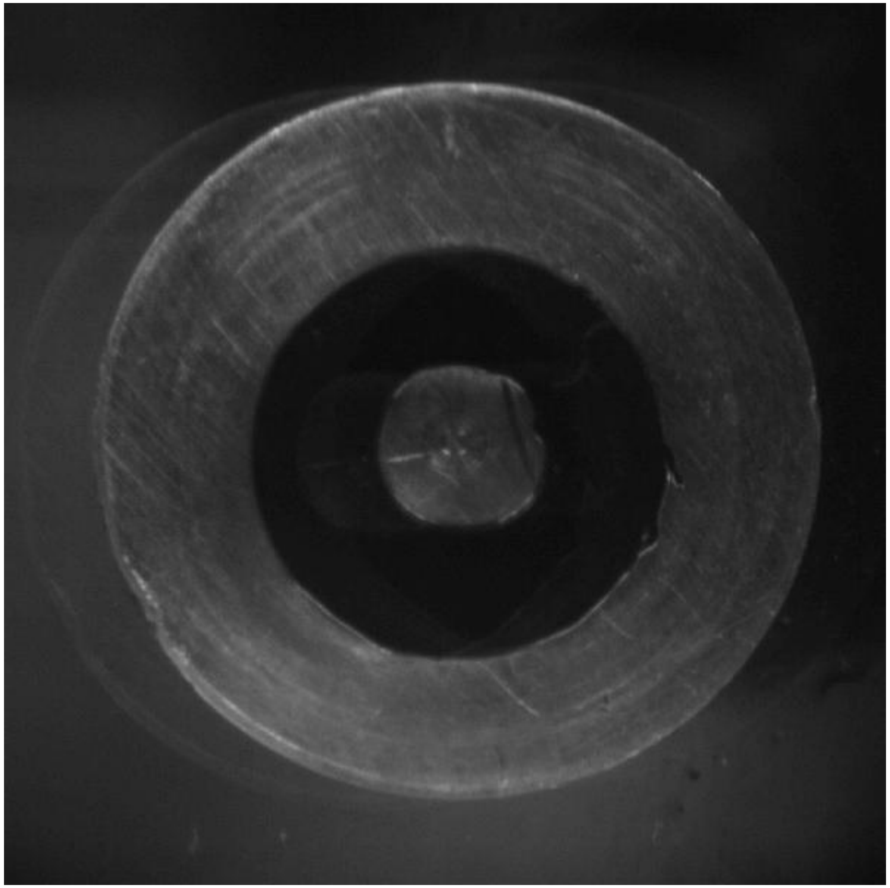
ϕ10 mm outer diameter

ϕ5 mm inner diameter

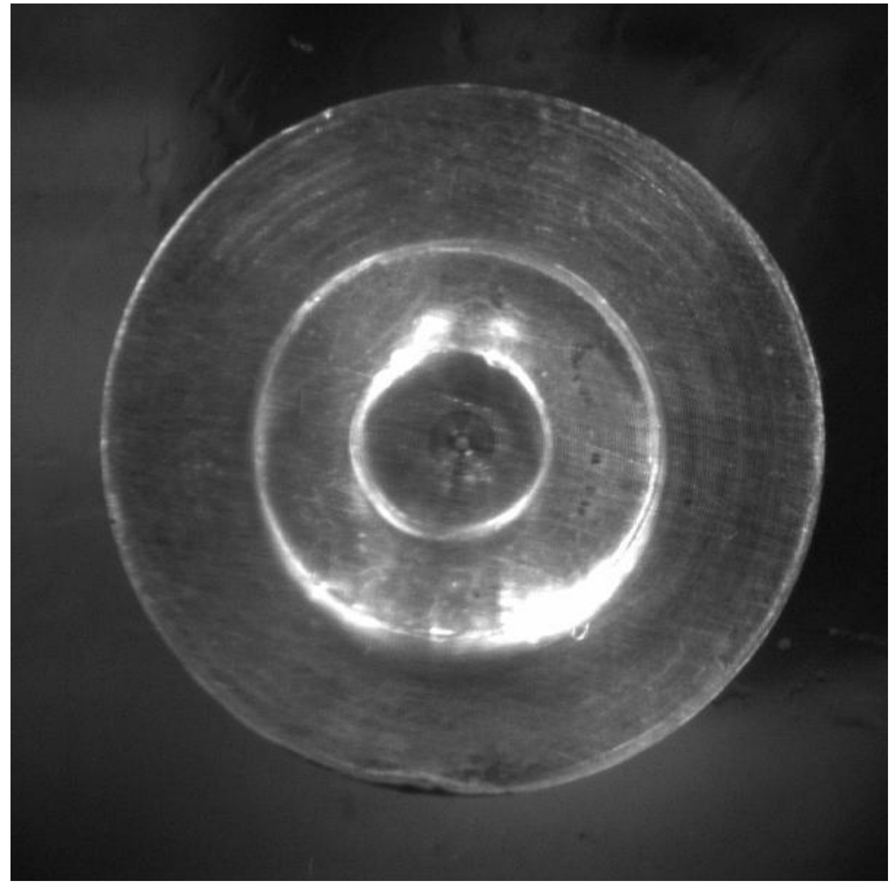
1.7 mm thickness

Camera frame rate: 50,000 fps

A Washer-shaped Gel Specimen under Compression



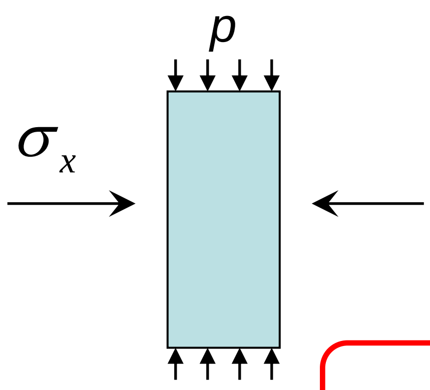
Strain Rate ~2,000/s
G ~ 5 MPa



66% Peak Axial Strain

Strain Rate ~2,000/s
G ~ 200 kPa

Disturbances in Measured Axial Stresses



Ideally, *p ~ 0*

$$\varepsilon_x = \frac{1}{E}\left[\sigma_x - \nu\left(\sigma_y + \sigma_z\right)\right]$$

$$= \frac{1}{E}\left(\sigma_x - p\right)$$

$\sigma_y = \sigma_z = p$

$\nu \approx 0.5$

$$\sigma_x = E\varepsilon_x + p$$

Measured axial stress dominated by pressure from inertia, friction, etc.

	$E\varepsilon_x$	p	$p/E\varepsilon_x$
Aluminum	3.5 GPa	~7 MPa	**0.002**
Plexiglass	0.2 GPa	~3 MPa	**0.015**
Soft Tissue	1.1 kPa	~2 MPa	**1800**

When

$\varepsilon_x = 5\% = 0.05$

Inertia pressure (Forrestal and Warren, 2010)

$$\bar{p} = \frac{3\rho a_o^2}{16\left(1-\varepsilon_x\right)^3}\left(\dot{\varepsilon}_x\right)^2 + \frac{\rho a_o^2}{8\left(1-\varepsilon_x\right)^2}\ddot{\varepsilon}_x$$

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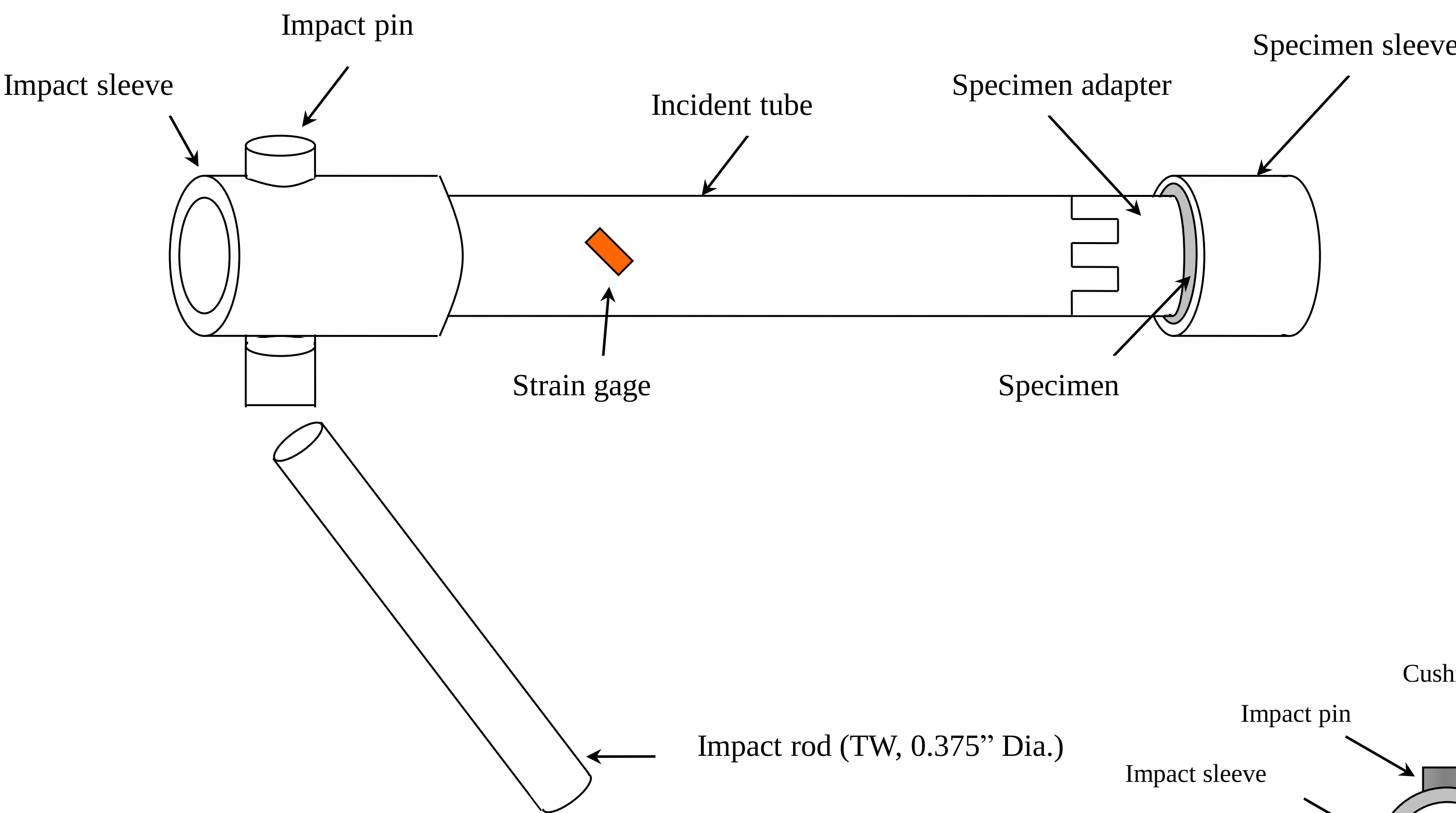
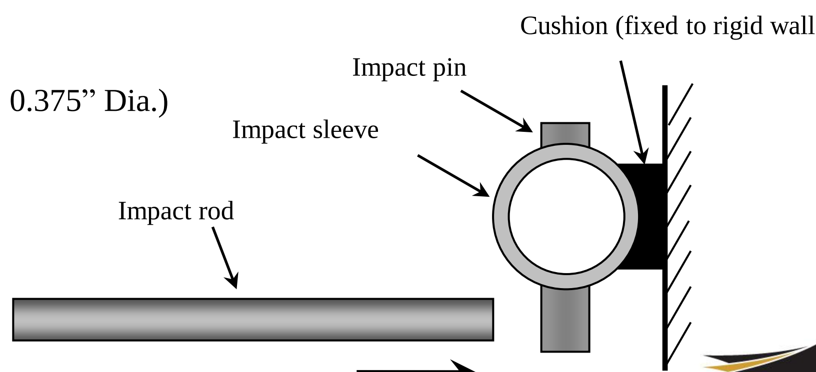
Kolsky Torsion Bar for Dynamic Shear Response

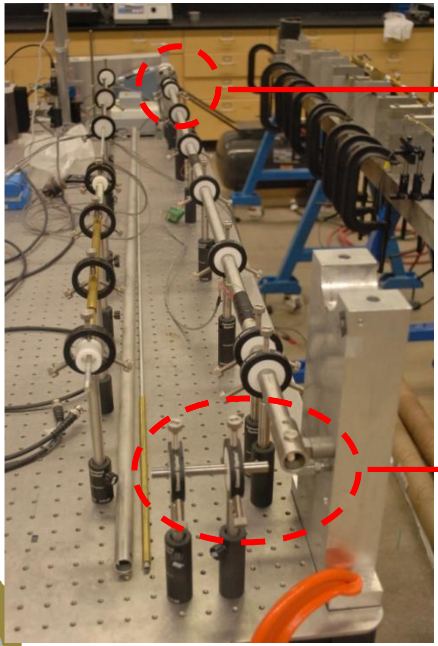


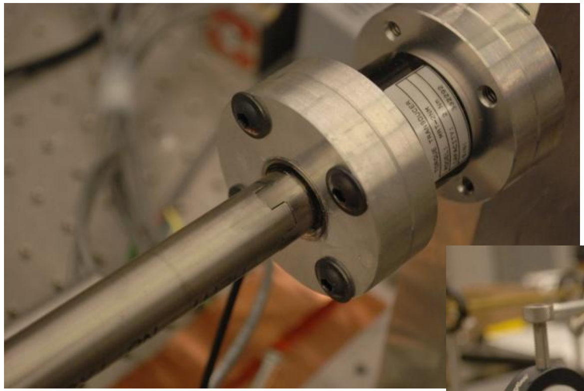


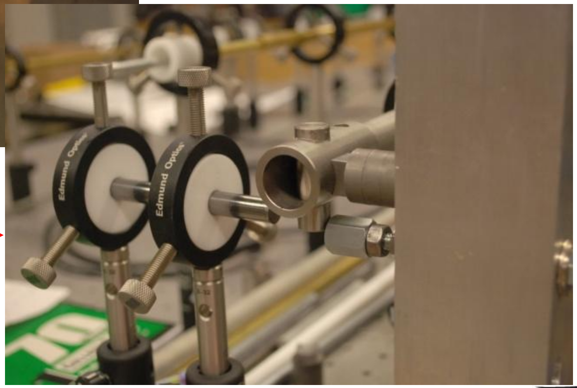
Kolsky Torsion Bar for Dynamic Shear Response

- **Dynamic shear response under torsional loading**
  - ✓ No radial-inertia effect.
  - ✓ No stress concentrations at the edges.
  - ✓ Pure shear properties of the material at high rates.

- **"Desk-top" Kolsky torsion bar setup**







High-speed Imaging of Deformation

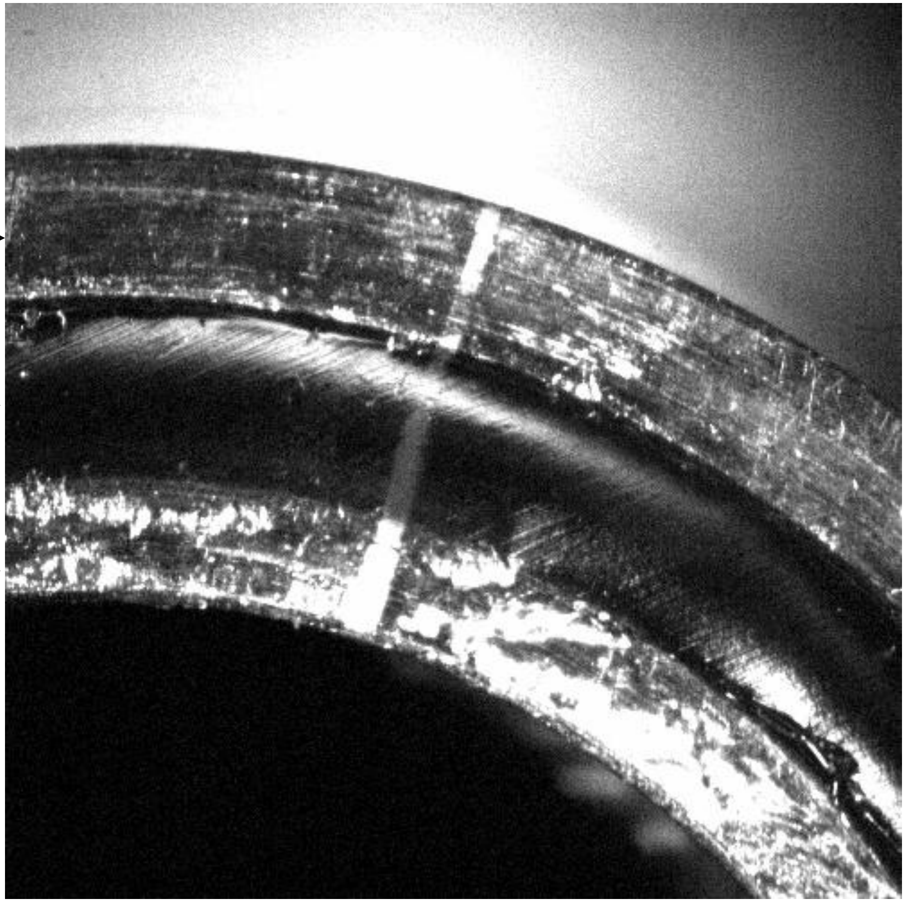
Camera model: Cordin 550

Frame rate=50,000 fps

Outer adapter, fixed to torque sensor.

Gel sample

Inner adapter, connected to torsion bar.



No slippage or debonding at the specimen-adapter interface.

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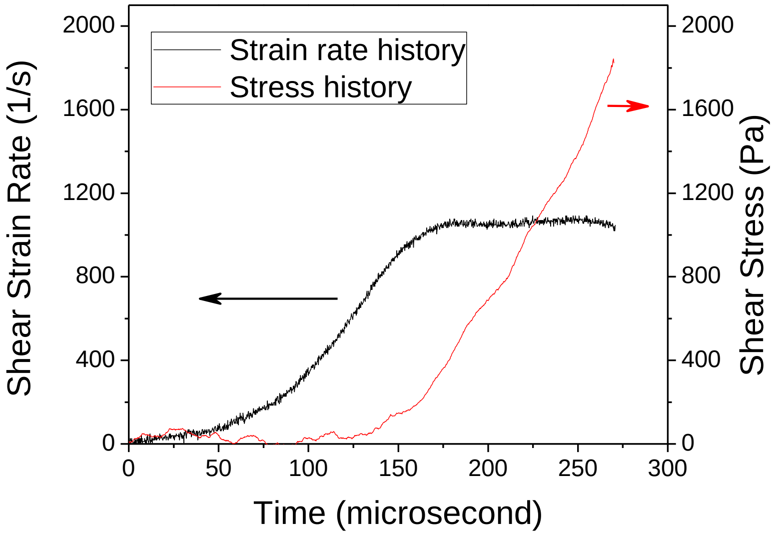
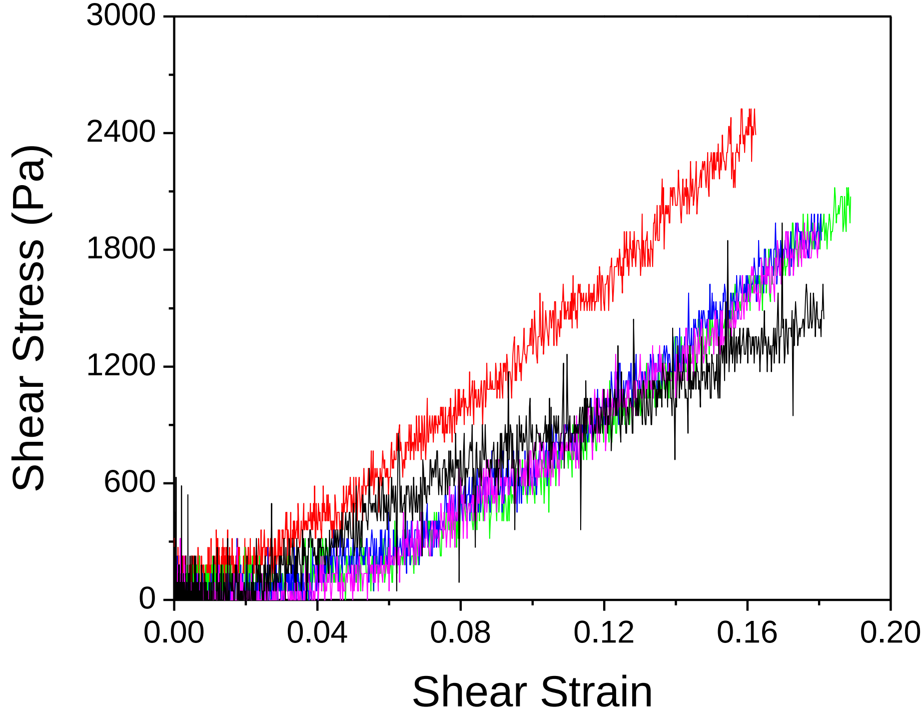
Dynamic Shear Stress-Strain Responses



- Shear strain rate history

- Shear stress-strain curves (Note the small stress amplitude)



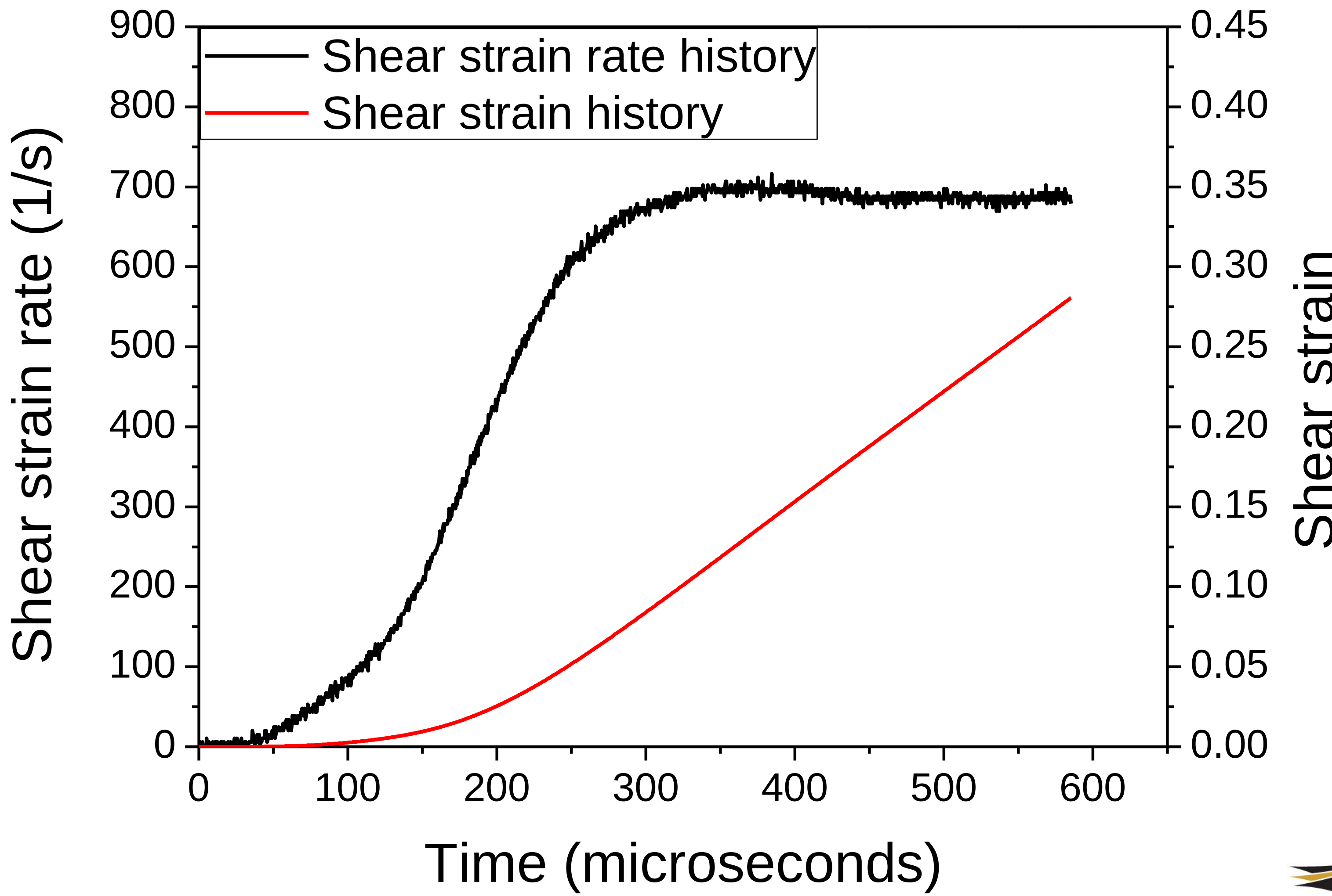
Ring-shaped Specimen

O.D.=19 mm

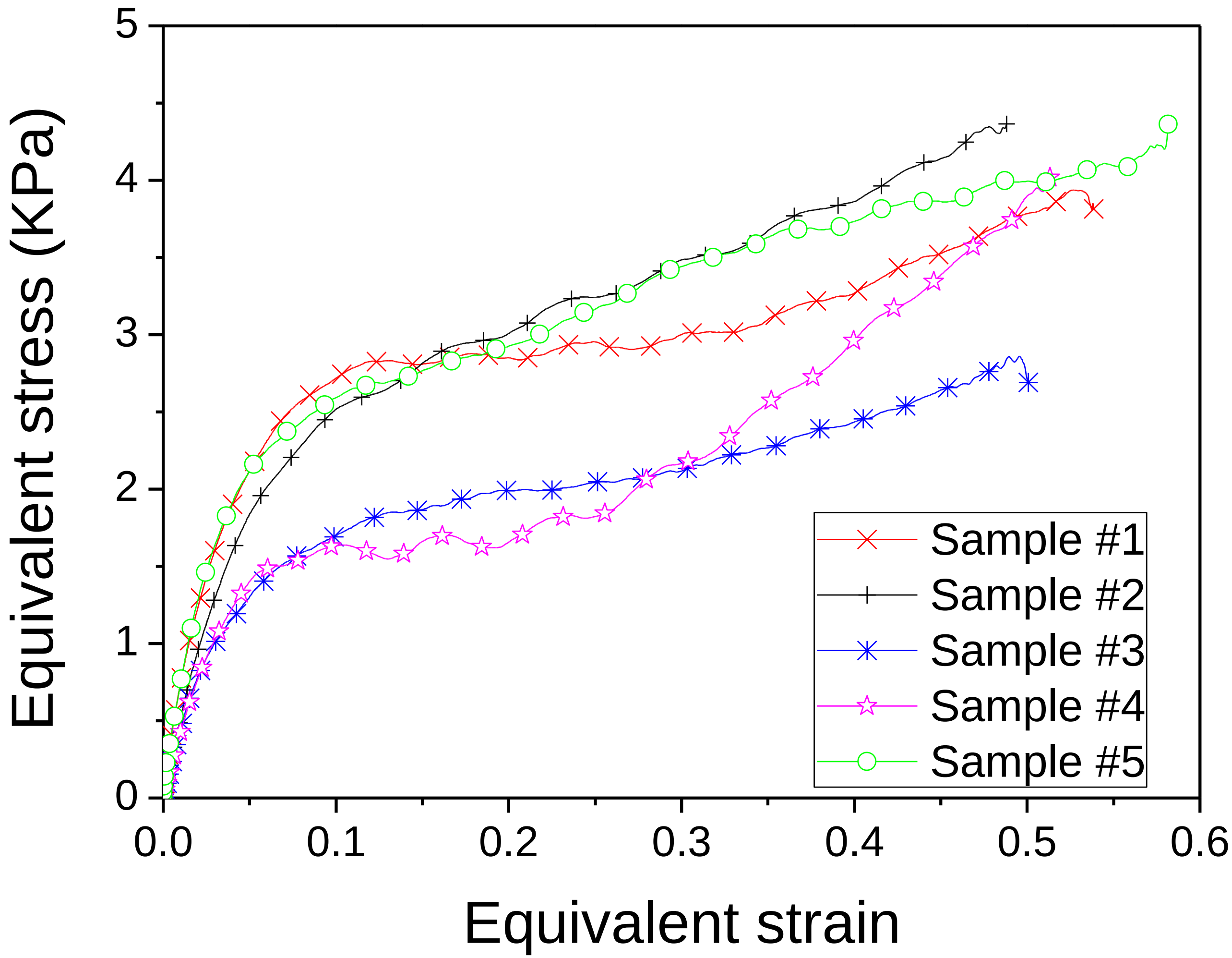
I.D.=14.3 mm

Thickness=2 mm

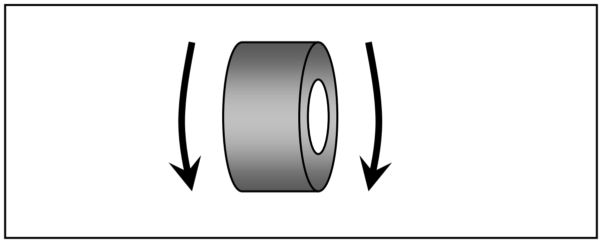
Dynamic Shear Strain Rate and Strain

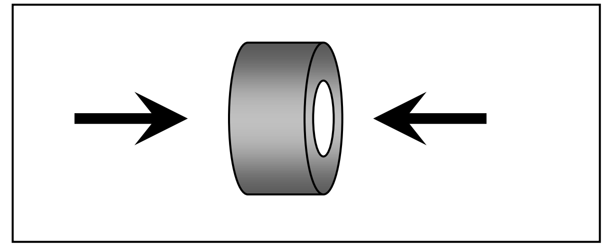


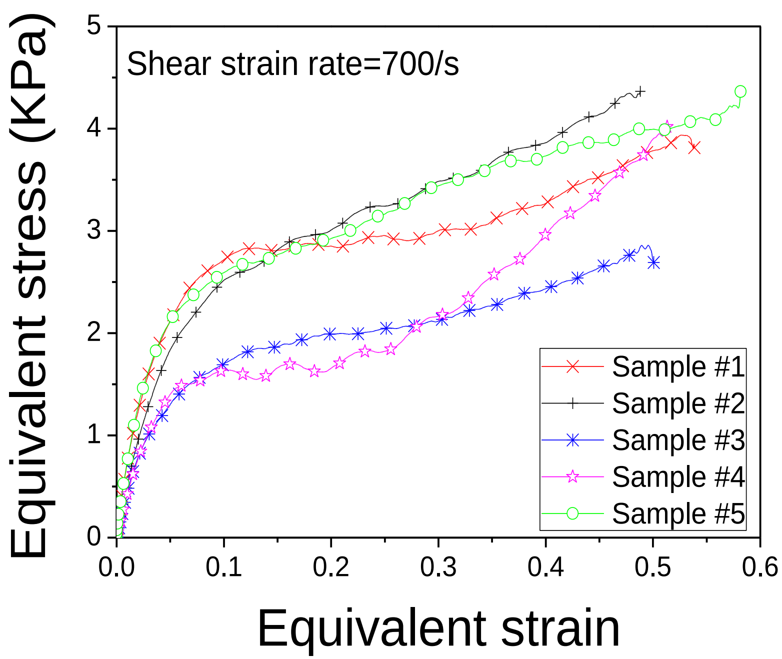
Dynamic Stress-Strain Curves

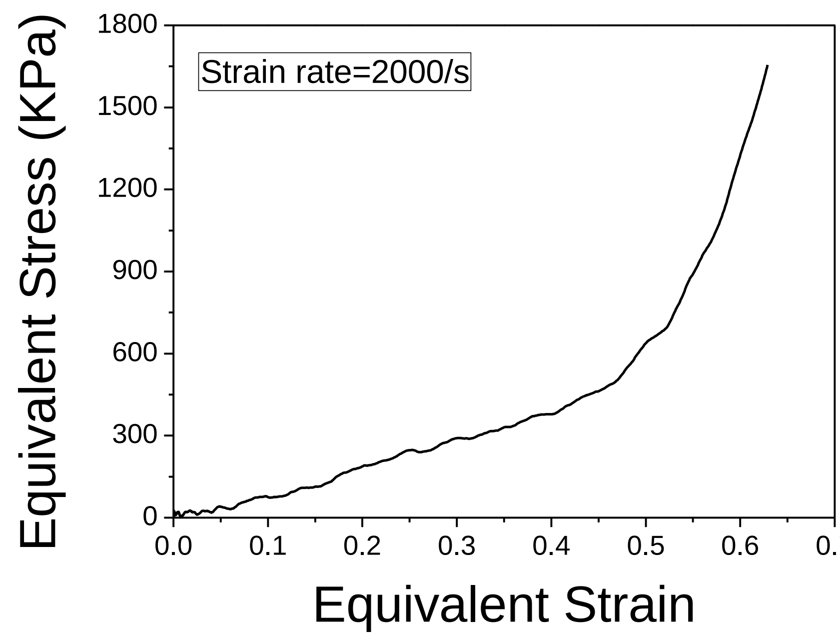


A Comparison of Axial/Shear Responses









Summary

- Uniaxial brain tissue compression experiments too sensitive to disturbances.
- Necessary to separate volumetric and shear responses.
- Novel dynamic shear experimental methods developed, calibrated, and used for brain tissue characterization.