Ultrasonic Measurements of Plastic Strain in Pipelines

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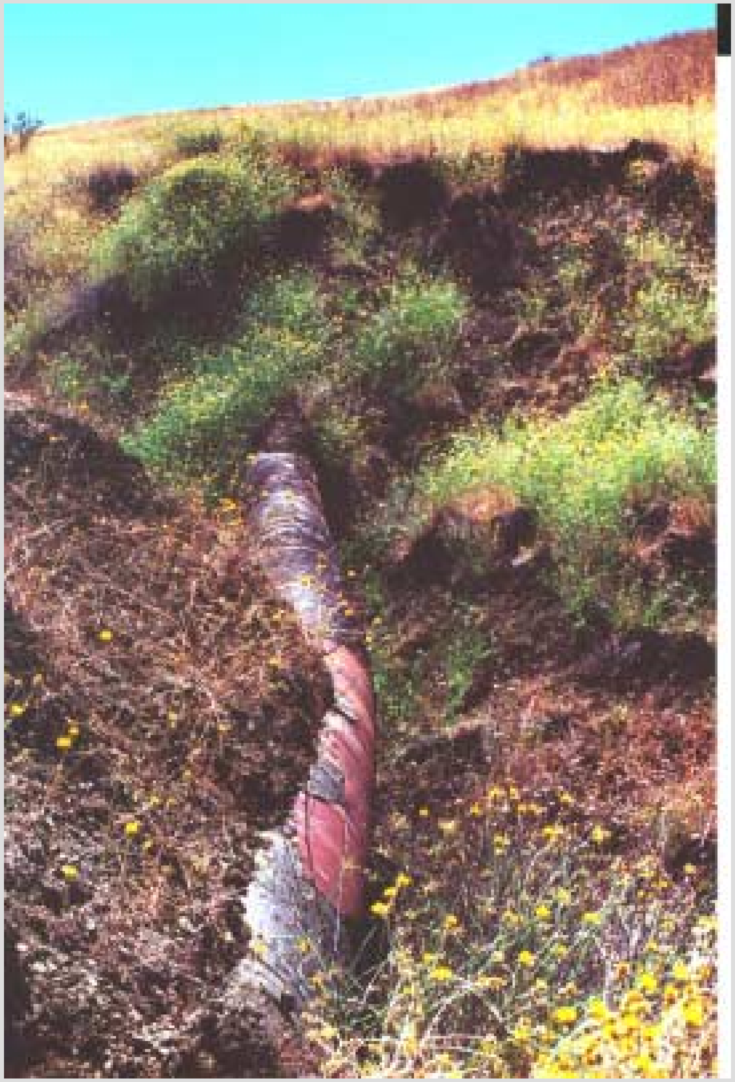
Motivation (Natural gas suppliers)

Third party damage to natural gas pipeline

- Damage currently detectable but not accurately characterized
- Problems/Difficulties
  - Multidirectional stress and strain (not uniaxial)
  - Gradients through thickness
  - Both stress and texture affect ultrasonic velocity

Outline

- Strategy
- Damage modeling
- Ultrasonic measurements
  - Theory
  - Elastic Measurements
  - Plastic Measurements
- Conclusions



Strategy

- Damage characterization
  - Bending
  - Dents
  - Dents with gouges

Third Party Damage

- Fracture mechanics models ⟹ remaining life
  - Dimensional measurements (incomplete information)
- Ultrasonic velocity sensitive to stress, strain, and texture
  - Velocity measurements
    - Longitudinal
    - Shear Horizontal
    - Shear Birefringence (Thickness independent)
    - Rayleigh (Depth dependence)
  - Comparison with established ultrasonic theories

Fracture Mechanics Approach

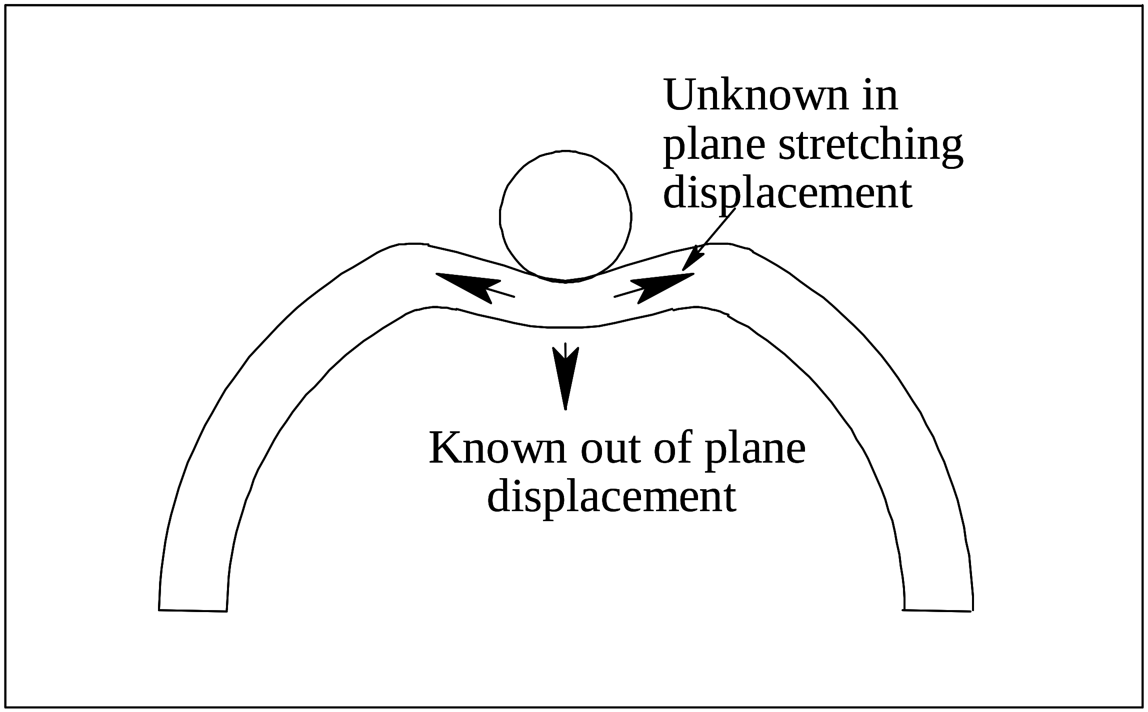
Fracture Mechanics Approach to Evaluating Severity of Third-Party Damage

Key factors:

- Line pressure during damage and subsequent re-rounding of pipe
- **Localized curvature including membrane stretching and related wall thinning**
- Cracking upon re-rounding to highest service pressure and during hydrostatic retesting
- Support conditions for the pipeline

Dent Rerounding

Unknowns in Dent Shape Measurements



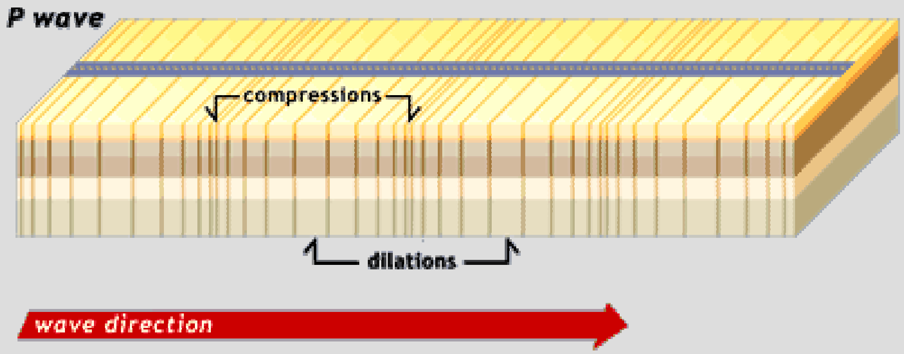
In plane and out-of-plane displacements in a dented pipe.

- Can calculate bending strains from out of plane displacements.
- Need in plane displacements to calculate membrane strain.
  - Cannot measure them directly

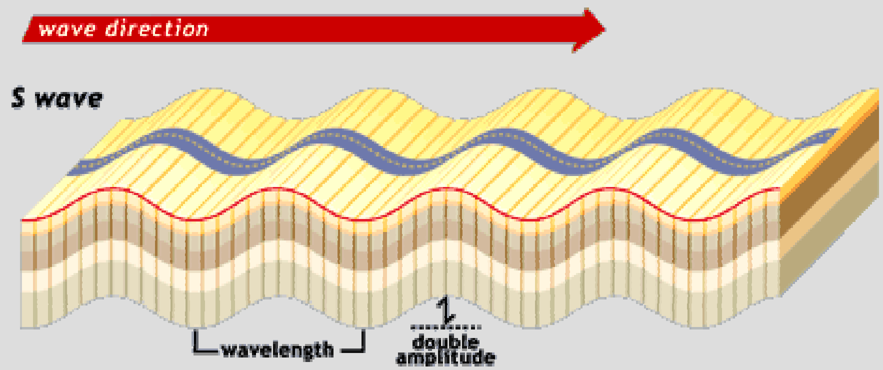
Ultrasonic Measurement Approach

Ultrasonic Waves

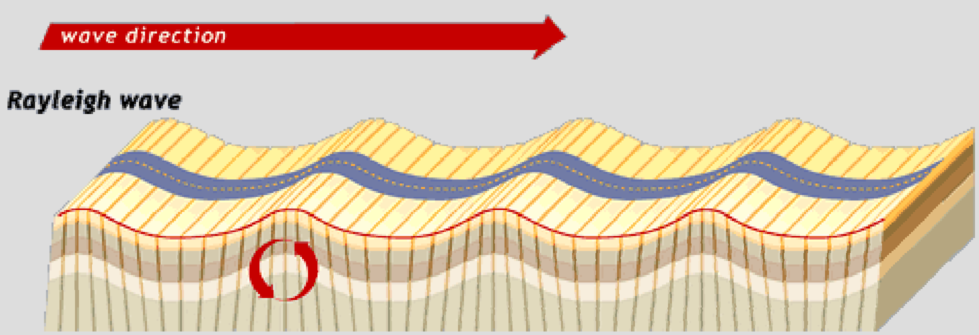
Longitudinal or Pressure Waves



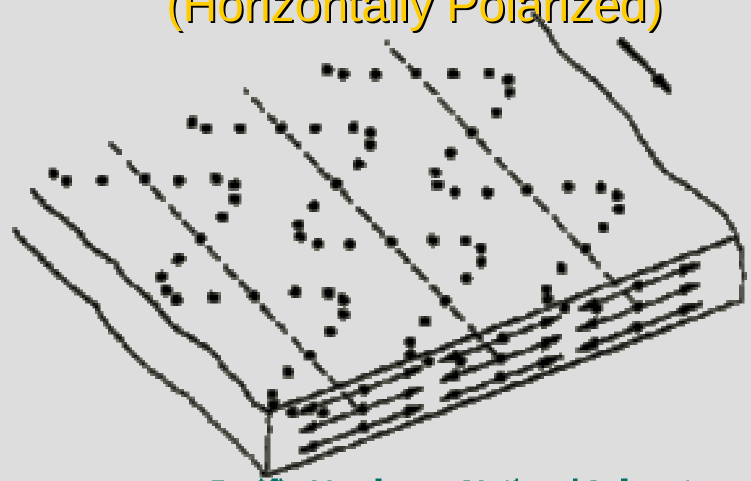
Shear or Transverse Wave (Vertically Polarized)



Surface Wave (Rayleigh Wave)



Shear or Transverse Wave (Horizontally Polarized)

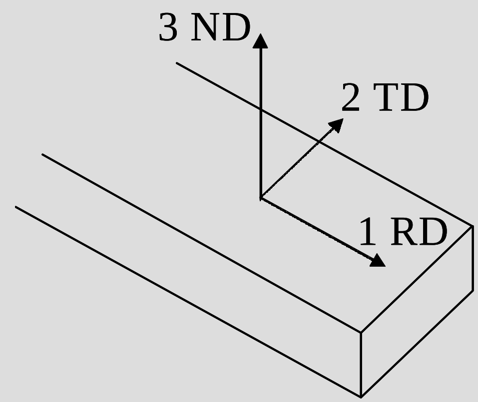


Ultrasonic Theory

L-wave

$$\rho\ V_{33}^2 = C_{33} = B + \frac{4G}{3} + 4.786 C_0 W_{400} + K_1 \sigma$$

Moduli Texture Stress



Shear

$$\rho\, V_{31}^2 = C_{31} = G - 6.381 C_0 W_{400} + 10.089 C_0 W_{420} + K_2 \sigma$$

$$\rho\, V_{32}^2 = C_{32} = G - 6.381 C_0 W_{400} - 10.089 C_0 W_{420} + K_3 \sigma$$

Shear Horizontal

$$\rho\, V_{12}^2 = C_{66} = G + 1.595 C_0 W_{400} - 13.348 C_0 W_{440} + K_4 \sigma$$

$$\rho\, V_{21}^2 = C_{66} = G + 1.595 C_0 W_{400} - 13.348 C_0 W_{440} + K_5 \sigma$$

$$\rho\left(V_{12}^2 - V_{21}^2\right) = \left(K_4 - K_5\right)\sigma$$

Texture Free

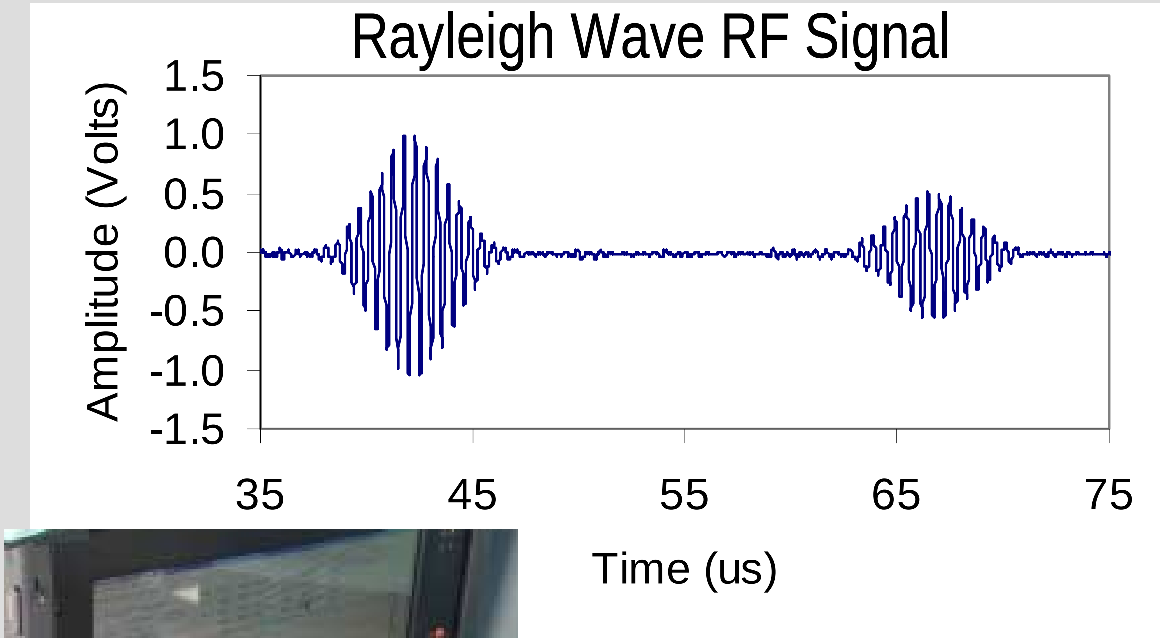
W_{lmn} - texture parameters

K_I - acoustoelastic constants

σ - tensile stress

Measurement system

Shear Wave Birefringence



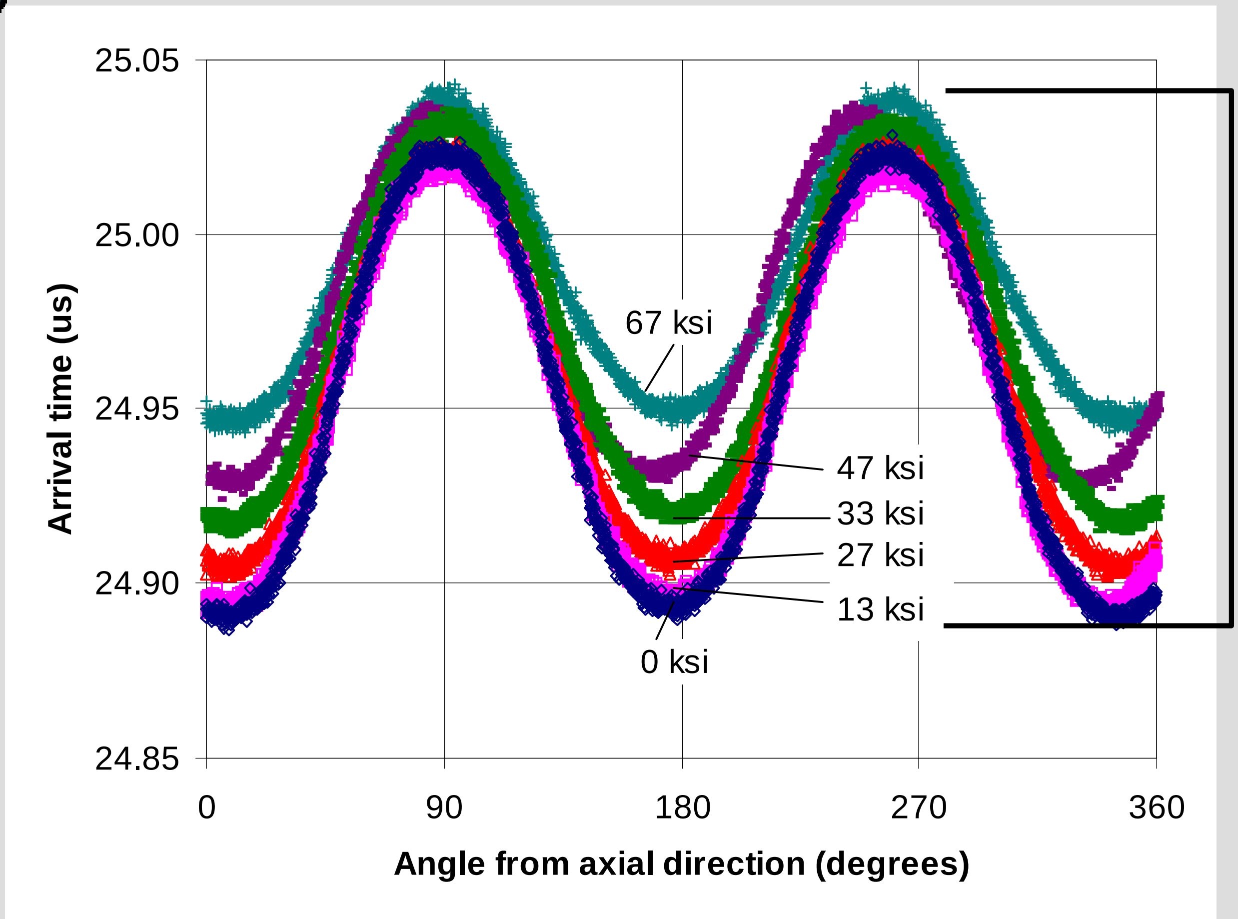
P → R R

Rayleigh Wave EMATS

P → R

Pulsed Magnet SH Wave EMATs

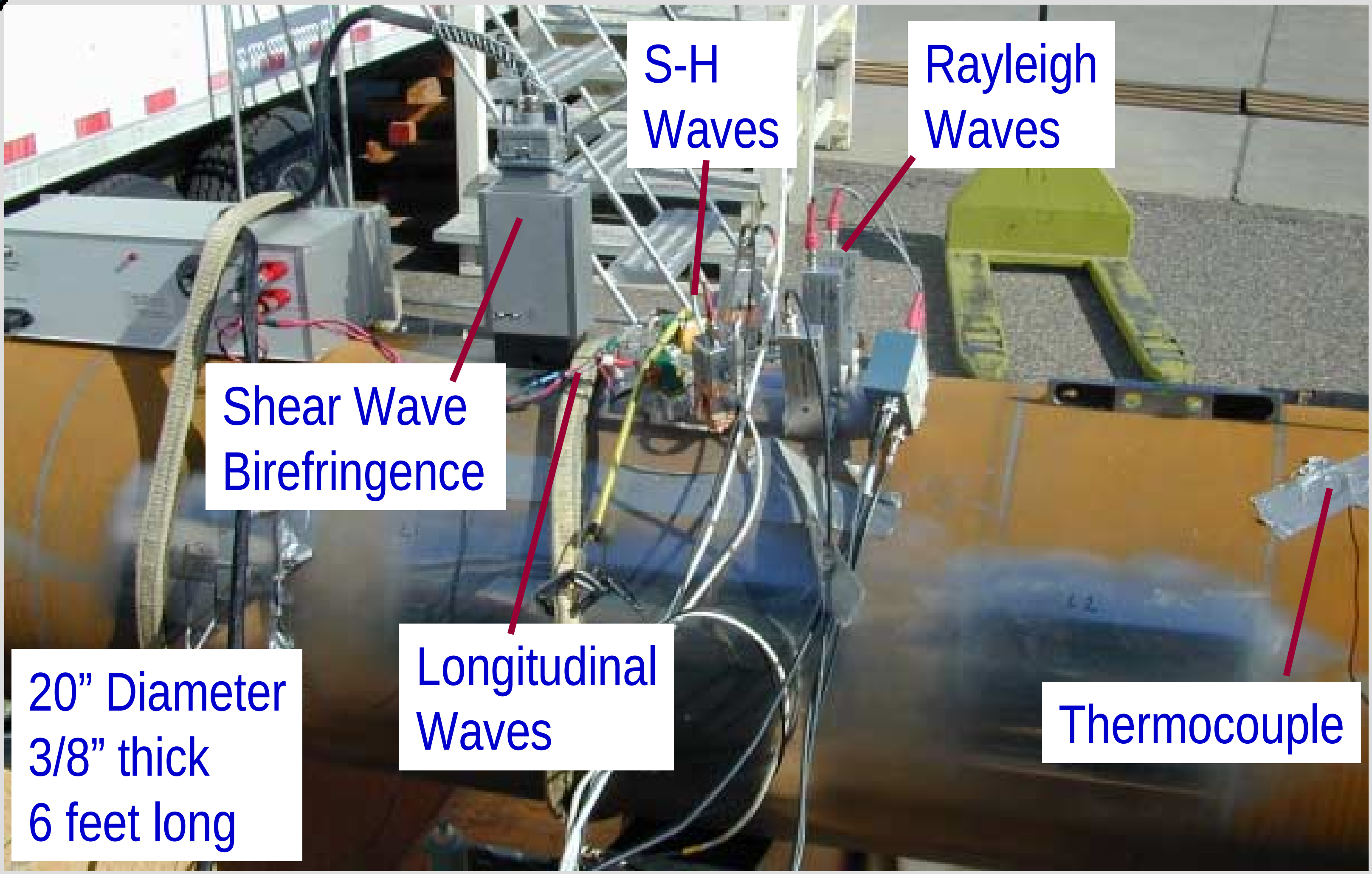
Arrival time vs. angle for biaxial stress (Pipe)



$$Birefringence = \frac{Max - Min}{Average}$$

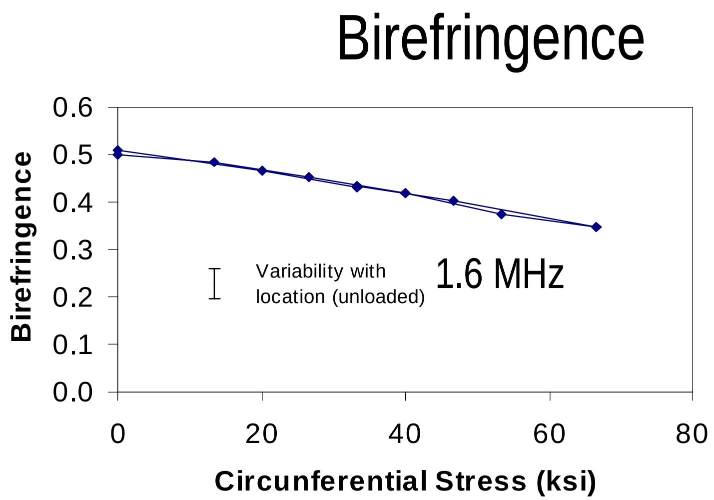
Elastic region
(Pipe Measurements)

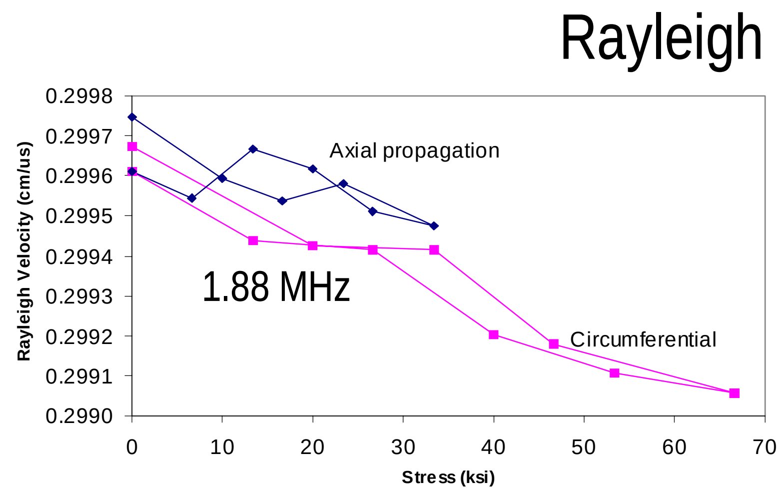
Biaxial Stress Experiment (Pipe)

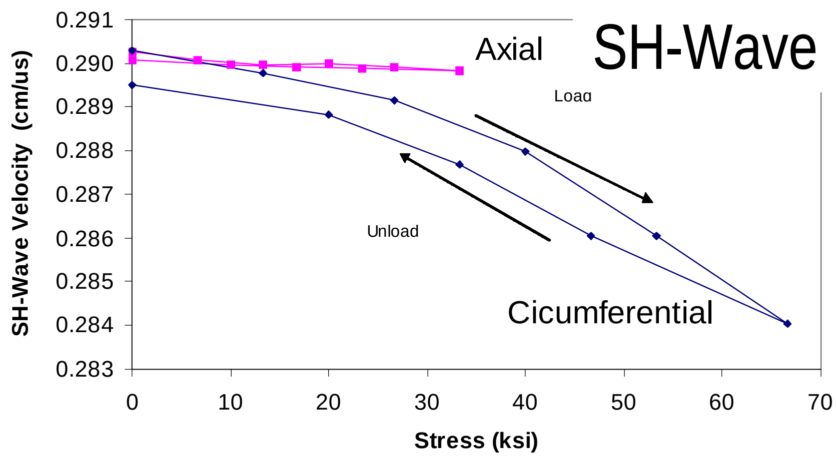


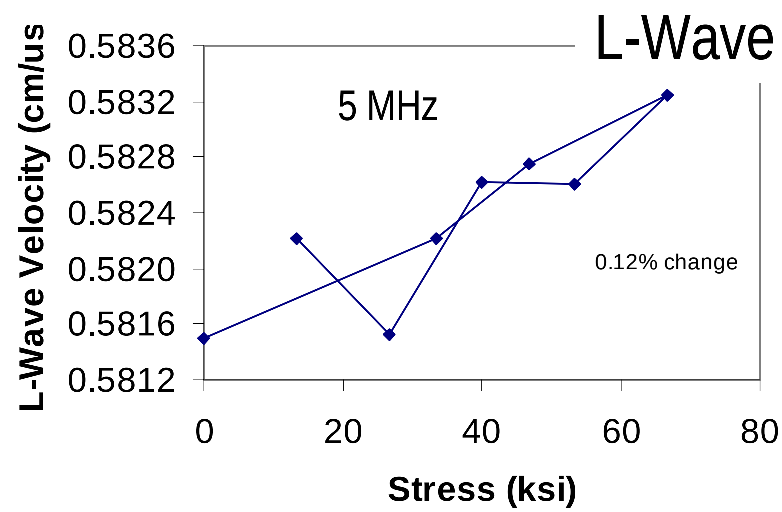
Pressurize pipe to create biaxial stress

Velocity results of biaxial test (elastic region)

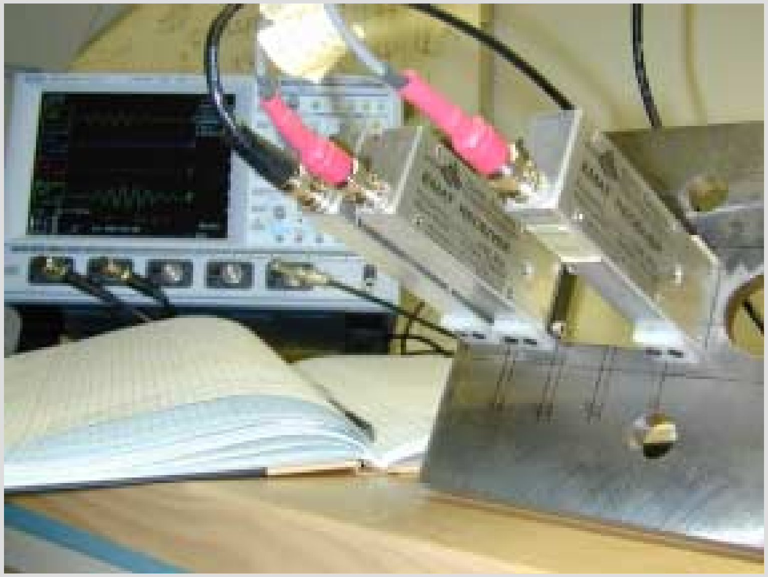




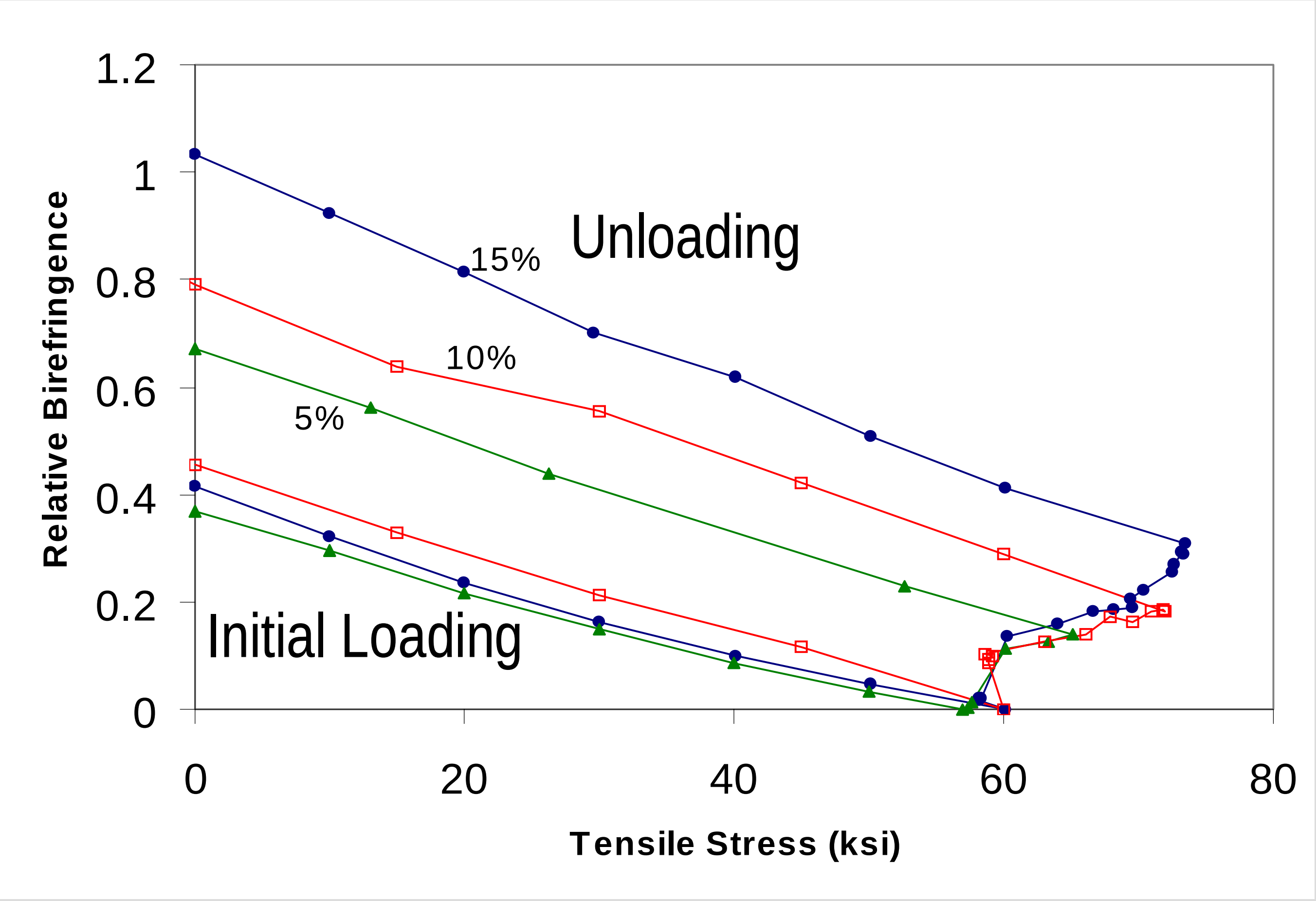




Plastic Deformation (Laboratory Measurements)

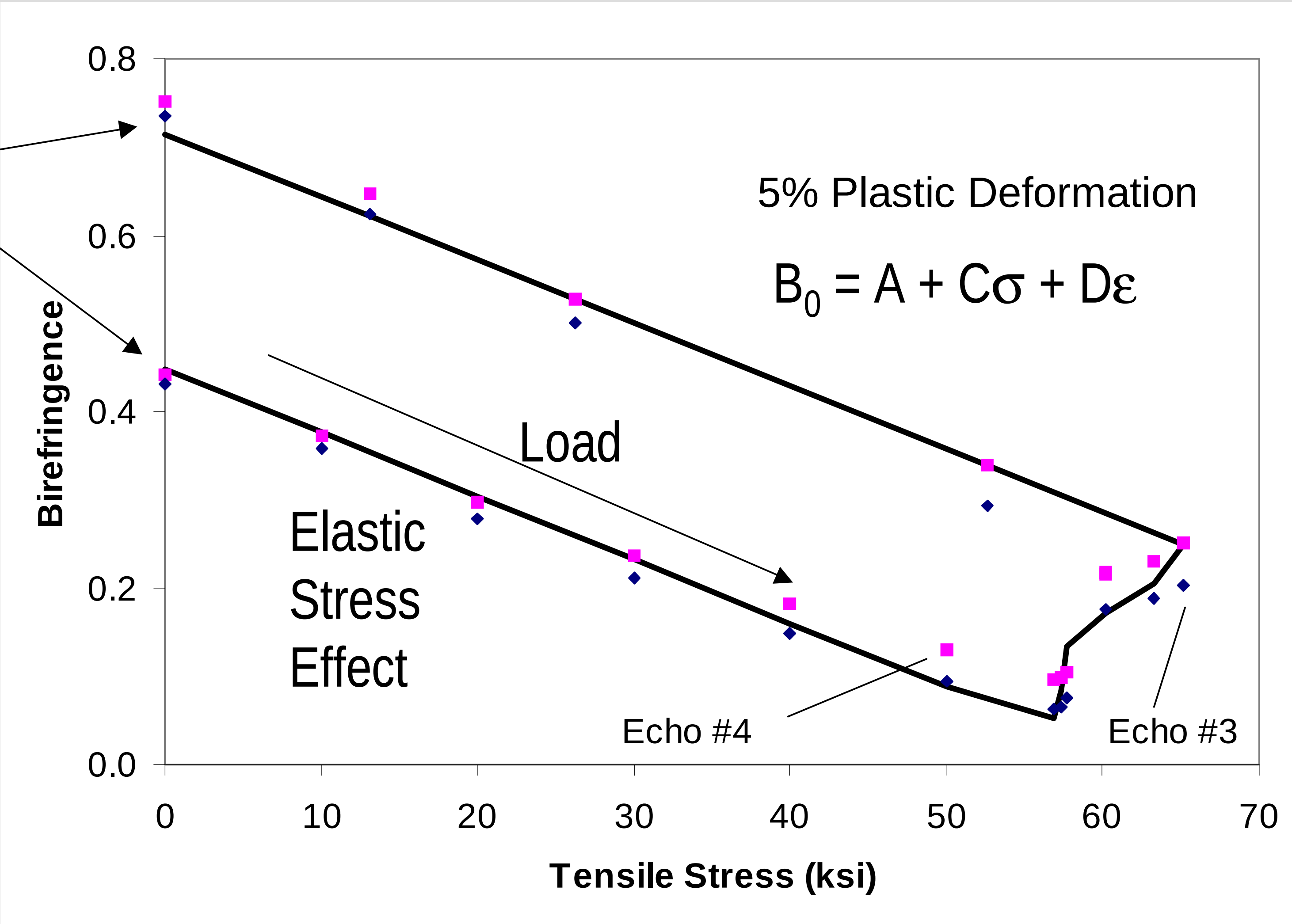


Birefringence as a function of tensile stress



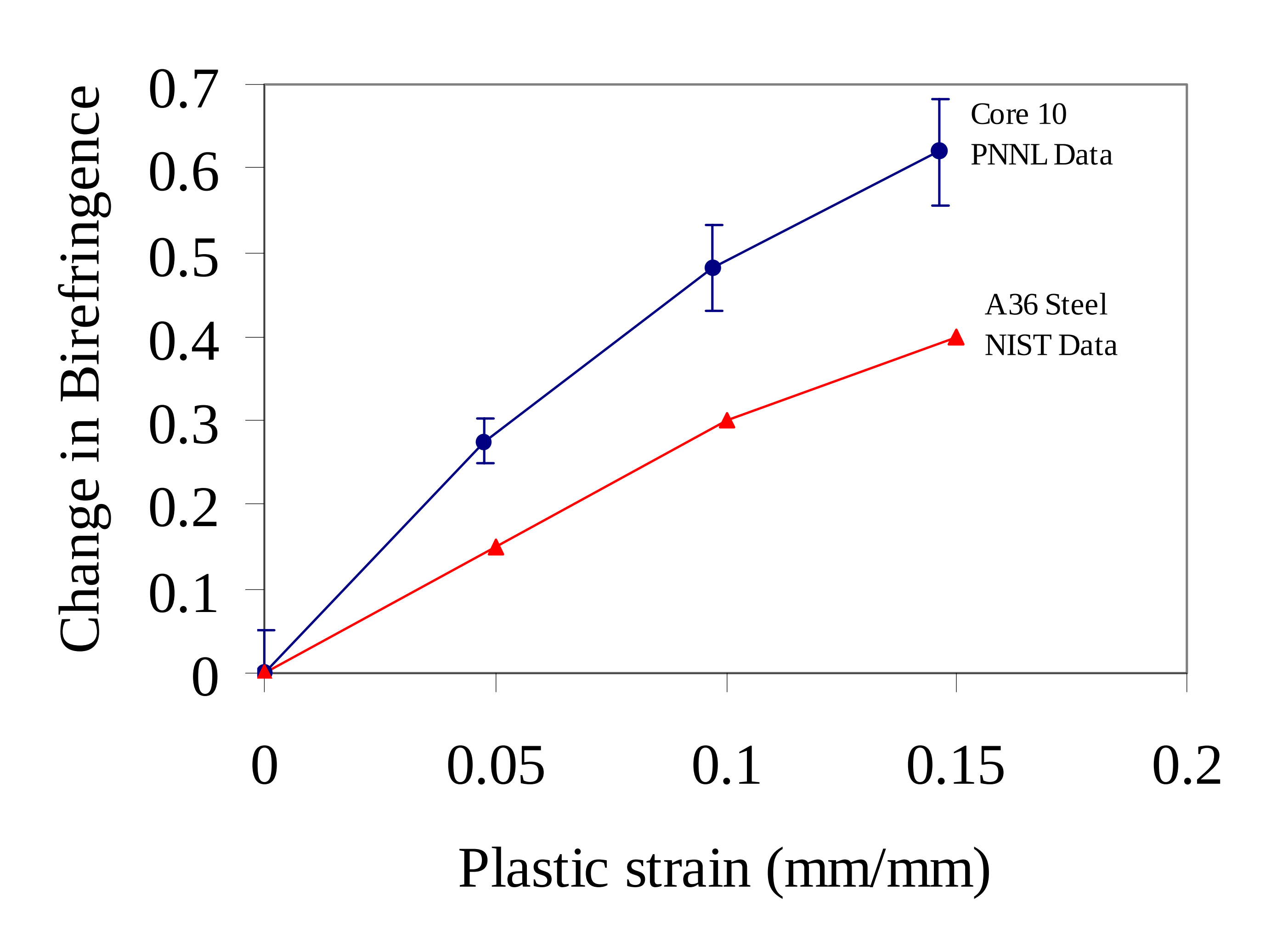
Uniaxial tension

Plastic Strain Effect



Shear wave birefringence vs. strain

Limitations:
- Stress free
- No texture change
- Known baseline



Current phase accomplishments

- Tensile test
- Pipe measurements
    - Shear Birefringence
    - Longitudinal
    - Rayleigh/Surface
    - SH to independently compensate for stress
- PG&E Preliminary Measurements
    - Ruptured specimens
    - Uniaxial
    - Biaxial
    - Localized damage

Plastic Strain Measurement Concept

- Multiple ultrasonic and physical measurements
  - Shear Birefringence
  - Longitudinal
  - Rayleigh/Surface

  Stress, strain, and texture effects
  - SH to independently compensate for stress
- Fracture mechanics models ⟹ remaining life

Future Plans

- Measure from inside
- Advanced EMATS (size and capability)
- Motion
- Crawler/field test

Conclusions

- Ultrasonic measurements being developed for measuring plastic strain in pipelines
- Multiple measurements required to isolate effects from:
  - Residual stress
  - Texture effects
  - Unknown baseline
- EMATs well suited for this application
- Provides critical information to damage severity models

Acknowledgements

- Department of Energy (DOE) National Energy Technology Laboratory (Natural Gas Infrastructure Reliability Program)
- Pacific Gas & Electric (PG&E)
- Measurements:
  - Kayte Judd
  - Seth Gulley
- EMAT System
  - Sonic Sensors