Outline

- Background
- Methods & Calibration
- Characteristics of Non-linear Materials
- Summary

Background

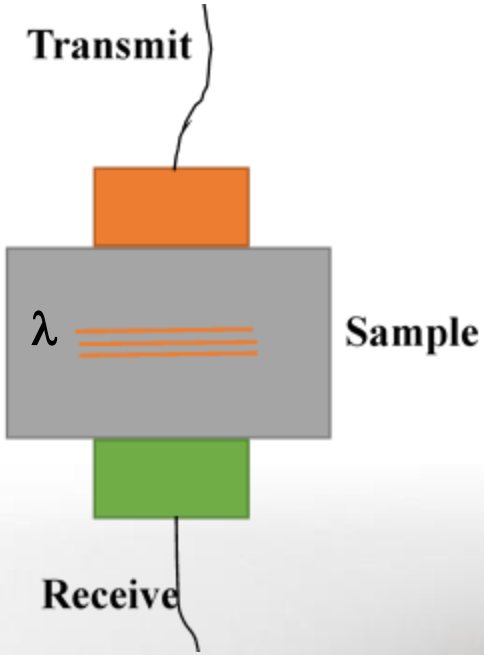
Compressive Modulus of Brakes depends on…..

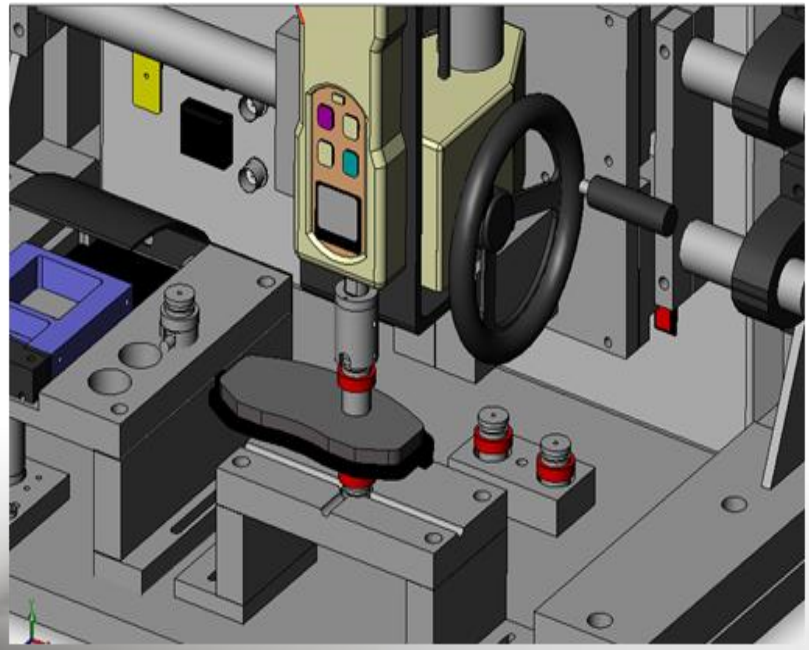
- **Flatness/parallelism of the steel backing**
- **Properties of the underlayer**
- **Friction material**
  - Static modulus differs from dynamic modulus
  - Modulus depends on pre-load
  - Modulus depends on strain amplitude
  - Modulus depends on loading history
  - Modulus depends on frequency (strain rate)
  - Modulus depends on temperature
  - Modulus is anisotropic

Background

Wavelength, λ, smaller than sample dimensions

Primary measurement is time-of-flight



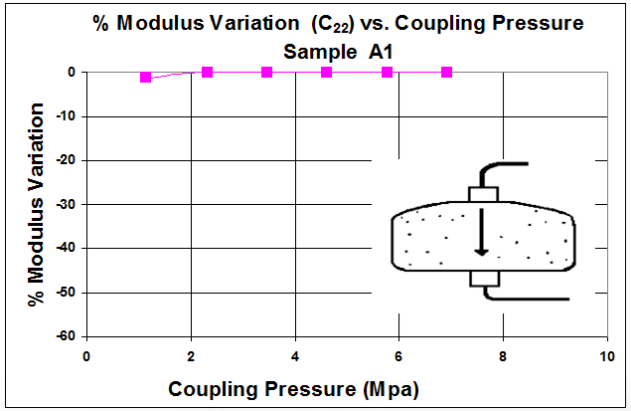


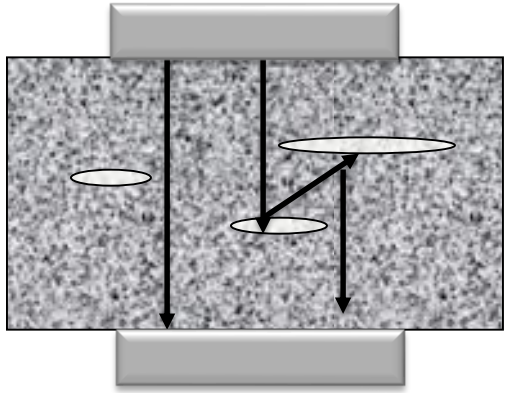
Conceptual Friction Model

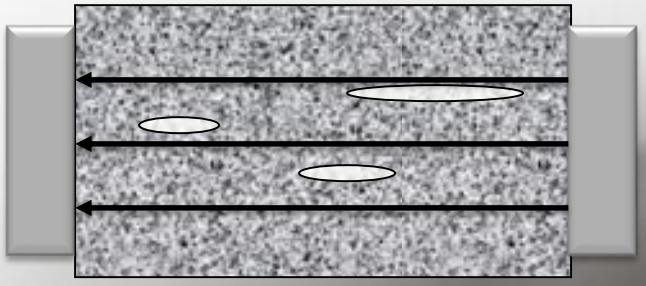
Non-Linear Aspects of Friction Material Elastic Constants

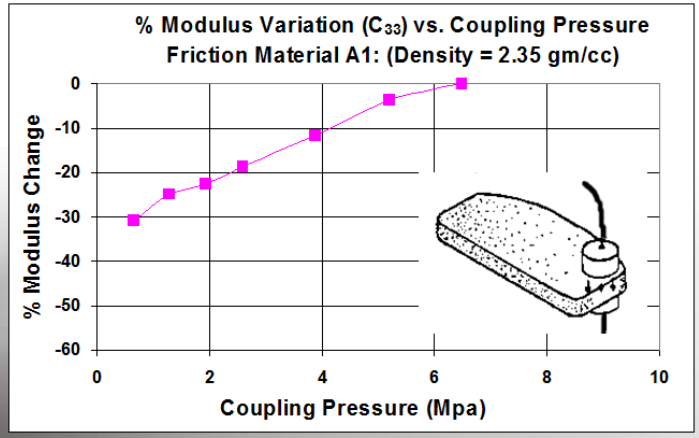
Non-Linear, Load-Dependent Behavior is *Anisotropic*

No Load-Dependence for in-plane modes





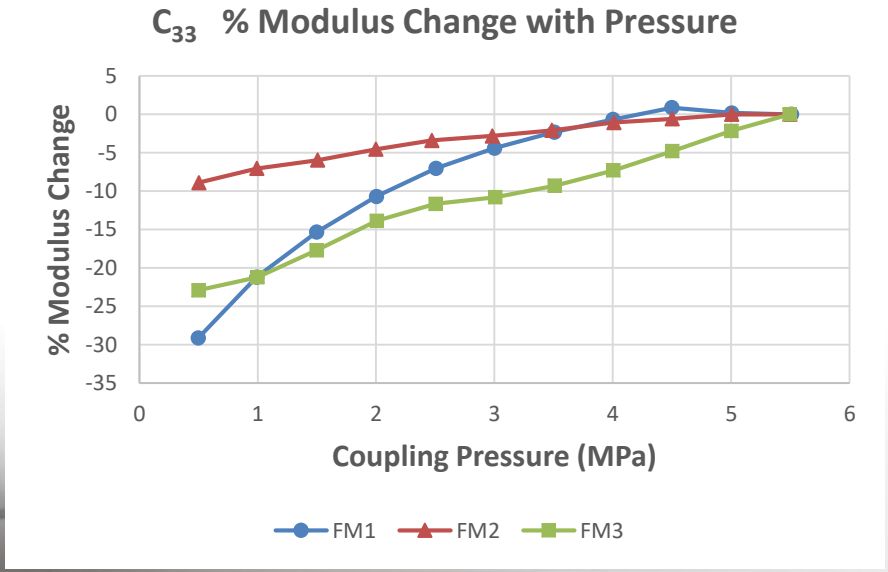




Characteristics of Non-linear Materials

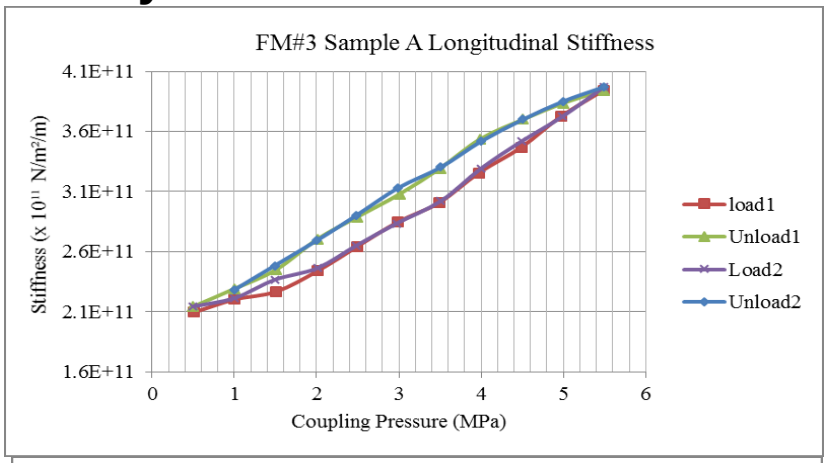
MATERIAL	DENSITY	C_{33}@4MPa	E_3@ 4 Mpa	C_{44}@4MPa
	g/cm^3	Gpa	Gpa	Gpa
FM#1	2.5	3.2	2.50	2.35
FM#2	3.1	4.8	4.08	3.30
FM#3	2.2	3.2	2.46	2.35

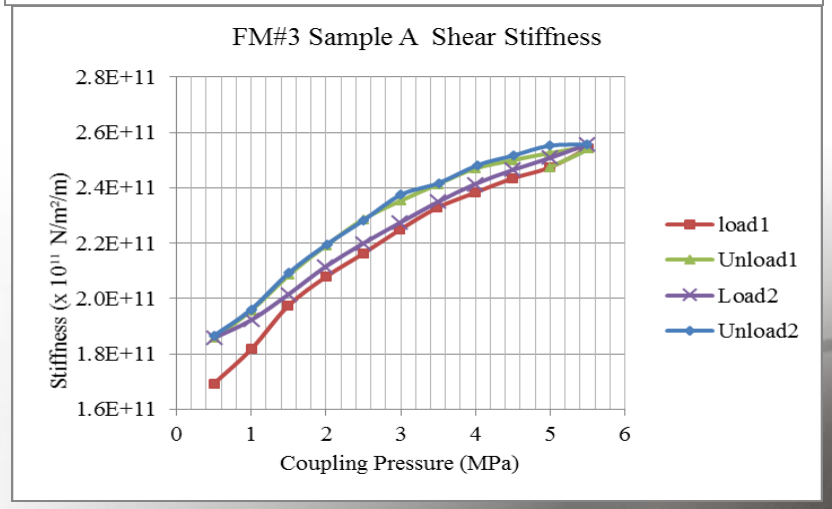
- Significant modulus variations with pre-load
- Magnitude differs from one material to the next



Characteristics of Non-linear Materials

Hysteresis



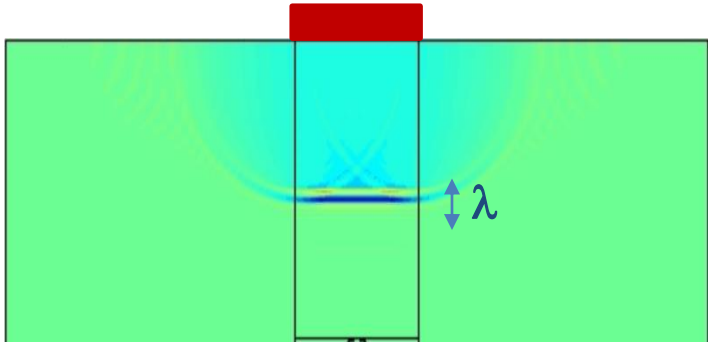


- Stiffness is greater when unloading the sample
- Magnitude differs from one material to the next

Frequency Dependence

Ultrasound $\lambda < L$

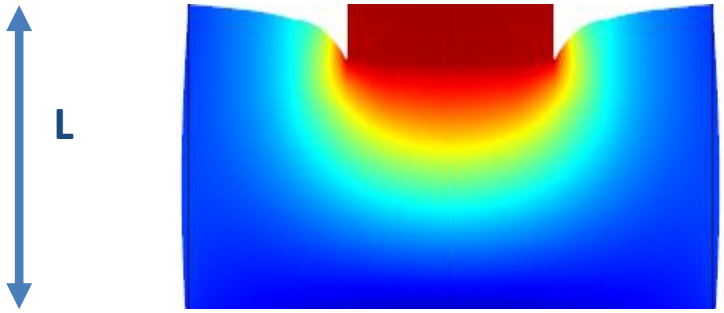
Measured Quantity: propagation Time



Net Stress & Strain =0
Max Local Strain Amplitude ~ 0.25 microns
Max Local Strain Rate 1.5 X 10^6 microns/sec

Others $\lambda > L$

Measured Quantity: Displacement, velocity, acceleration and/or frequency.



Stress & Strain Distributed

Summary

- Non-linear nature of friction materials leads to significant reduction in the ultrasonic velocity and thus modulus at low pre-loads.
  - Load-dependence is anisotropic; Out-of-plane modes are load-dependent; In-plane modes are not
  - Magnitude & shape of the variation varies with formulation
  - Increased measurement variability at low loads
  - Hysteresis is observed in all materials; Stiffness for unload condition is always greater than for the loading test condition
  - Magnitude of the stiffness derived from ultrasonic methods is comparable to that obtained from dynamic stiffness measurements in kilohertz range.

Thanks For Your Attention

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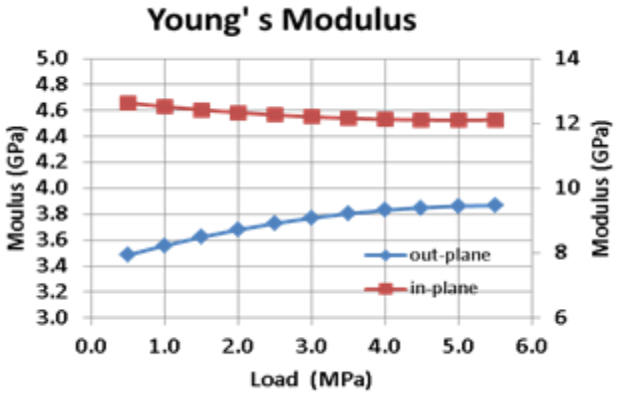
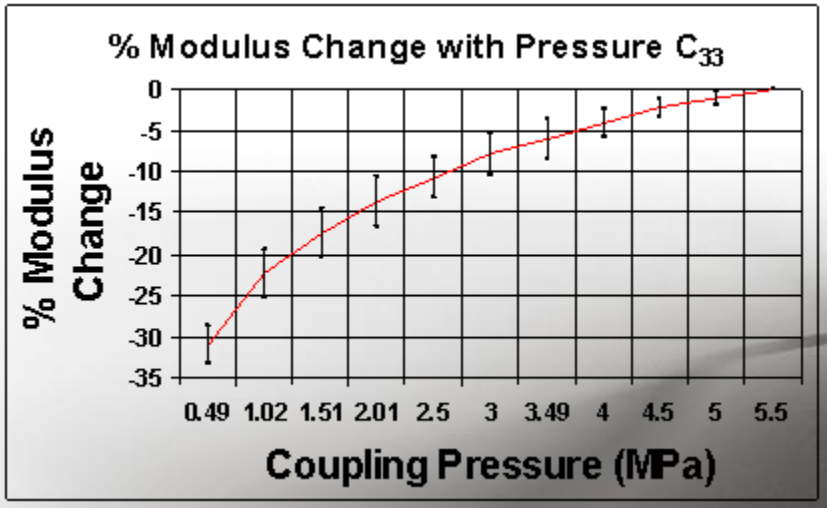
Backup slides

Background

Load-dependent Properties





Temperature-dependent Properties