MPI 2026 WORKSHOP PROBLEM

CABLE FLEXING, POLYMER DEFORMATION, AND FATIGUE

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June 14-18
Drexel University

Together, improving life

Background

W.L. Gore & Associates is making cables for the Semiconductor, Aerospace, and Defense industry.

In many of these applications, the cables are being flexed and repeatedly bend for millions of cycles.

We would like to:

- understand better what the mechanical stresses, strains, and strain rates are on the cables for various geometries.
- translate the ‘real world’ stress, strains and strain rates into an alternative characterization system.
- predict the lifetime for different cable constructions using Fatigue models for the metal conductor and the polymeric insulators

Applications

Typical Applications

- Cleanroom automation
- Advanced packaging equipment
- Front-end wafer inspection
- Wafer metrology equipment
- Semiconductor automated optical inspection (AOI)
- Semiconductor processing equipment
- Linear motion stages
- Pick & place equipment
- Wafer handling
- Flat panel display (FPD) manufacturing equipment
- CMOS image sensor (CIS) packaging equipment
- Lens manufacturing equipment

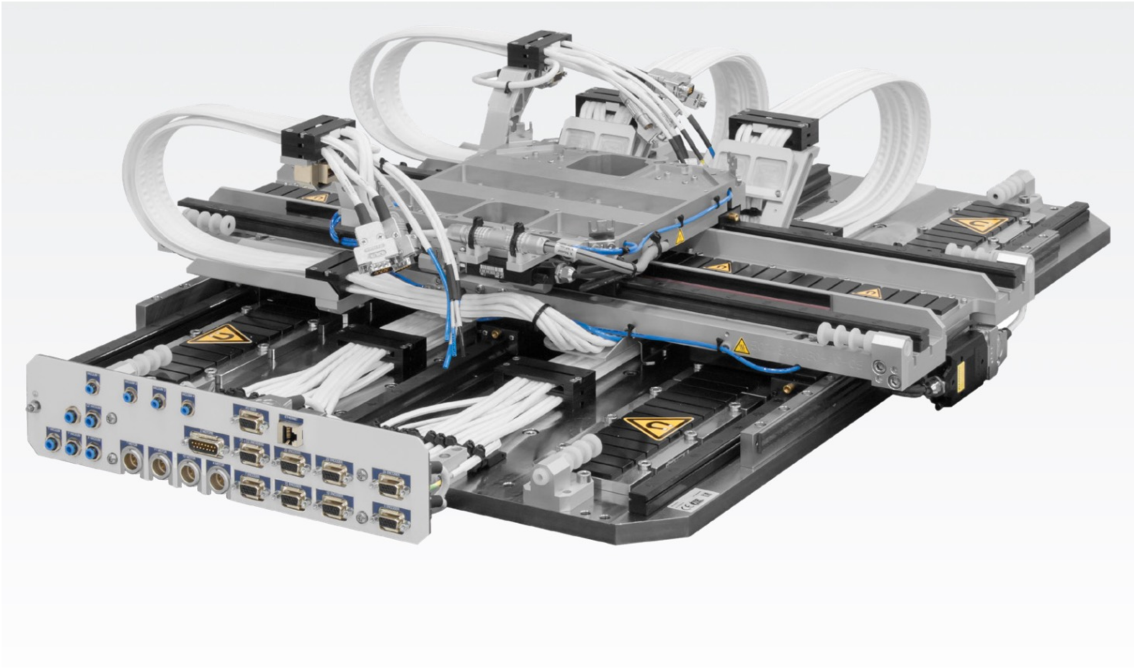
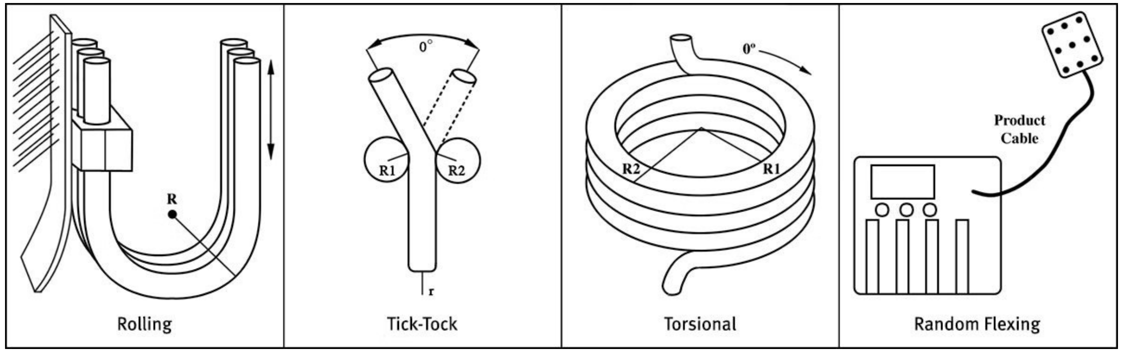


Image courtesy of ETEL S.A.



Focus for this workshop: Trackless cables

Focus on one cable only, not the entire cable assembly

Used for connecting to movable devices that need power and signal processing

- Often in cleanroom environment, eg, semiconductor industry

Typical Applications

- Electronic component packaging equipment
- Advanced bonding equipment
- Pick & place mounter equipment
- Back-end manufacturing & inspection processes
- Lens manufacturing equipment
- Manufacturing equipment sensitive to ESD

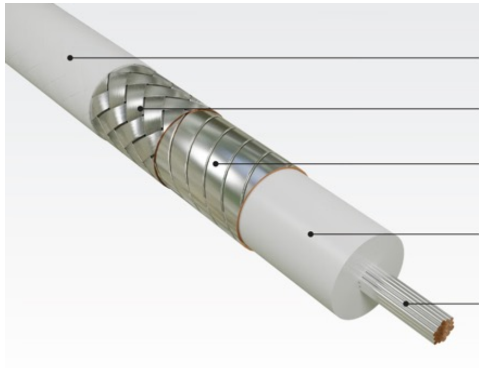
Application requirements

- Maximum Acceleration g (m/sec2) 5.0 (50)
- Speed 5.0 m/sec
- Maximum Self-Supporting Stroke Length 1000 mm
- Overall Width up to 100 mm
- Minimum Bend Radius 50 mm
- Flex Life Cycles > 10 million

Cable Stress and Failure in High Flex Applications

In its simplest form, a cable is composed of

- (i) a helical stranded Cu conductor
- (ii) a flexible polymer dielectric
- (iii) potentially, a foil or stranded Cu braid shield
- (iv) a polymer jacket



Each time a cable bends or flexes, (i) the helical stranded Cu conductor and potential shield rotates and unfurls to compensate for the strain; (ii) the polymer dielectric and jacket deforms.

- We are primarily interested in the deformation and fatigue of the polymer dielectric

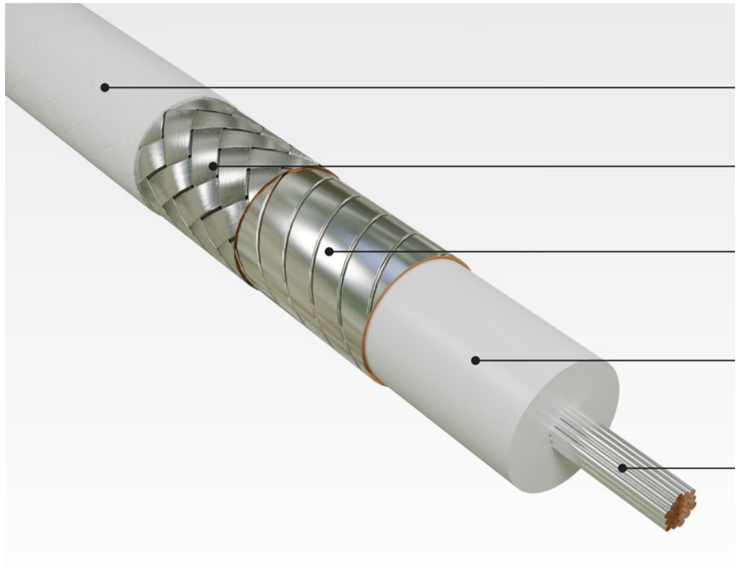
There are three basic causes of failure in any cable subjected to flexing:

- Degradation of the polymer dielectric (=> focus for this MPI workshop!)
- Fatigue of the stranded conductor and shield in the flex area
- Fatigue of the conductor and shield at the point of termination

Cable Geometries

– Concentric

– Conductor pair



Engineered polymer jacket.

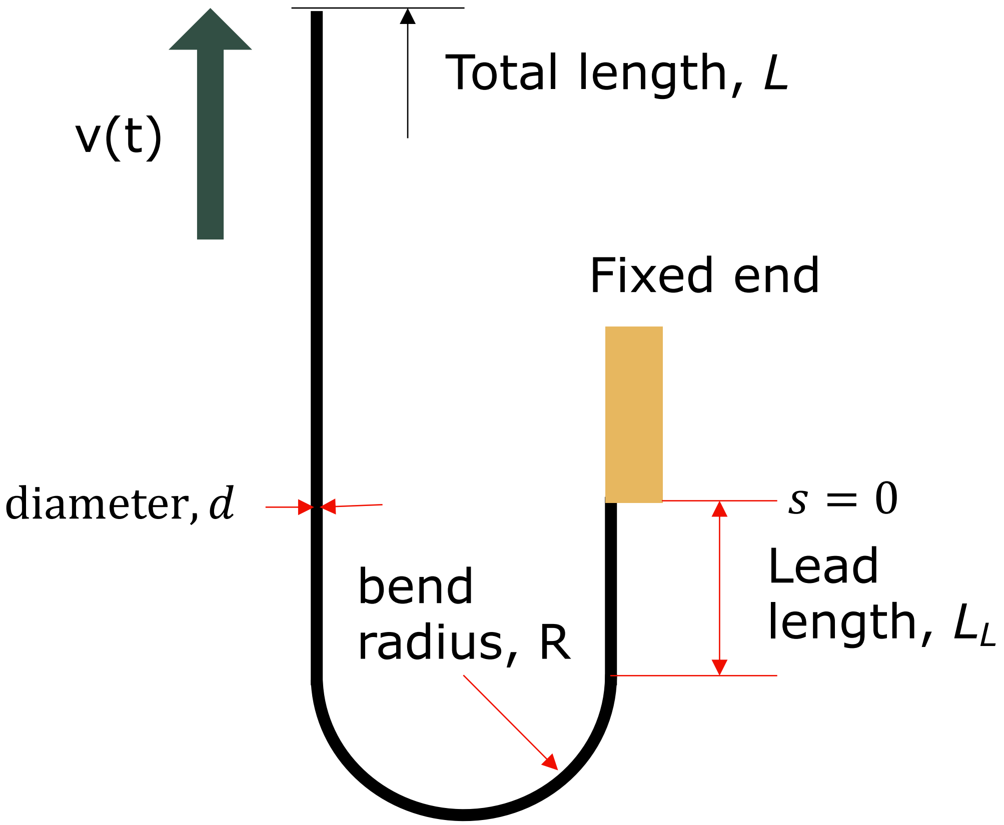
Braided shield

Helically wrapped, silver-plated
copper outer conductor

Polymeric dielectric

Silver-plated copper conductor

Cable Cycling – problem definition



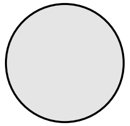
Cable end travels between 0.1m and 1m at various velocity profiles v(t)

Cable cycles at ~1Hz for ~10 million cycles

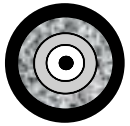
Geometry varies (L, L_L, d, R)

Application requirements: v(t), (stroke length, acceleration)

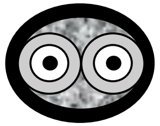
Cross-section of cable varies based on simplification:



– Homogenous

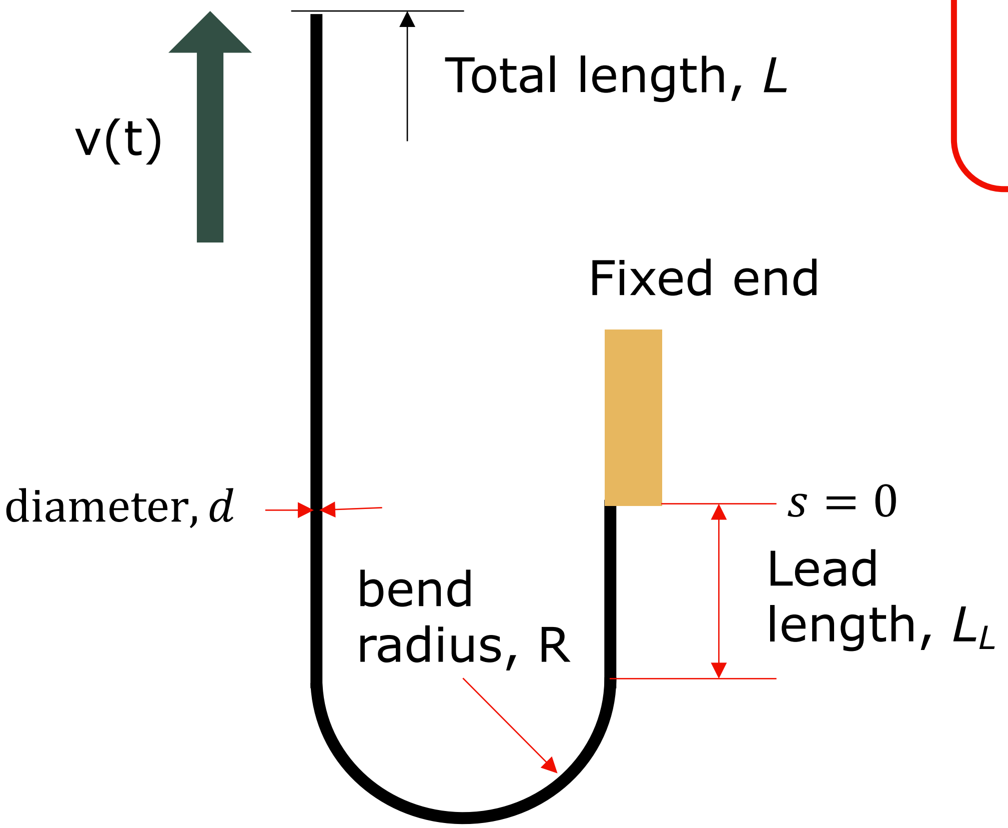


– Concentric



– Conductor pair

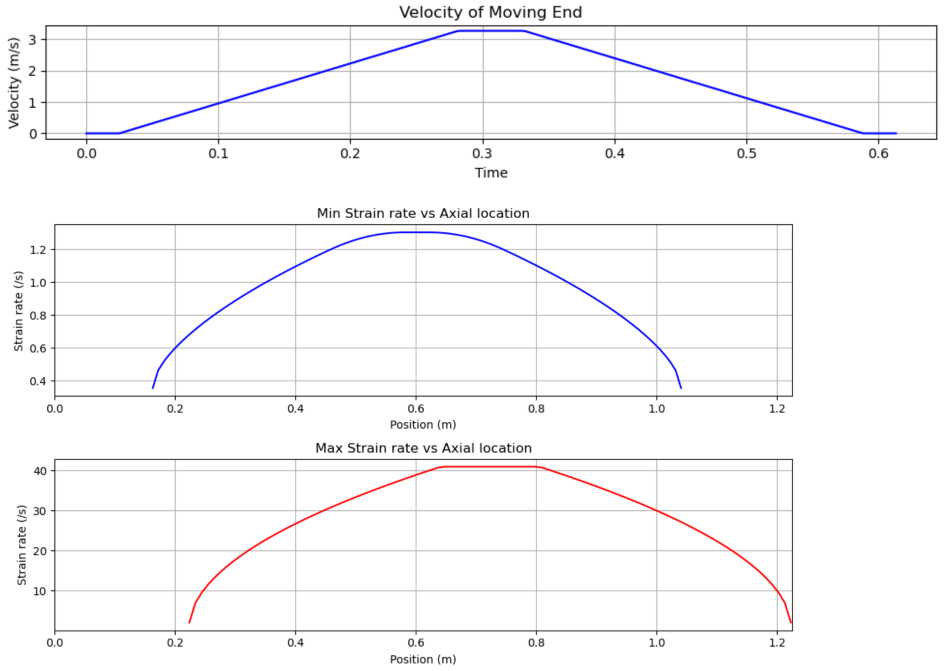
Cable Cycling – A specific use case



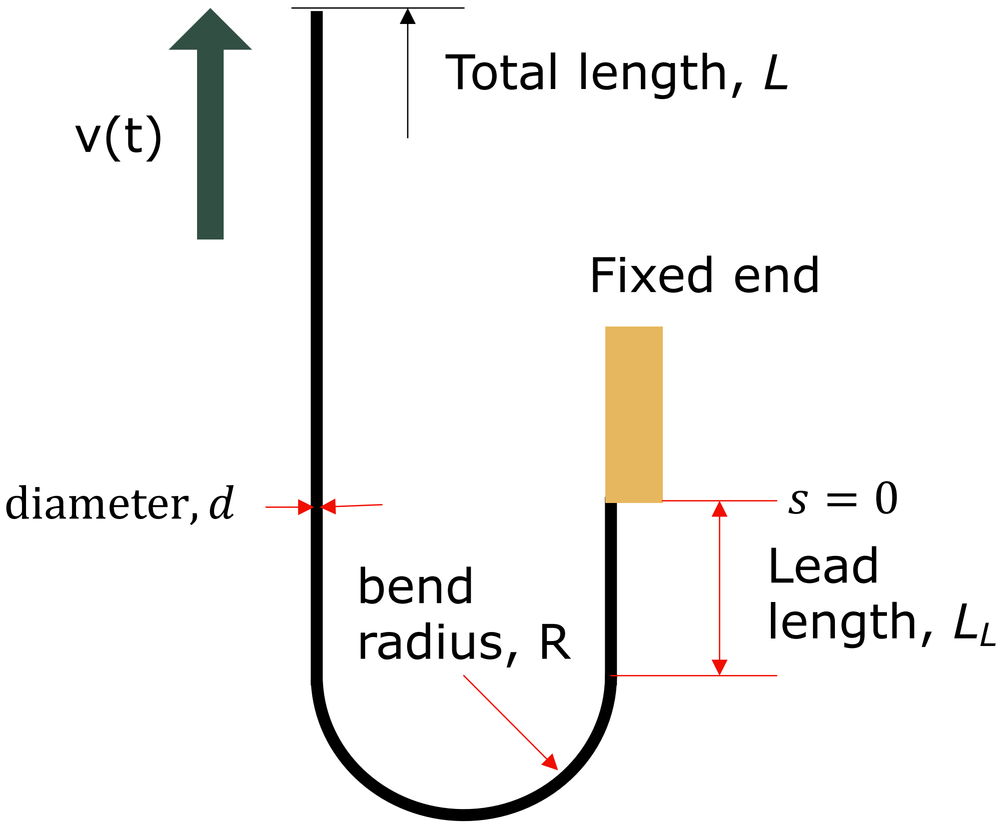
At an acceleration of 1.2g, bend radius (R) of 40mm, stroke length of 0.3m, v(t) would be 1.64m/sec.

At an acceleration of 2g, bend radius of 40mm, stroke length of 0.3m, v(t) would be 1.98m/sec.

Example:

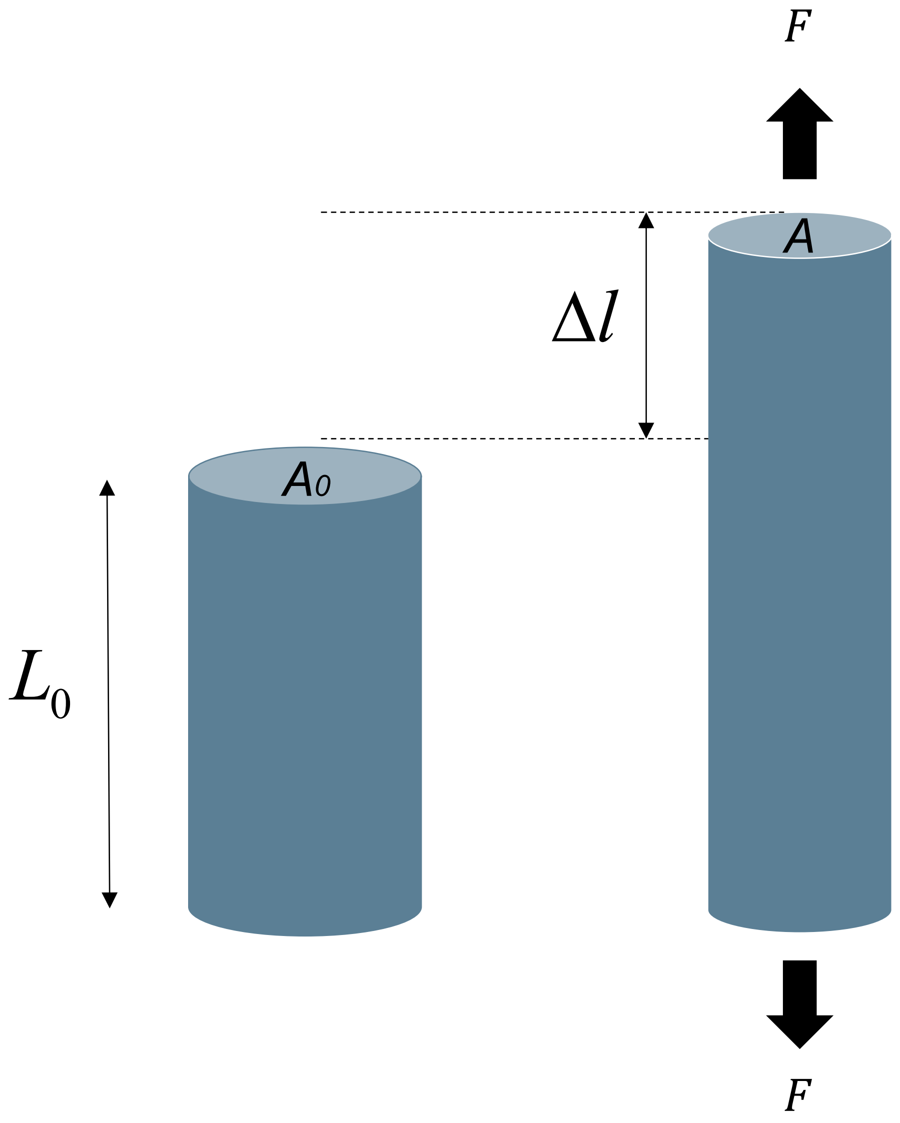


Cable Cycling - questions



1. What is the stress, strain, and strain rate inside the cable at different cycling velocities and cable geometries?
2. How does the polymeric mechanical model change the stress, strain, and strain rate?
3. Polymer materials properties can be highly resolved by torsional shear testing. Can the stress, strain and strain rates of the cycled cable be transformed into torsional shear test inputs?
4. How will the cycle time/velocity change the performance over time?

Mechanics background: Concepts of Stress & Strain



Stress: force over cross-sectional area [Force per area]

$$\sigma = \frac{F}{A_0}$$

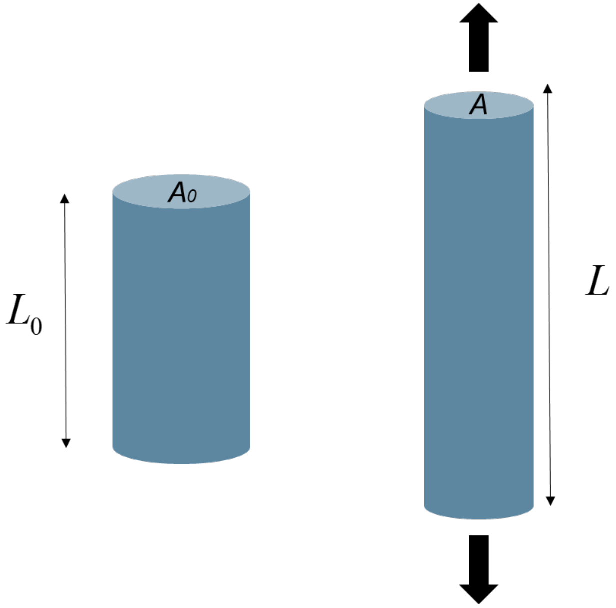
Normalized force
Units of psi (lbf/in^2), Pa (N/m^2)

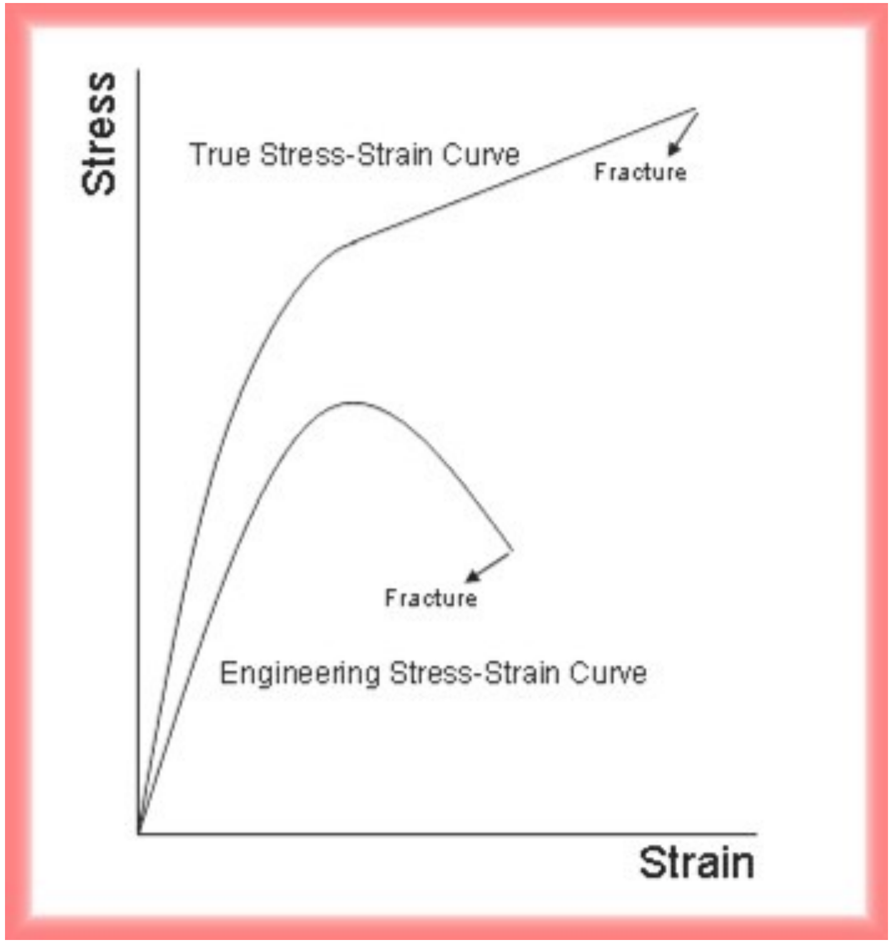
Strain: change in length over initial length [dimensionless]

$$\varepsilon = \frac{\Delta l}{L_0}$$

Normalized displacement
Unitless (or %)
0.01 = 1% strain

Engineering vs true stress/strain

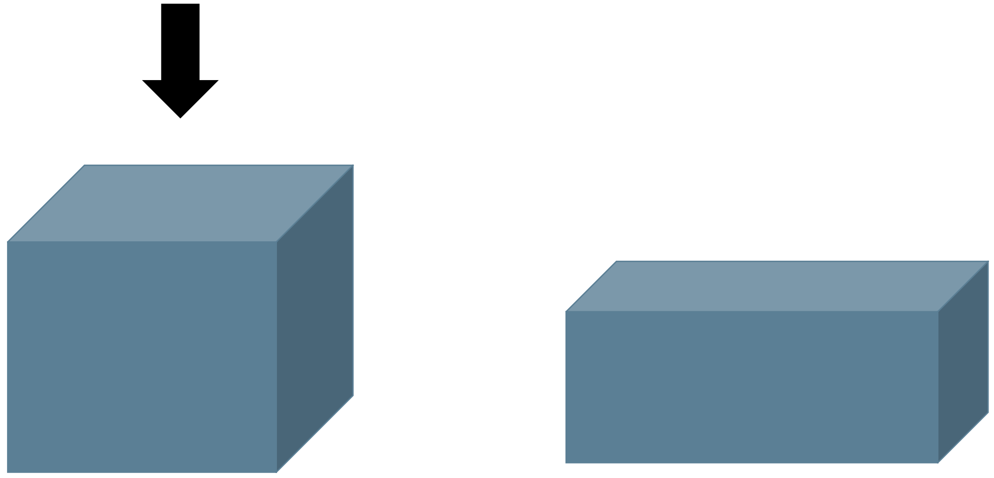




"**Engineering stress/strain**": normalized by INITIAL length/area

"**True stress/strain**": normalized by DEFORMED length/area

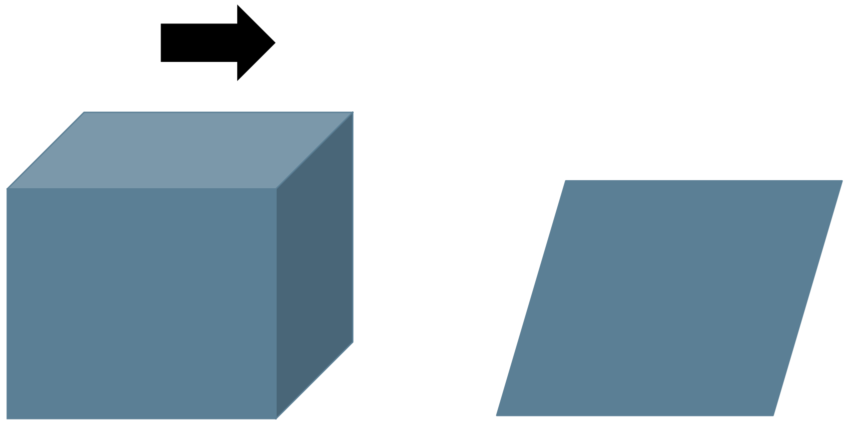
Normal stress and shear stress



Normal stress: force is applied perpendicular to surface

$$\sigma = E\varepsilon$$

Young's Modulus



Shear stress: force is applied parallel to surface

$$\tau = G\gamma$$

Shear Modulus

Practical applications of 2D Linear Elasticity

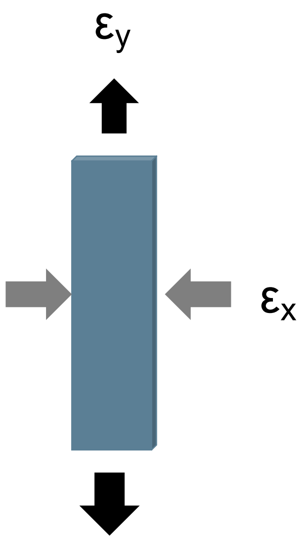
Poisson's Ratio: 'Necking' of a uniaxial specimen

$$\nu = -\frac{\varepsilon_x}{\varepsilon_y}$$

No interaction (cork), v = 0

Volume preserved (rubber), v = 0.5

polymers: v= ~1 (or larger)



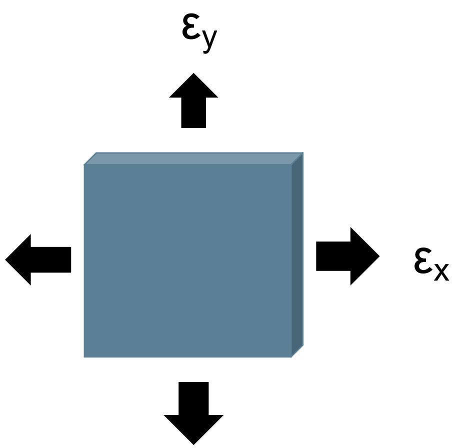
Biaxial Stretching: Higher stress than same uniaxial stretch (prevent 'necking')

$$Y = \frac{E}{1 - \nu^2}$$

Apparent
Biaxial Modulus

$$\sigma = Y\varepsilon$$

Equi-biaxial stretch
($\varepsilon_x = \varepsilon_y$)

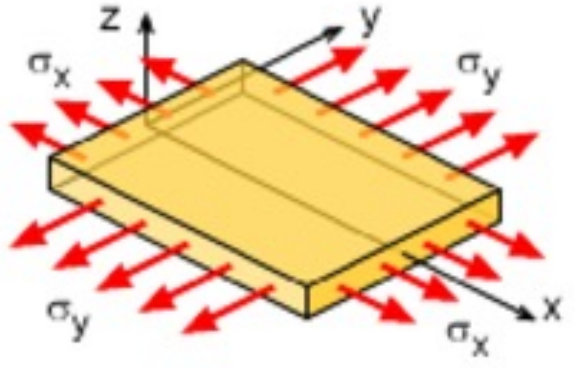


Extend to 2D: Plane Stress Hooke's law

$$\sigma_x = \frac{E}{1-\nu^2}\epsilon_x + \frac{\nu E}{1-\nu^2}\epsilon_y$$

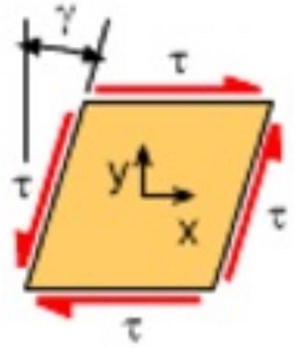
$$\sigma_y = \frac{\nu E}{1-\nu^2}\epsilon_x + \frac{E}{1-\nu^2}\epsilon_y$$

Normal stress



$$\tau = G\gamma = \frac{E\gamma}{2(1+\nu)}$$

Shear stress

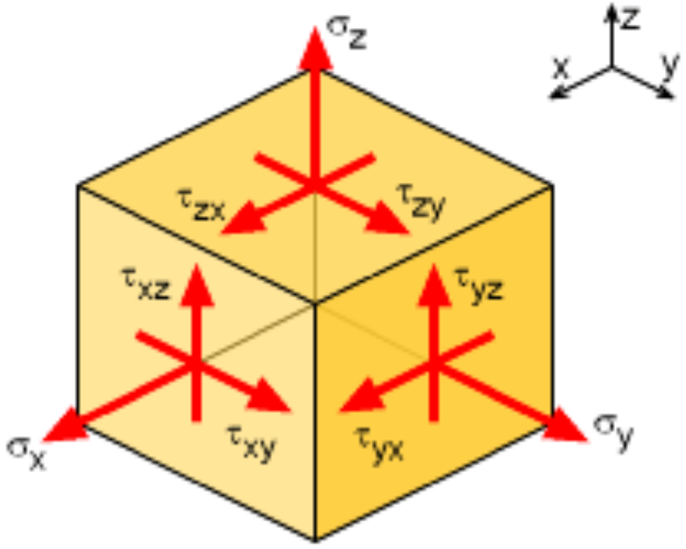


Key parameters: **Young's modulus** (*E*)
Poisson's Ratio (*v*)
Shear modulus (G) can be calculated from *E* and *v* (not independent)

Extension to 3D linear elasticity

Same material properties (E, v), but in 3 directions

Enables analysis of more complex loading states



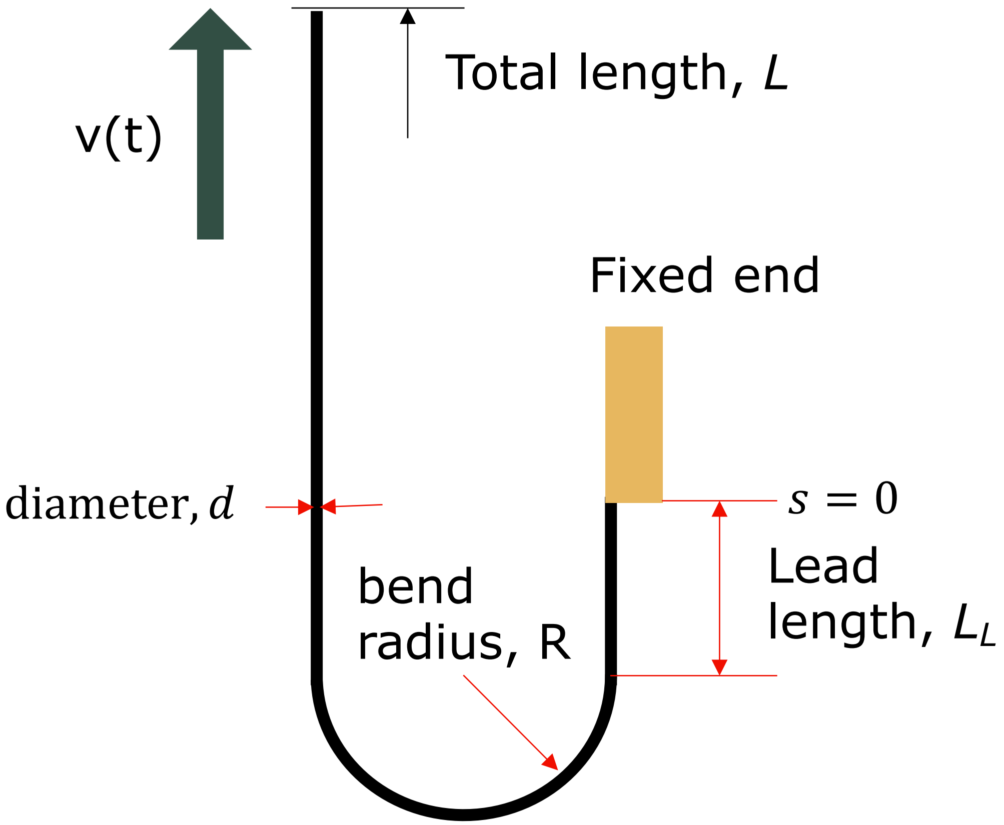
$$\sigma_x = \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_x + \nu(\varepsilon_y + \varepsilon_z)\right]$$

$$\sigma_y = \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_y + \nu(\varepsilon_z + \varepsilon_x)\right]$$

$$\sigma_z = \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_z + \nu(\varepsilon_x + \varepsilon_y)\right]$$

$$\tau_{xy} = G\gamma_{xy};\quad \tau_{yz} = G\gamma_{yz};\quad \tau_{xz} = G\gamma_{xz}$$

Cable Cycling - questions



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4. How will the cycle time/velocity change the performance over time?

In cylindrical coordinates

Elastic constants C_{ij} can be different in different directions

– similar to Youngs Modulus

For certain boundary conditions, this system can be solved analytically for constant C_{ij}

– Extension, torsion, bending, shearing, pressuring

See Literature list at end of presentation

Limitation: constant C_{ij} - *linear elastic model*

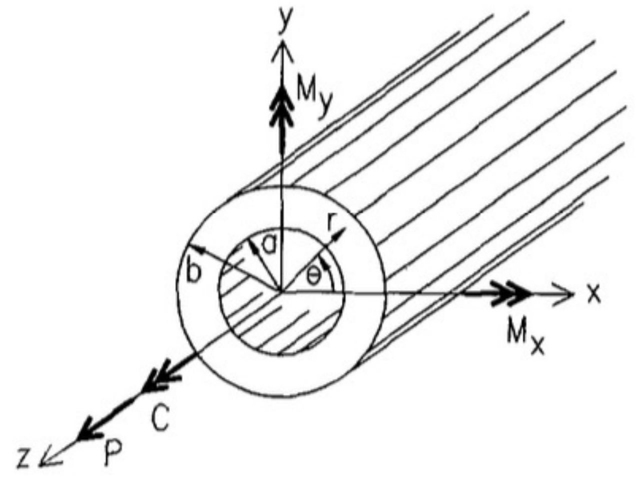
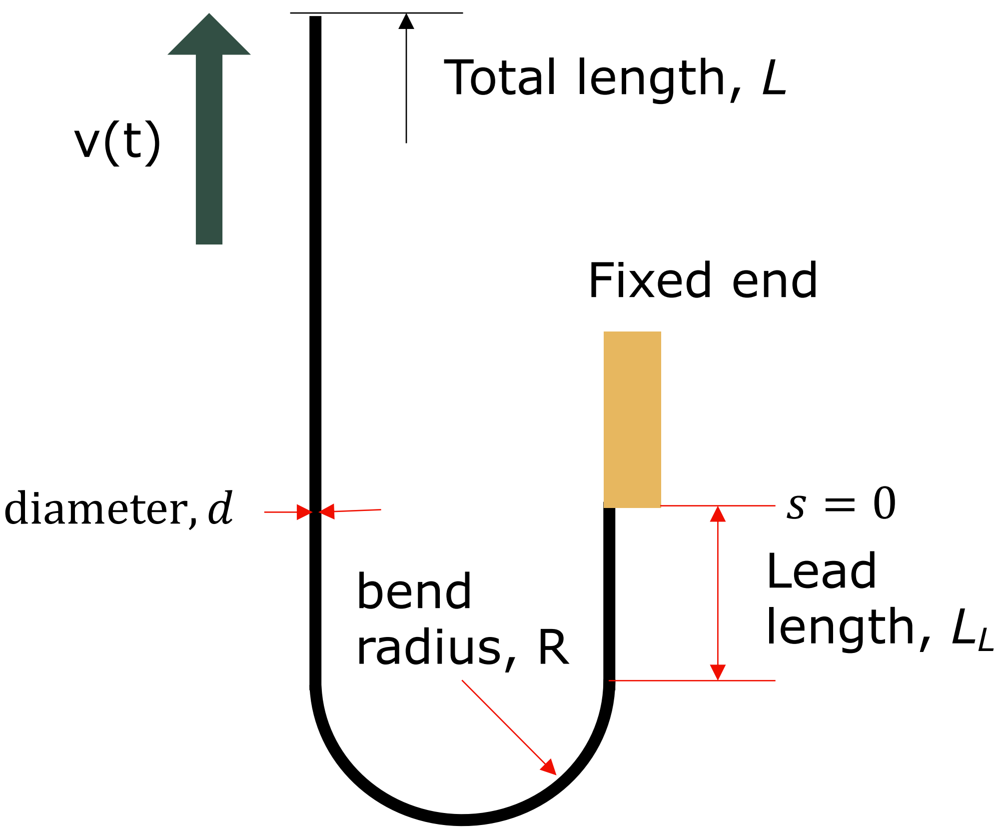


FIG. 1. Cylinder under Study and Applied Loads

$$\begin{Bmatrix} \varepsilon_r \\ \varepsilon_\theta \\ \varepsilon_z \\ \gamma_{\theta z} \\ \gamma_{rz} \\ \gamma_{r\theta} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & 0 & 0 \\ & C_{22} & C_{23} & C_{24} & 0 & 0 \\ & & C_{33} & C_{34} & 0 & 0 \\ & & & C_{44} & 0 & 0 \\ & \text{sym} & & & C_{55} & C_{56} \\ & & & & & C_{66} \end{bmatrix} \begin{Bmatrix} \sigma_r \\ \sigma_\theta \\ \sigma_z \\ \tau_{\theta z} \\ \tau_{rz} \\ \tau_{r\theta} \end{Bmatrix}$$

Cable Cycling - questions



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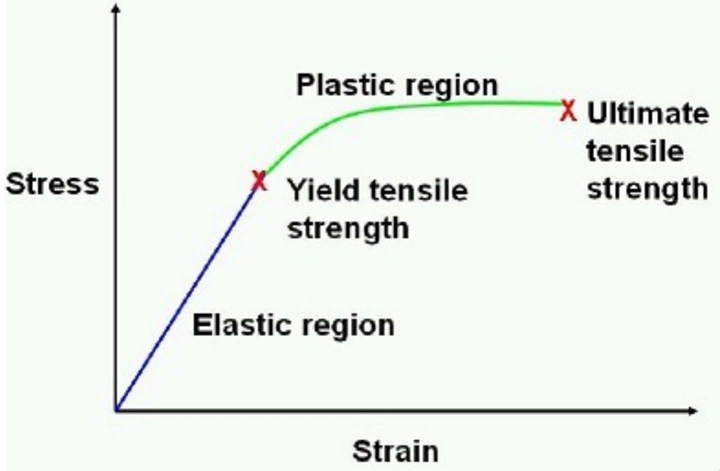
Polymer Mechanical Models

(1) Linear Elastic

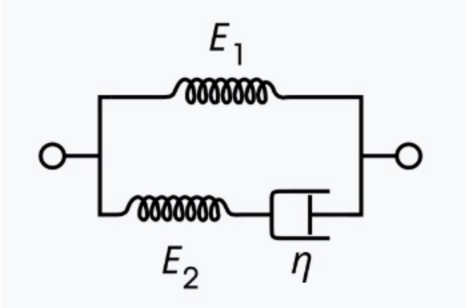
$$\sigma = E\varepsilon$$

constitutive law linking stress and strain

E = Young's modulus

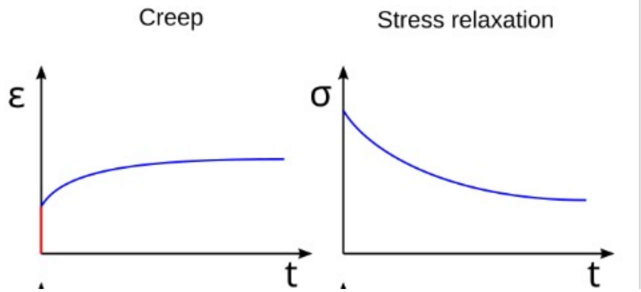


(2) Viscoelastic (Maxwell 3 component system)



$$\sigma + \frac{\eta}{E_2}\dot{\sigma} = E_1\varepsilon + \frac{\eta(E_1 + E_2)}{E_2}\dot{\varepsilon}$$

Three-element solid (Zener model/SLS)



Question 2: What if C_{ij} are not constant?

Cylindrical coordinates z, r, θ

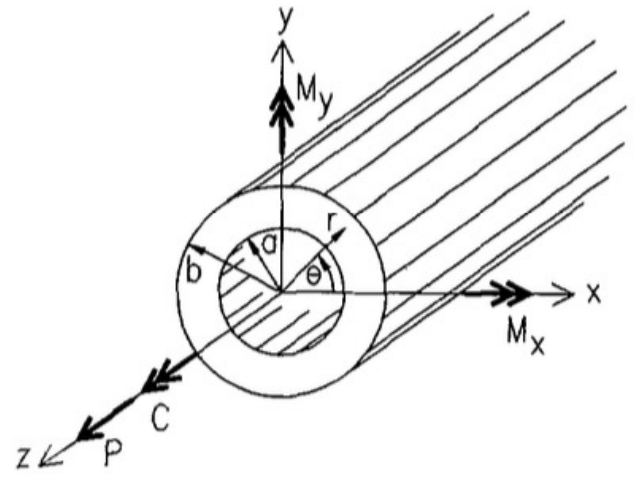
Strain ε_i, shear γ_{ij} in all directions

We would like to know how to solve this for non constant C_{ij} and for rate dependent strain/stresses !!

- E.g., viscoelastic deformation
- Elastic factors C_{ij} are functions of strain and strain rate
- How to determine Stresses σ_i , shear stresses τ_{ij}
- Focus on bending first

First step simplification

- Start with 0, 90, 180, 270 degrees
- There, we have tension, compression, torsion only



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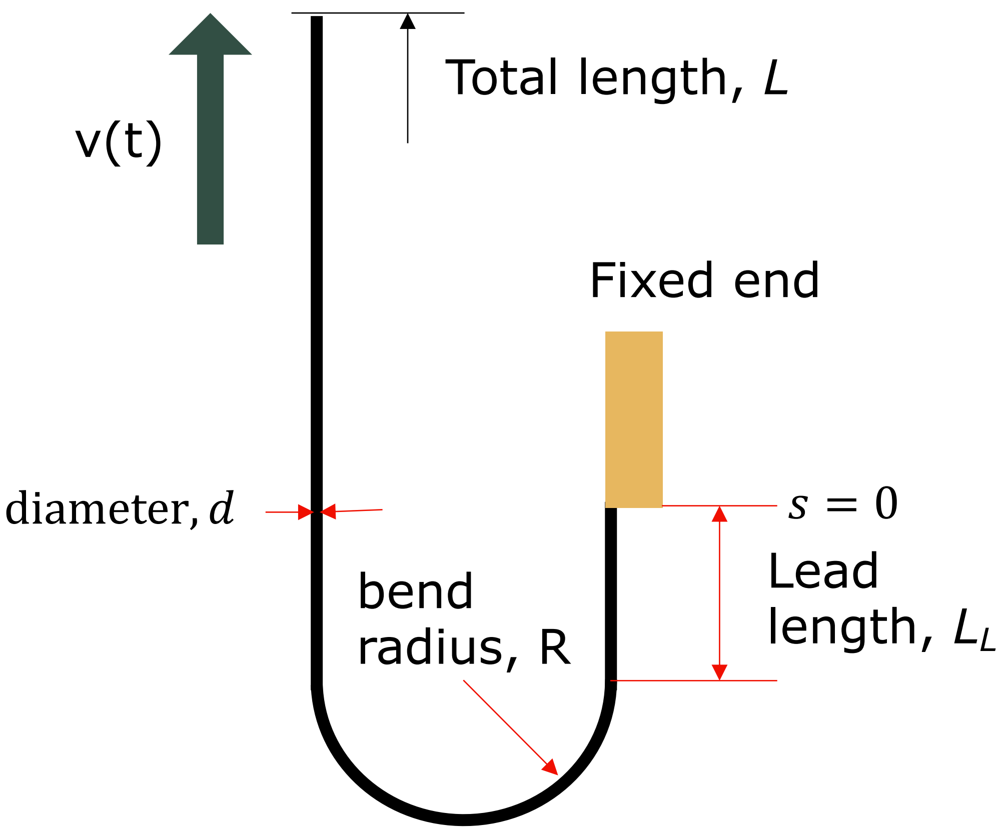

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   - See Slides 23-25
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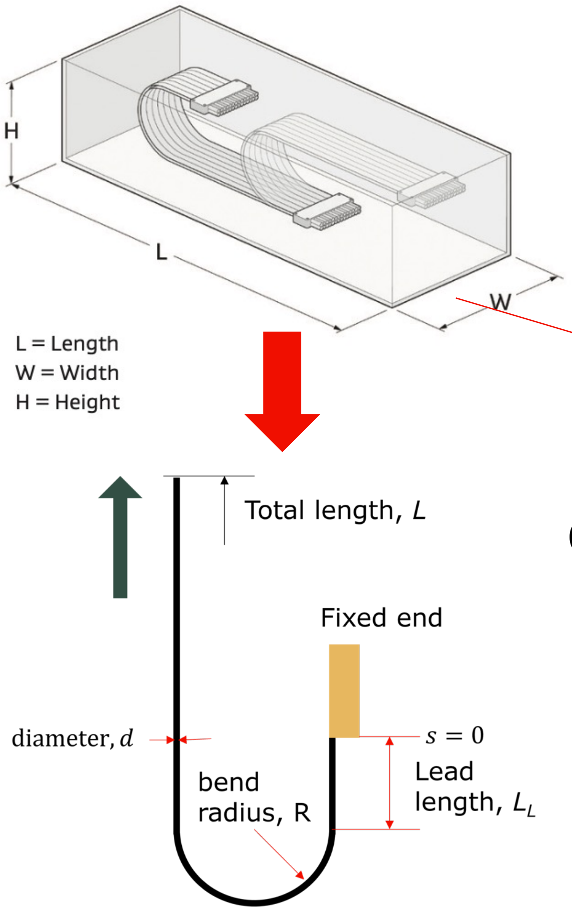
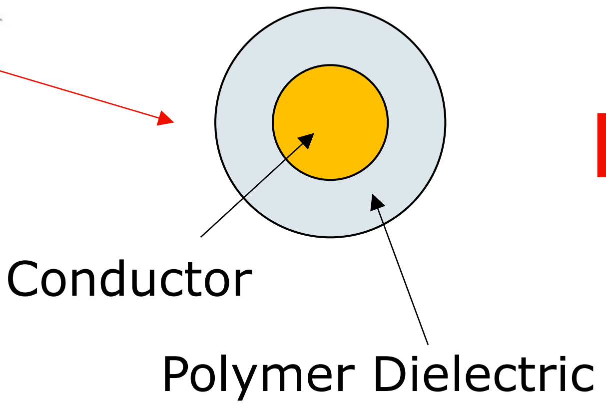
Question 3: Translating Cable Flexural Behavior to Torsional Shear

<u>Application Flexing Stress/Strain State</u>

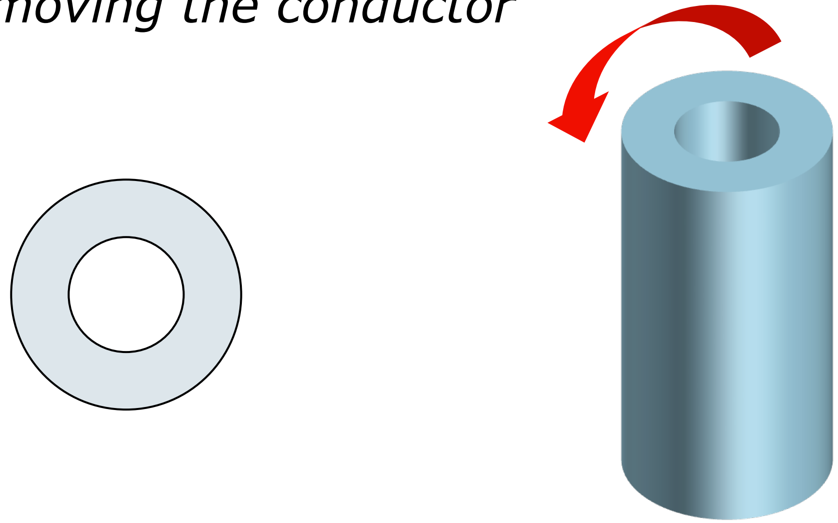


<u>Simplified Individual Cable Cross section</u>

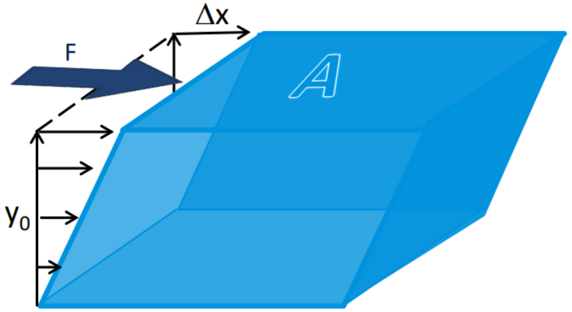


<u>Characterize the 'formed' polymer dielectric Using Dynamic rheometers in torsion</u>

- *Removing the conductor*



'formed' Polymer dielectric



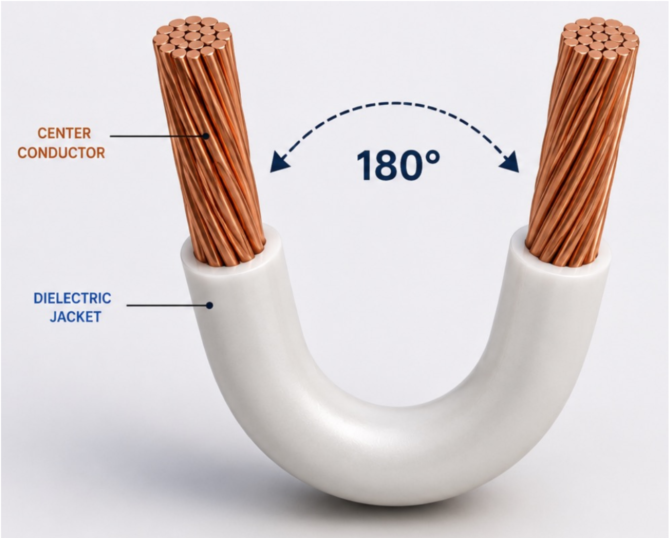
Shear stress $\sigma = \frac{F}{A}$

Shear strain $\gamma = \frac{\Delta x}{y_0}$

Shear rate $= \dot{\gamma} = \frac{1}{y_0} \cdot \frac{dx(t)}{dt}$

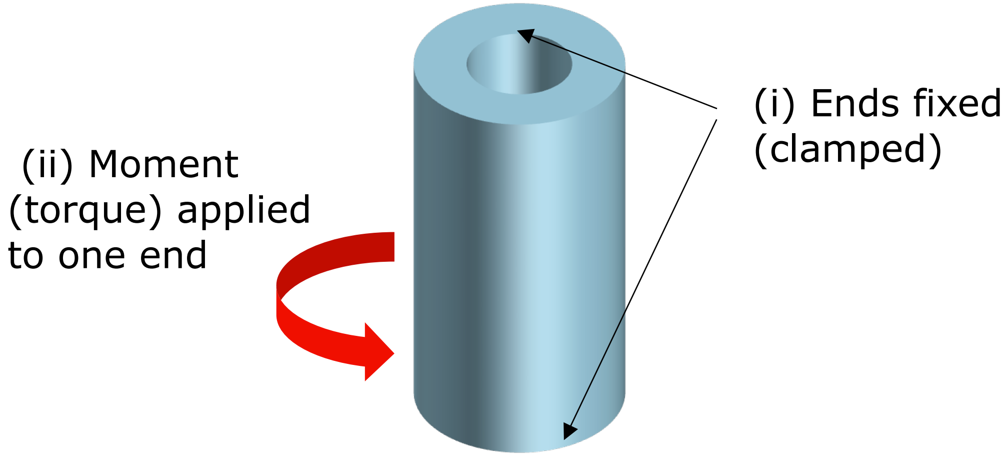
Translating Cable Flexural Behavior to Torsional Shear

<u>Application Flexing Stress/Strain State</u>



What are the stress, strain and strain rates in the dielectric during flexing?

<u>Testing torsional Stress/Strain State</u>

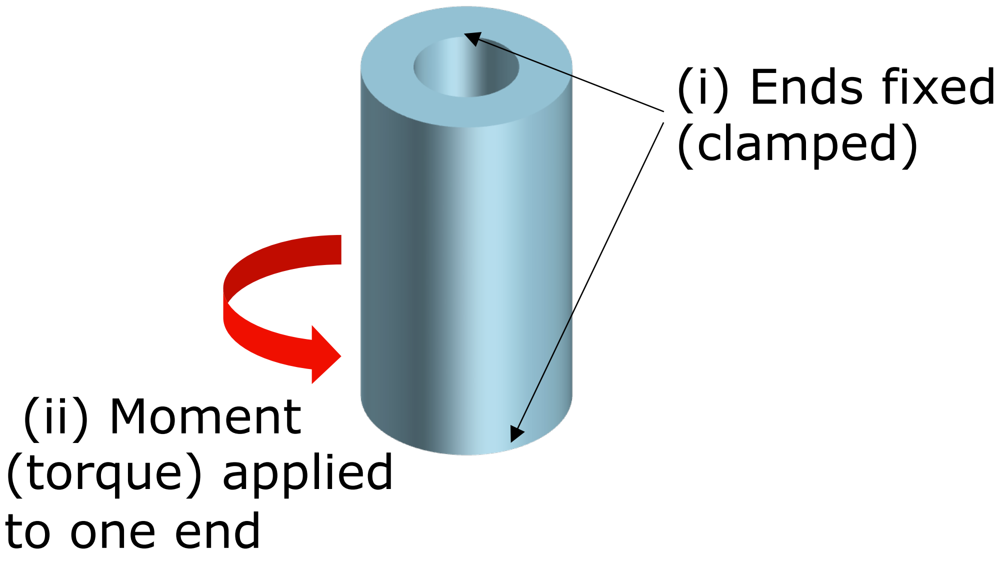


Can the stress, strain and strain rates be translated into:

(i) shear stress;
(ii) angular displacement (strain);
(iii) angular velocity (strain rate)

Translating Cable Flexural Behavior to Torsional Shear

Testing torsional Stress/Strain State



Shear Stress

$$\sigma = M.K_\sigma$$

$M = r.F.\sin\theta$

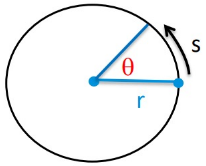
$K_\sigma = stress\ constant$

Angular Displacement

$$\theta = s/r$$

S = arc length

r = radius of circle



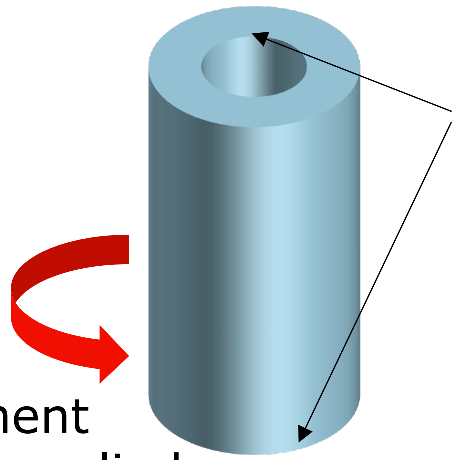
Shear Strain

$$\gamma = \theta.K_\gamma$$

$$Modulus\ G = \frac{\sigma}{\gamma} = \frac{M.K_\sigma}{\theta.K_\gamma}$$

Translating Cable Flexural Behavior to Torsional Shear

Testing torsional Stress/Strain State



(i) Ends fixed (clamped)

(ii) Moment (torque) applied to one end

Shear Stress

$$\sigma = M.K_\sigma$$

$M = r.F.\sin\theta$

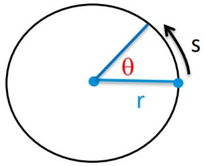
$K_\sigma = stress\ constant$

Angular Displacement

$$\theta = s/r$$

S = arc length

r = radius of circle



Shear Strain

$$\gamma = \theta.K_\gamma$$

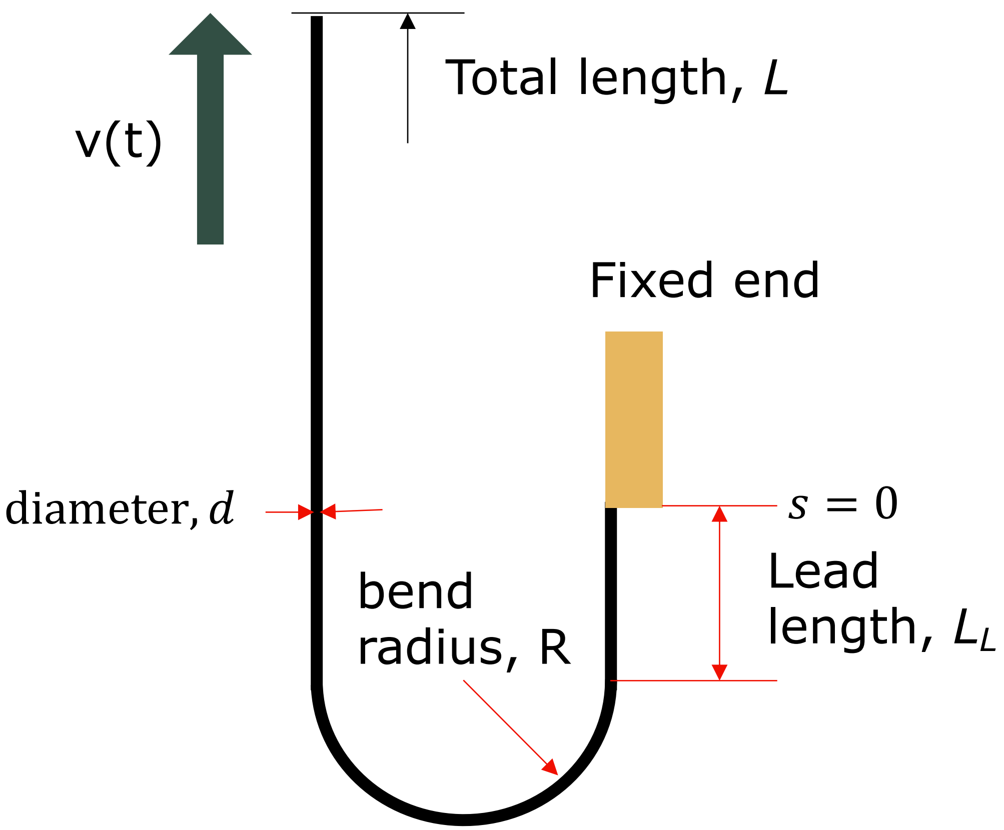
Angular Velocity

$$\Omega = \frac{\Delta\theta}{\Delta t}$$

Shear Rate

$$\dot{\gamma} = \Omega.K_\gamma$$

Cable Cycling - questions



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   - See Slides 23-25
4. How will the cycle time/velocity change the performance over time?
   - Polymer degradation and/or fatigue, see Slide 27-28

Polymer degradation and/or fatigue

Polymers change their behavior over time, which eventually leads to failure

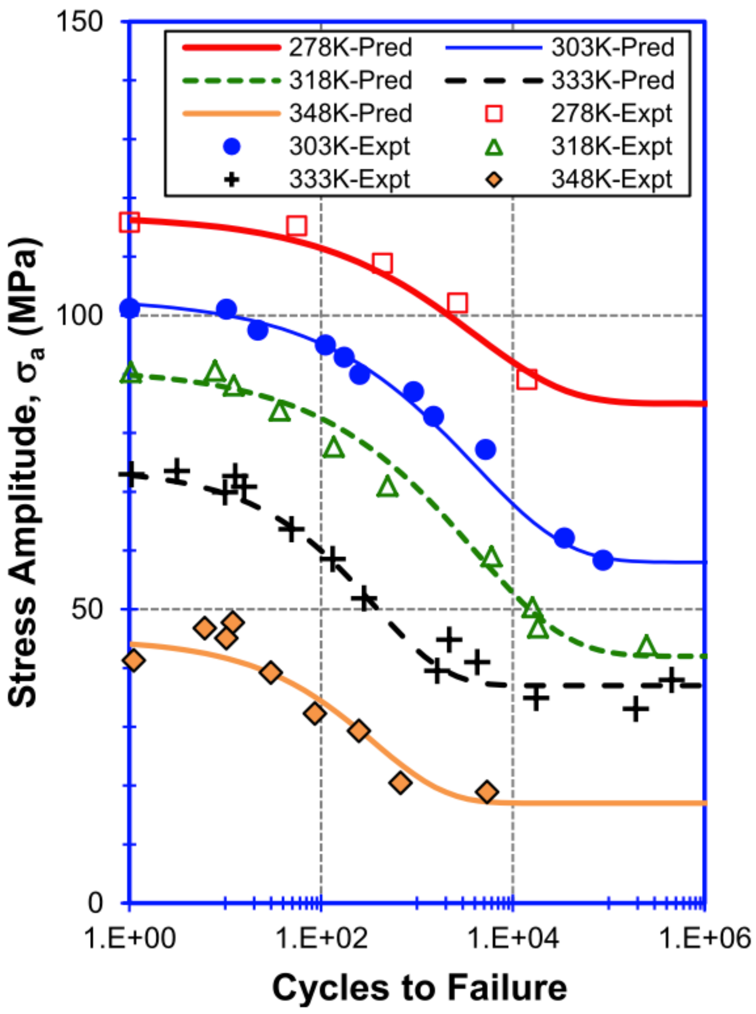
The mechanisms are well understood for metals, but not so much for polymers.

Two groups of failure mechanisms exist:

- Mechanical fatigue by crack propagation
- Thermal fatigue by self heating and thermal softening

Several Models exist to describe the Stress-Life behavior (or S-N curve)

- Mostly are empirical, $\sigma_a = A\,(N_f)^B$
  - where σ_a is stress amplitude, N_f is cycles to Failure, A and B empirical constants
- Some are based on physical descriptions of crack propagation



Polymer degradation and/or fatigue

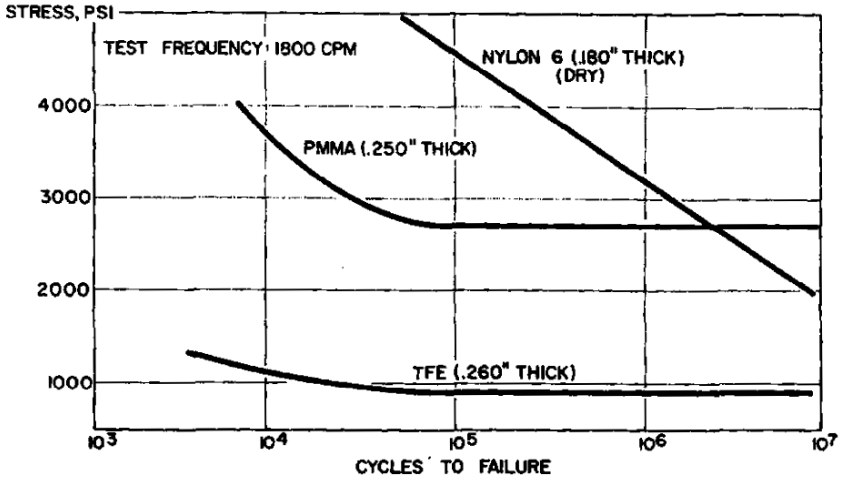
For Gore, it would be interesting to see how different polymers would be influenced by the cycling.

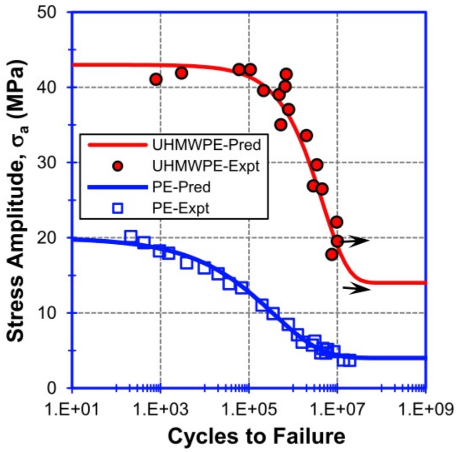
Solid material models do not exist, so we have to rely on crack propagation models and these are influenced by the polymer type.

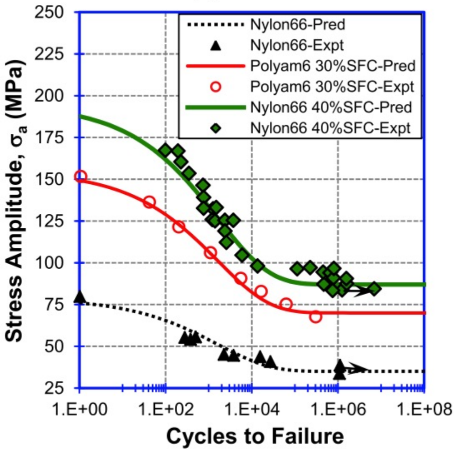
We may use information from the provided references or search for more.

– Particularly for viscoelastic materials

This question may be beyond the scope for the one-week MPI.







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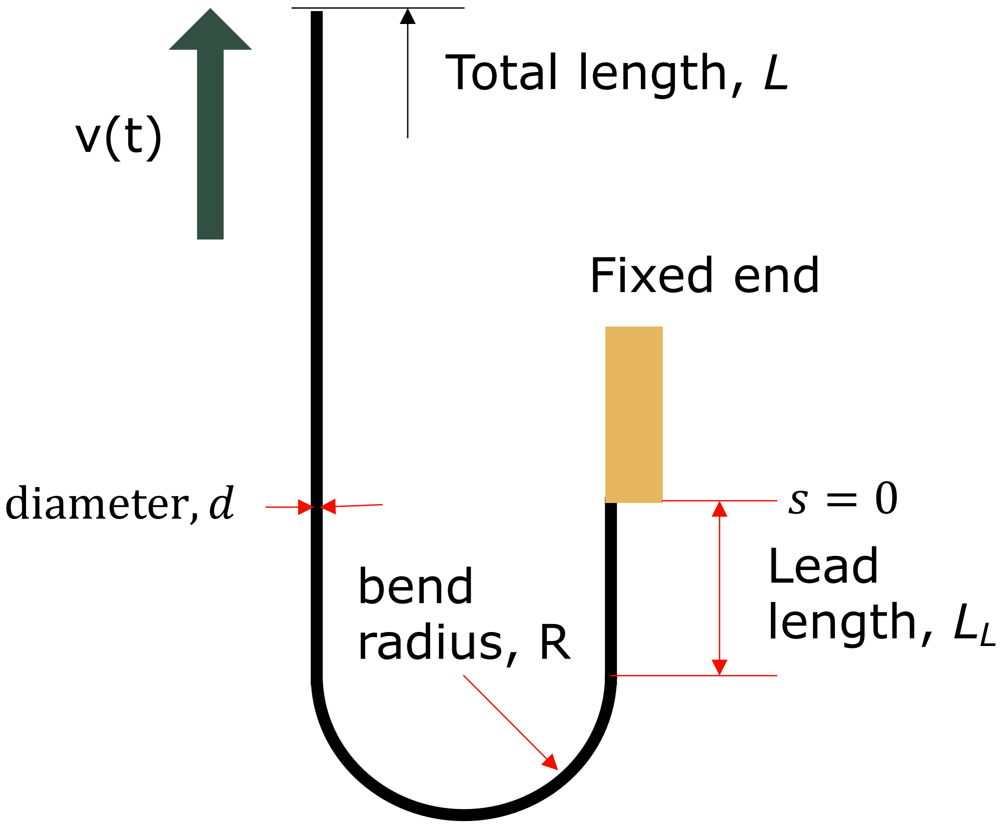
Cable Cycling – any questions

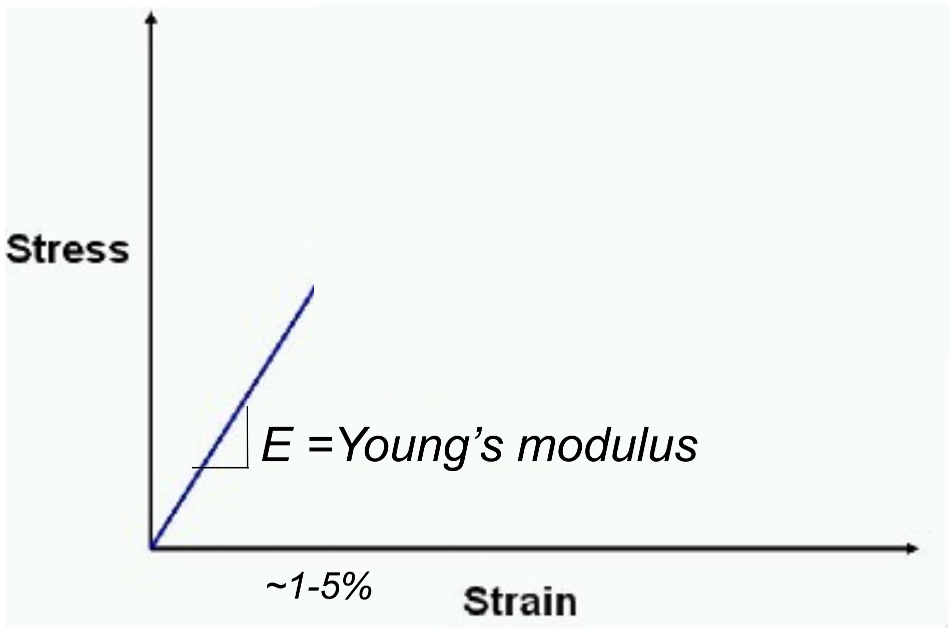


1. What is the stress, strain, and strain rate inside the cable at different cycling velocities and geometries?
   - See Slides 17 with 7, 9 (use case acceleration, bend radius, stroke length) and 6 (suggested cable geometries)
2. How does the polymeric mechanical model change the stress, strain, and strain rate?
   - See Slides 19 and 20 (elastic vs visco elastic)
3. Polymer materials properties can be highly resolved by torsional shear testing. Can the stress, strain and strain rates of the cycled cable be transformed into torsional shear test inputs?
   - See Slides 23-25
4. How will the cycle time/velocity change the performance over time?
   - Polymer degradation and/or fatigue, see Slide 27-28

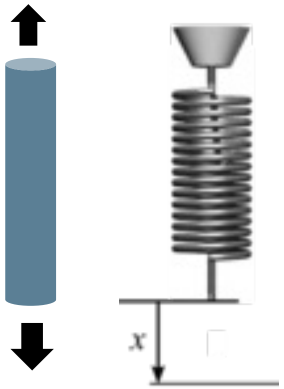
APPENDIX

Together, improving life

Starting simple: 1D Linear Elasticity (Hooke's Law)



http://physics.tutorvista.com/fluid-dynamics/strain.html



Hooke's Law:

$$\sigma = E\varepsilon$$

constitutive law linking stress and strain

E = Young's modulus

Example values:

Stainless Steel	E = 200 Gpa
Copper	E =
ePTFE	E = 10 MPa – 1 GPa
PATT	E = 1 - 10 MPa
FEP	E = 650 MPa
Jello	E = 1 – 100 kPa