CHAPTER 6: Mechanical Properties of Materials

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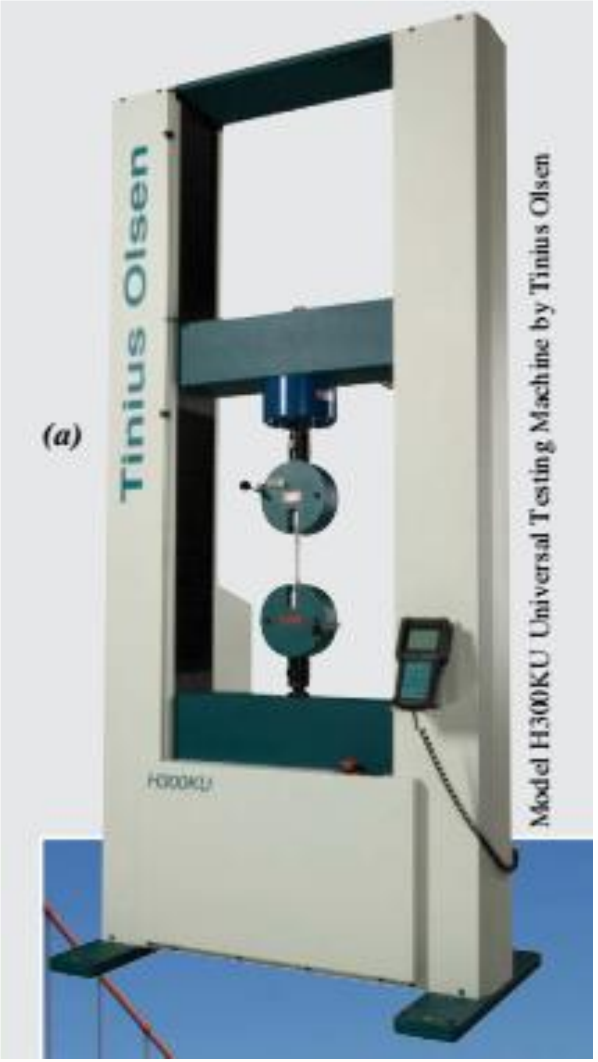
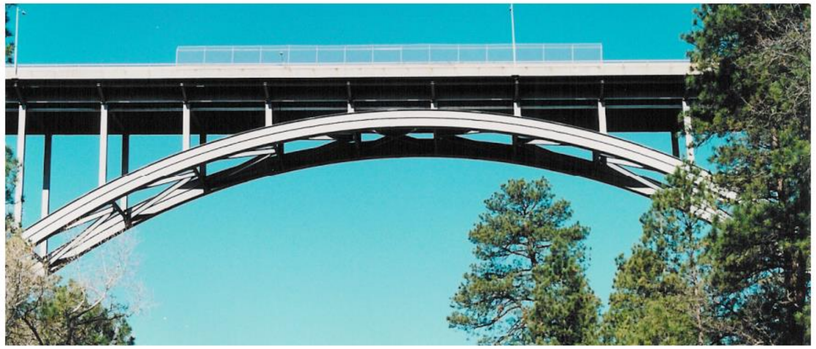


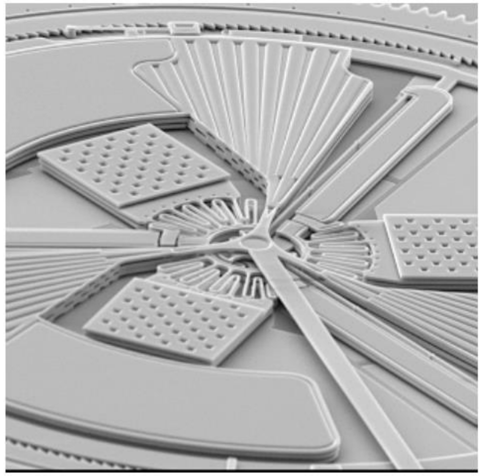
Why mechanical properties?

- Need to design materials that will withstand applied load and in-service uses for…

Bridges for autos and people



MEMS devices



skyscrapers

Space elevator?

Space exploration

Why mechanical properties?

- Motivation
  - Many engineering materials are subjected to forces or loads
    - How the material responds is central to many applications
  - The mechanical behavior of a material reflects the relationship between an applied force/load and its response (or deformation)

- **How do engineers figure in?**
  - Structural Engineers. Determine stress/strain distributions in objects subjected to well-defined loads (beams in bridges)
  - Materials/Metallurgical Engineers. Produce materials that will have the desired mechanical properties
  - The starting point for what follows are two concepts: **Stress** and **Strain**

ISSUES TO ADDRESS...

- Stress and strain: What are they and why are they used instead of load and deformation?

- Elastic behavior: When loads are small, how much deformation occurs? What materials deform least?

- Plastic behavior: At what point do dislocations cause permanent deformation? What materials are most resistant to permanent deformation?

- Toughness and ductility: What are they and how do we measure them?

- Ceramic Materials: What special provisions/tests are made for ceramic materials?

Stress/Strain behavior

- **Stress**: related to the force/load applied to the material
- **Strain:** related to the deformation/response of the material to the force

- Idea: if an applied load is static (?), or varies slowly with time (and is uniformly applied), can determine mechanical properties by stress-strain tests.

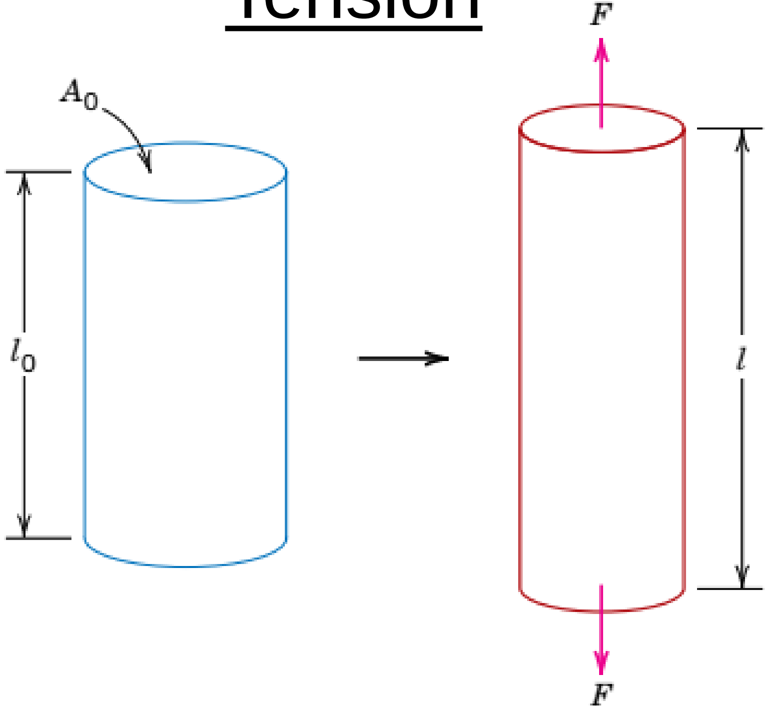
In other words, apply force → observe how material responds

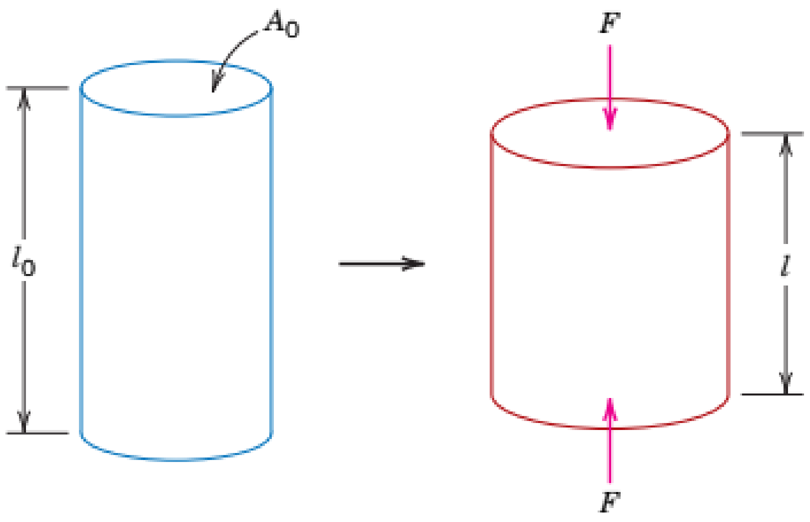
Tension

Compression

There are three types of load:

- Tension,
- compression,
- Shear

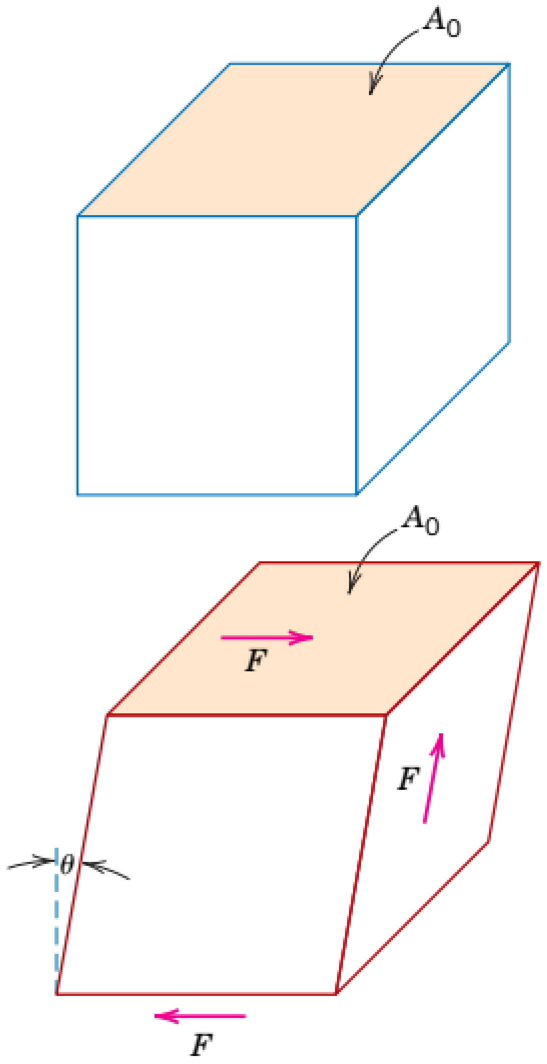




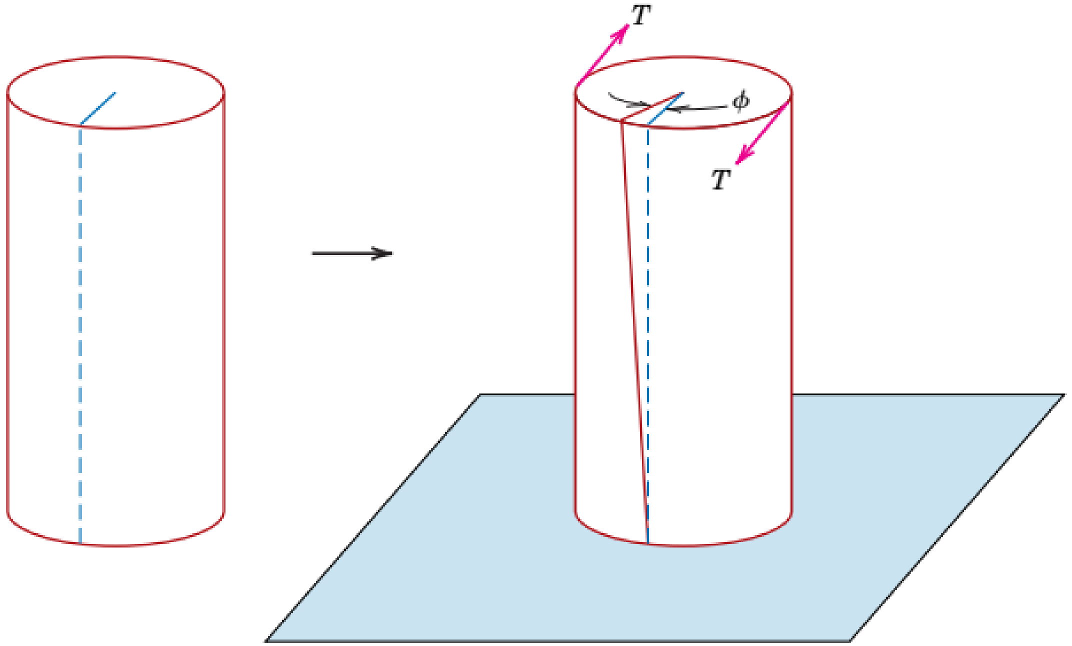
Stress/strain behavior : shear

There are three types of load: tension, compression, **shear**

Shear



Torsion

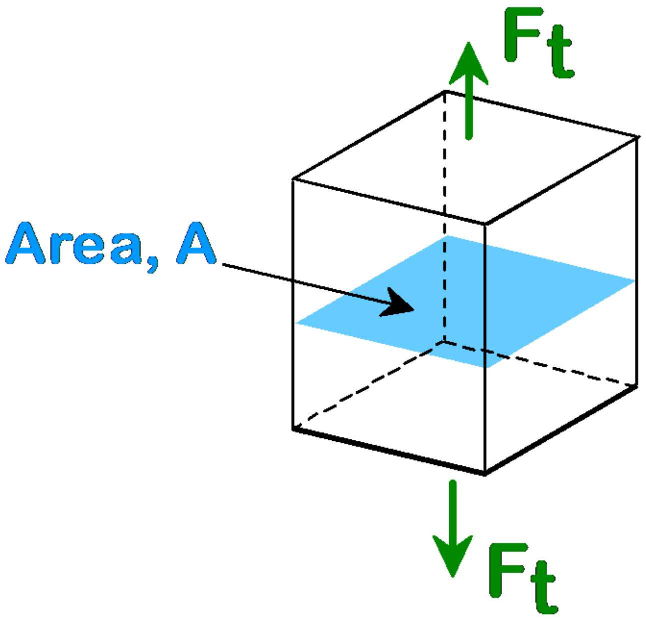


ENGINEERING STRESS

To minimize these geometrical factors, load and elongation are normalized to the respective parameters of **engineering stress**

• Engineering Stress *σ* : Engineering stress *σ* is defined by the relationship *σ* and *F* *in which* the instantaneous load applied perpendicular to the specimen cross section area A_0 before any applied load

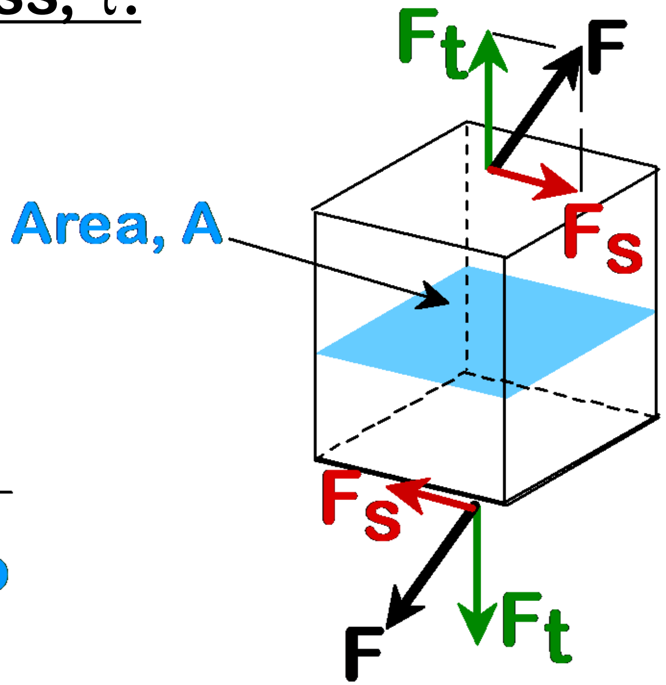
Tensile stress *σ* **:**



$$\sigma = \frac{F_t}{A_o}$$

original area before loading

• Shear stress, τ:



$$\tau = \frac{F_s}{A_o}$$

Stress has units: N/m^2 or pounds force lb$_f$/in^2

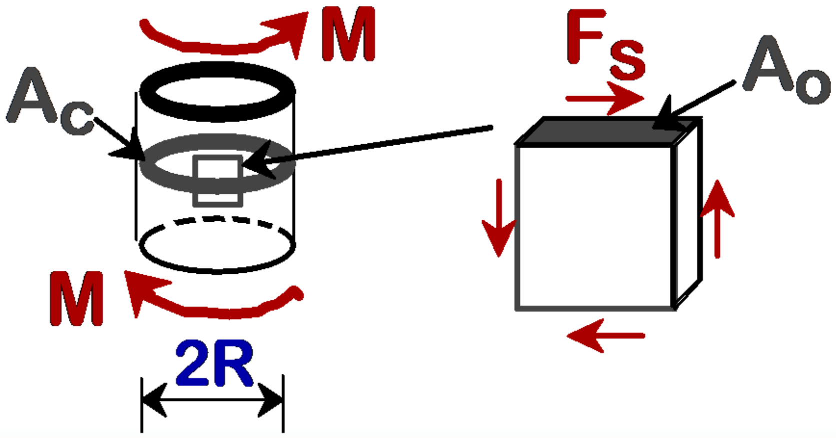
Common States Of Stress

- **Simple tension: cable**

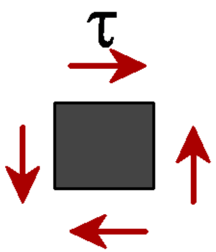
A_o = cross sectional Area (when unloaded)

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

- **Simple shear: drive shaft**

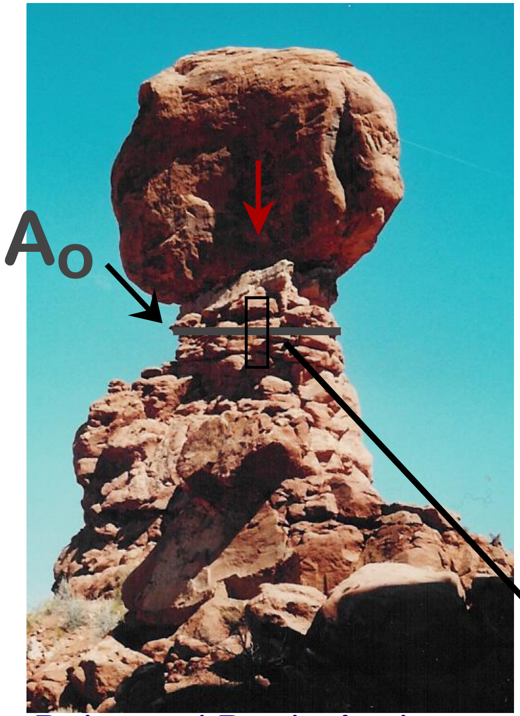


$$\tau = \frac{F_s}{A_o}$$

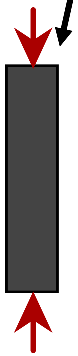


- **Simple compression:**

A$_o$

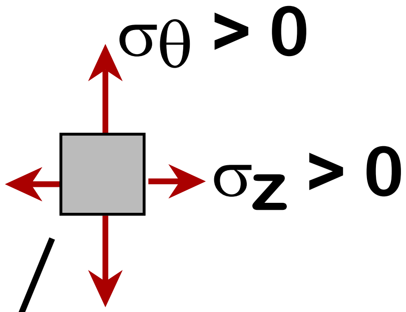


Balanced Rock, Arches National Park



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

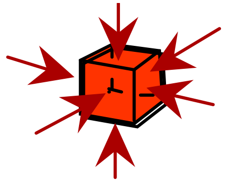
Note: compressive structure member ($\sigma < 0$ here).



Pressurized tank

- **Bi-axial tension:**

$\sigma_h < 0$



- **Hydrostatic Compression**

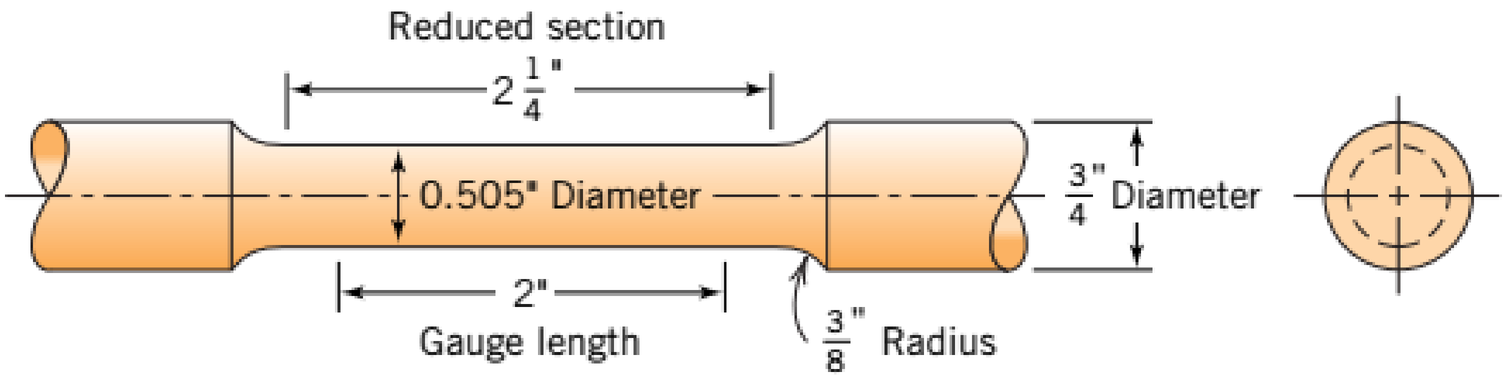
Fish under water

Tensile stress– strain tests

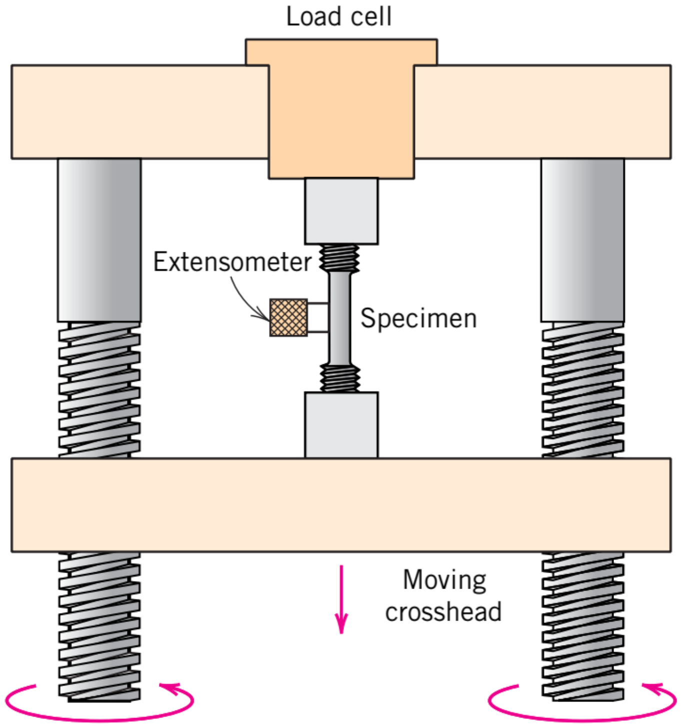
One of the most common mechanical stress–strain tests is performed in *tension*.

A standard tensile specimen with circular cross section

“dogbone” specimen configuration



A specimen is deformed, usually to fracture, with a gradually increasing tensile load that is applied uniaxially along the long axis of a specimen.



Most common mechanical test

- Apply stress uniaxially along sample
- Continually increase force on ends
- Perform test until fracture (i.e. sample breaks)
- Measure force ~ sample elongation

It requires twice the load to produce the same elongation if the cross-sectional area of the specimen is doubled.

Tension and Compression test

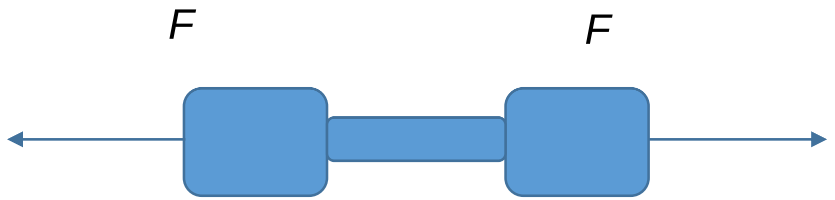
Tension measurements:

$$\text{Engineering stress } \sigma = \frac{F}{A_o}$$

$$\text{Engineering strain } \varepsilon = \frac{l_i - l_o}{l_o} = \frac{\Delta l}{l_o}$$

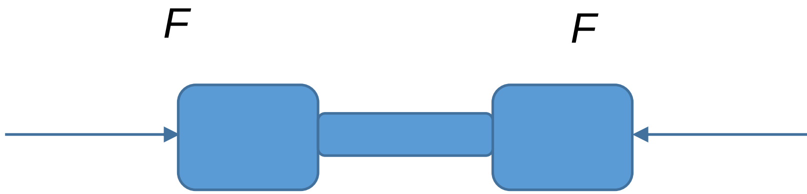
F – force normal to sample, Units N or pounds force (lb_f)
A_o – original cross sectional area

1 MPa (SI) = 10^6 N/m^2



Compression measurements:

- A compression test is conducted in a manner similar to the tensile test, except that the force is compressive and the specimen contracts along the direction of the stress.
- Turns out tensile tests are much easier than compression tests



- Compression tests are more useful <u>if</u>:
  - Material’s behavior under large and permanent (i.e. plastic) strain is needed
  - A material is brittle in tension

By convention, a compressive force is taken to be negative, which yields a negative stress.

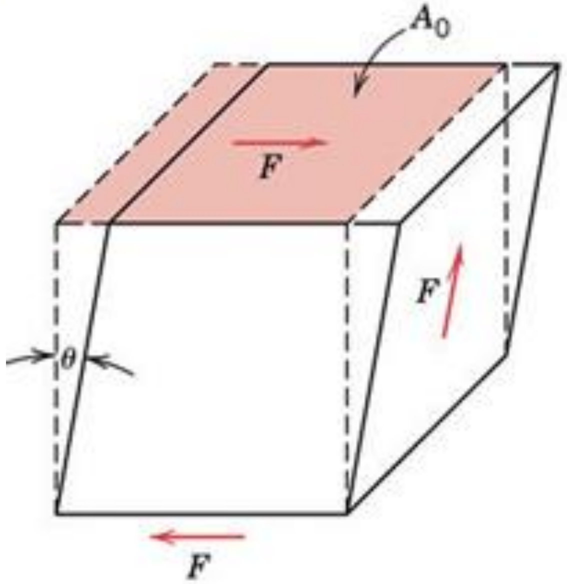
Shear and Torsional Tests

- **Shear and torsional tests**

For pure **Shear Stress**

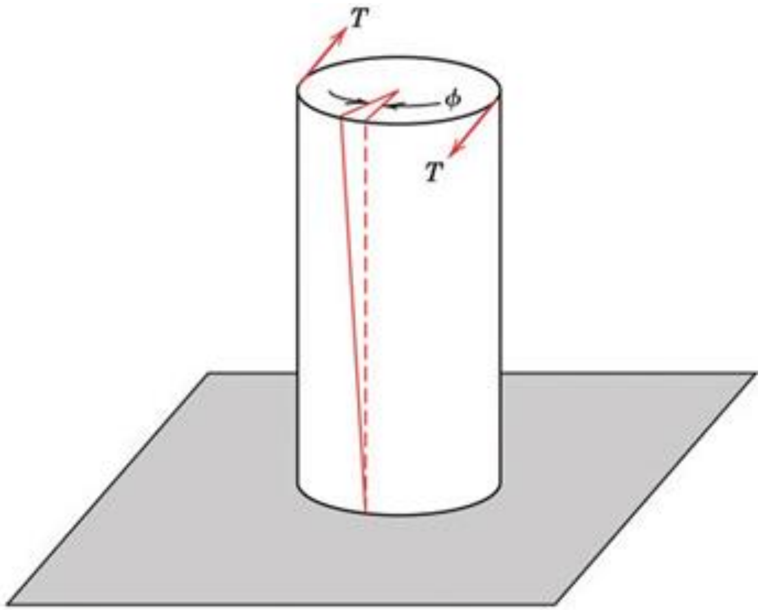
$$\tau = \frac{F}{A_o}$$

- The **shear stress is τ.**
- *F* here is the applied force to the top and bottom face
- The **shear strain** γ is the tangent of the strain angle
- Note analogies between $\tau \Leftrightarrow \sigma$ and $\gamma \Leftrightarrow \varepsilon$



Torsion → variant of pure shear; object is twisted

- Torsional force produces rotation of one end of the object relative to the other (drive shaft)
- τ = function of the applied torque *T*;
- γ = Function of the angle of twist, ϕ



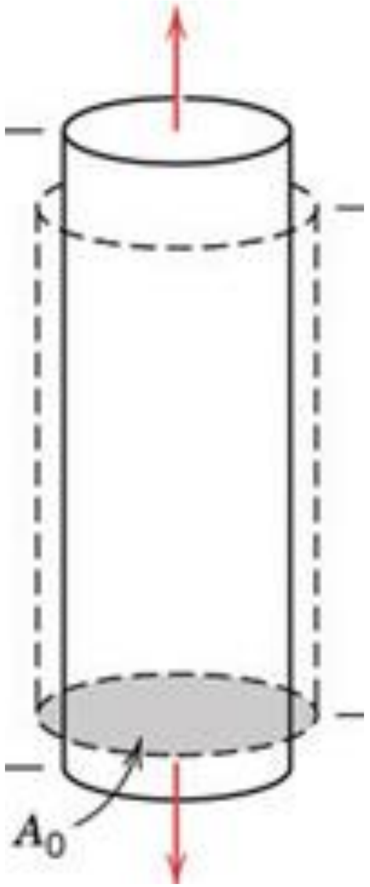
Examples of torsion are found for machine axles and drive shafts as well as for twist drills.

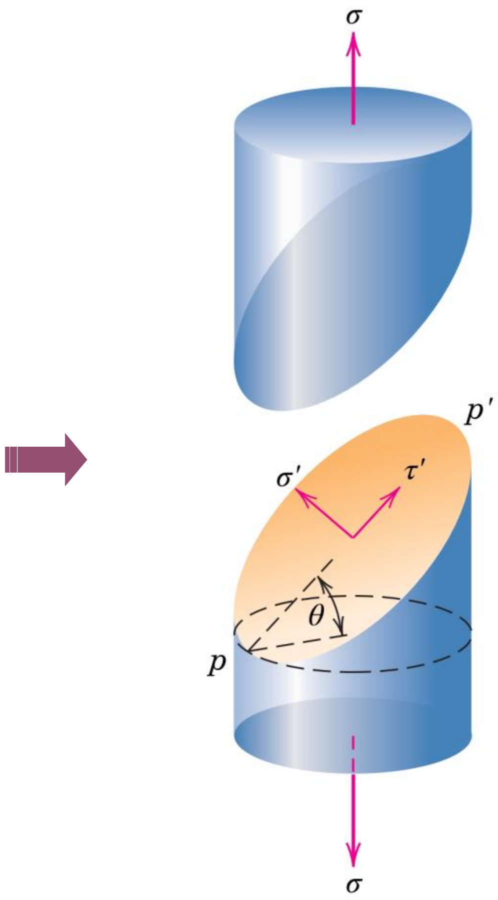
Geometry effects

Measurement depends on sample size (why?)

Forces are perpendicular or parallel to planar faces of objects

- This does not have to be true … in general the stress is a function of the orientation of the planes on which it acts

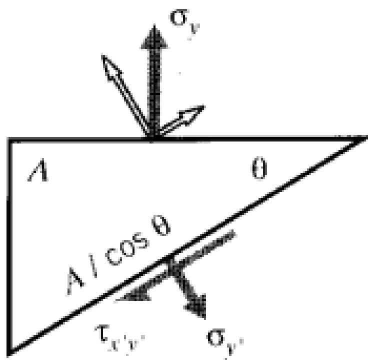




- In plane p-p’ stress is not purely tensile, rather a more complex stress state is present that consists of a tensile (or normal) stress σ' that acts normal to the p-p' plane and, in addition, a shear stress τ' that acts parallel to this plane
- Often have both a tensile (normal) stress and shear stress

HOME ASSIGNMENT

Balancing forces in the y' direction $$(\sigma_y A)\cos\theta = \sigma_{y'}\left(\frac{A}{\cos\theta}\right)$$



$$\sigma' = \sigma\cos^2\theta = \sigma\left(\frac{1+\cos 2\theta}{2}\right)$$

$$\tau = \sigma\sin\theta\cos\theta = \sigma\left(\frac{\sin 2\theta}{2}\right)$$

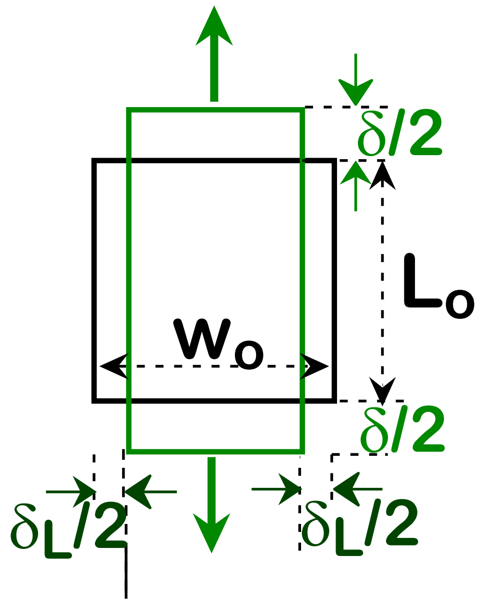
(force balance in the tangential direction)

ENGINEERING STRAIN

The degree to which a structure deforms or strains depends on the magnitude of an imposed stress.

- **Tensile strain:**

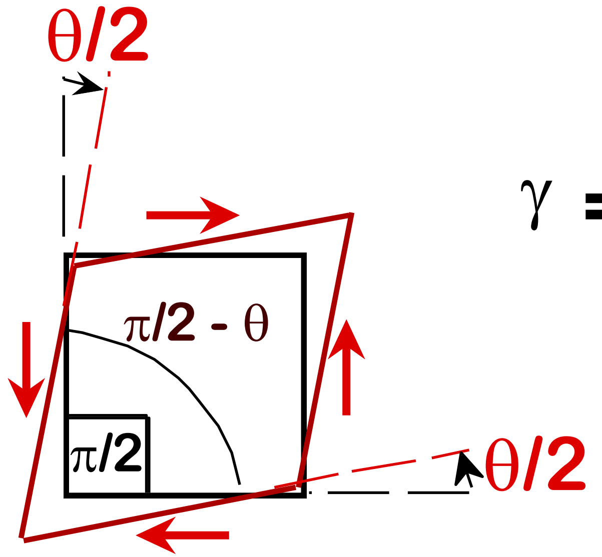
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral strain:**

$$\varepsilon_L = \frac{-\delta_L}{w_o}$$

- **Shear strain:**



$$\gamma = \tan\theta$$

Strain is always Dimensionless

Elastic Deformation

Deformation in which stress and strain are proportional is called **elastic deformation**

Hooke's law— relationship between engineering stress and engineering strain for elastic deformation (tension and compression)

Hooke's law → $\sigma = E\varepsilon$

E is the modulus of elasticity, or Young's modulus

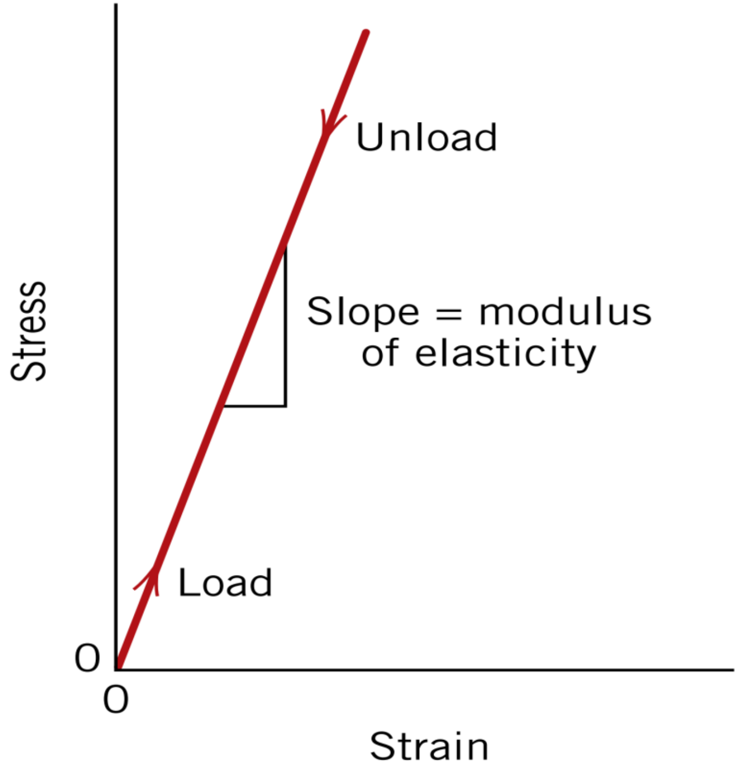
This tells you stress and strain are proportional;

Two key features of elastic deformation

1. Stress is proportional to strain
2. Deformation is entirely reversible (remove force → material recovers initial shape)

E (GPa or psi)

Material	range of *E*
Metal	45 – 400 GPa
Ceramics	70 – 500 GPa
Polymers	0.007 – 4 GPa



Elastic deformation is nonpermanent

What is the physical meaning of *E* being large or small?

This modulus may be thought of as stiffness, or a material's resistance to elastic deformation. The greater the modulus, the stiffer is the material, or the smaller is the elastic strain that results from the application of a given stress.

Room-Temperature Elastic and Shear Moduli and Poisson’s Ratio for Various Materials

	Modulus of Elasticity		Shear Modulus		
Material	**GPa**	**10^6 psi**	**GPa**	**10^6 psi**	**Poisson’s Ratio**
Metal Alloys					
Tungsten	407	59	160	23.2	0.28
Steel	207	30	83	12.0	0.30
Nickel	207	30	76	11.0	0.31
Titanium	107	15.5	45	6.5	0.34
Copper	110	16	46	6.7	0.34
Brass	97	14	37	5.4	0.34
Aluminum	69	10	25	3.6	0.33
Magnesium	45	6.5	17	2.5	0.35
Ceramic Materials					
Aluminum oxide (Al_2O_3)	393	57	—	—	0.22
Silicon carbide (SiC)	345	50	—	—	0.17
Silicon nitride (Si_3N_4)	304	44	—	—	0.30
Spinel ($MgAl_2O_4$)	260	38	—	—	—
Magnesium oxide (MgO)	225	33	—	—	0.18
Zirconia (ZrO_2)[a]	205	30	—	—	0.31
Mullite ($3Al_2O_3$-$2SiO_2$)	145	21	—	—	0.24
Glass–ceramic (Pyroceram)	120	17	—	—	0.25
Fused silica (SiO_2)	73	11	—	—	0.17
Soda–lime glass	69	10	—	—	0.23
Polymers[b]					
Phenol-formaldehyde	2.76–4.83	0.40–0.70	—	—	—
Poly(vinyl chloride) (PVC)	2.41–4.14	0.35–0.60	—	—	0.38
Poly(ethylene terephthalate) (PET)	2.76–4.14	0.40–0.60	—	—	0.33
Polystyrene (PS)	2.28–3.28	0.33–0.48	—	—	0.33
Poly(methyl methacrylate) (PMMA)	2.24–3.24	0.33–0.47	—	—	0.37–0.44
Polycarbonate (PC)	2.38	0.35	—	—	0.36
Nylon 6,6	1.59–3.79	0.23–0.55	—	—	0.39
Polypropylene (PP)	1.14–1.55	0.17–0.23	—	—	0.40
Polyethylene—high density (HDPE)	1.08	0.16	—	—	0.46
Polytetrafluoroethylene (PTFE)	0.40–0.55	0.058–0.080	—	—	0.46
Polyethylene—low density (LDPE)	0.17–0.28	0.025–0.041	—	—	0.33–0.40

How materials respond to forces – by deforming!

- What follows essentially is an explanation of how materials respond to applied forces
- This will (more or less) be structured around the magnitude of the force

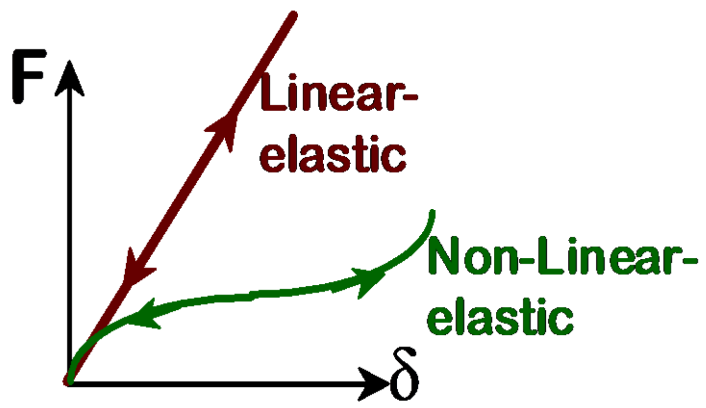
✓ **Elastic deformation (small forces)**

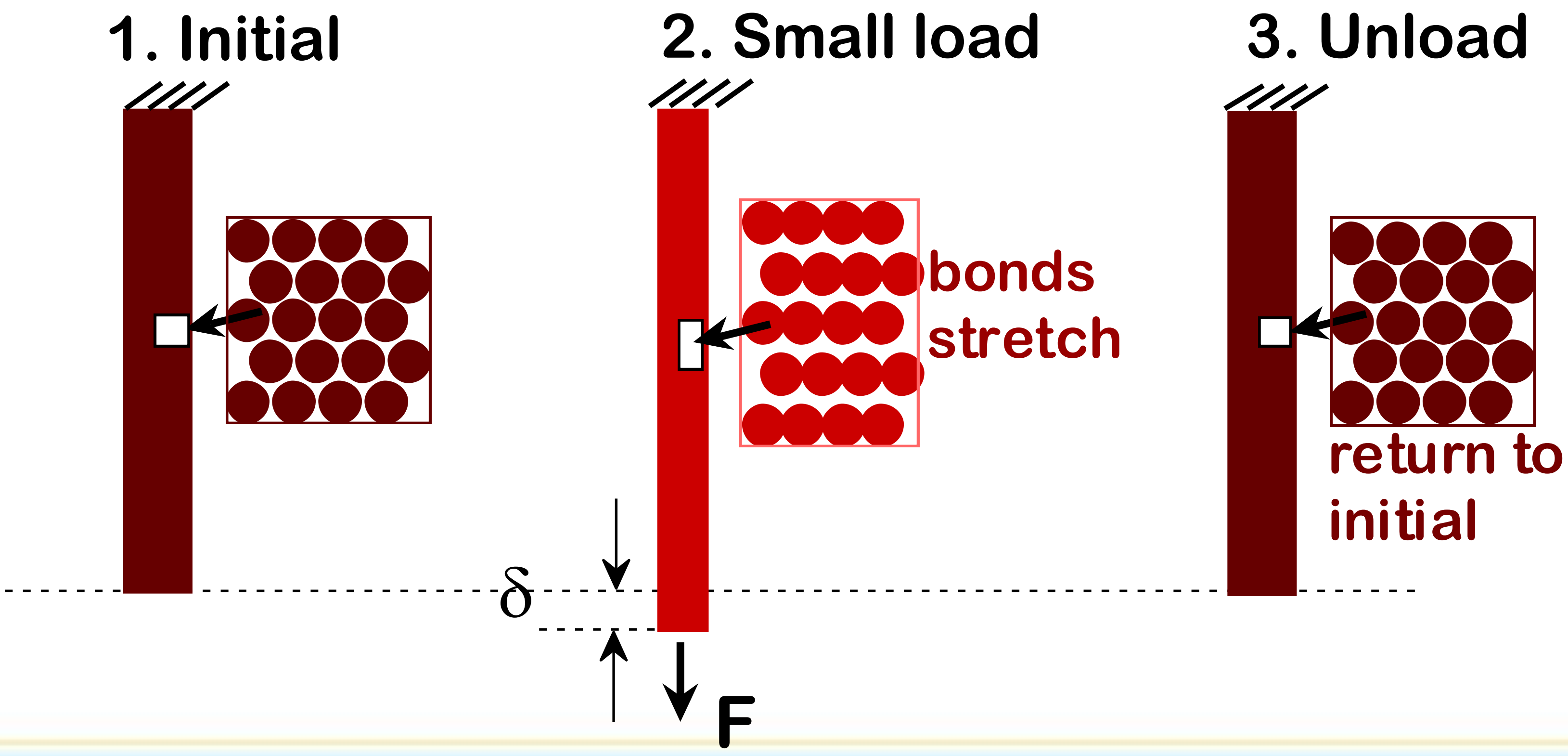
✓ Plastic deformation (larger forces)

✓ Fracture (material failure)

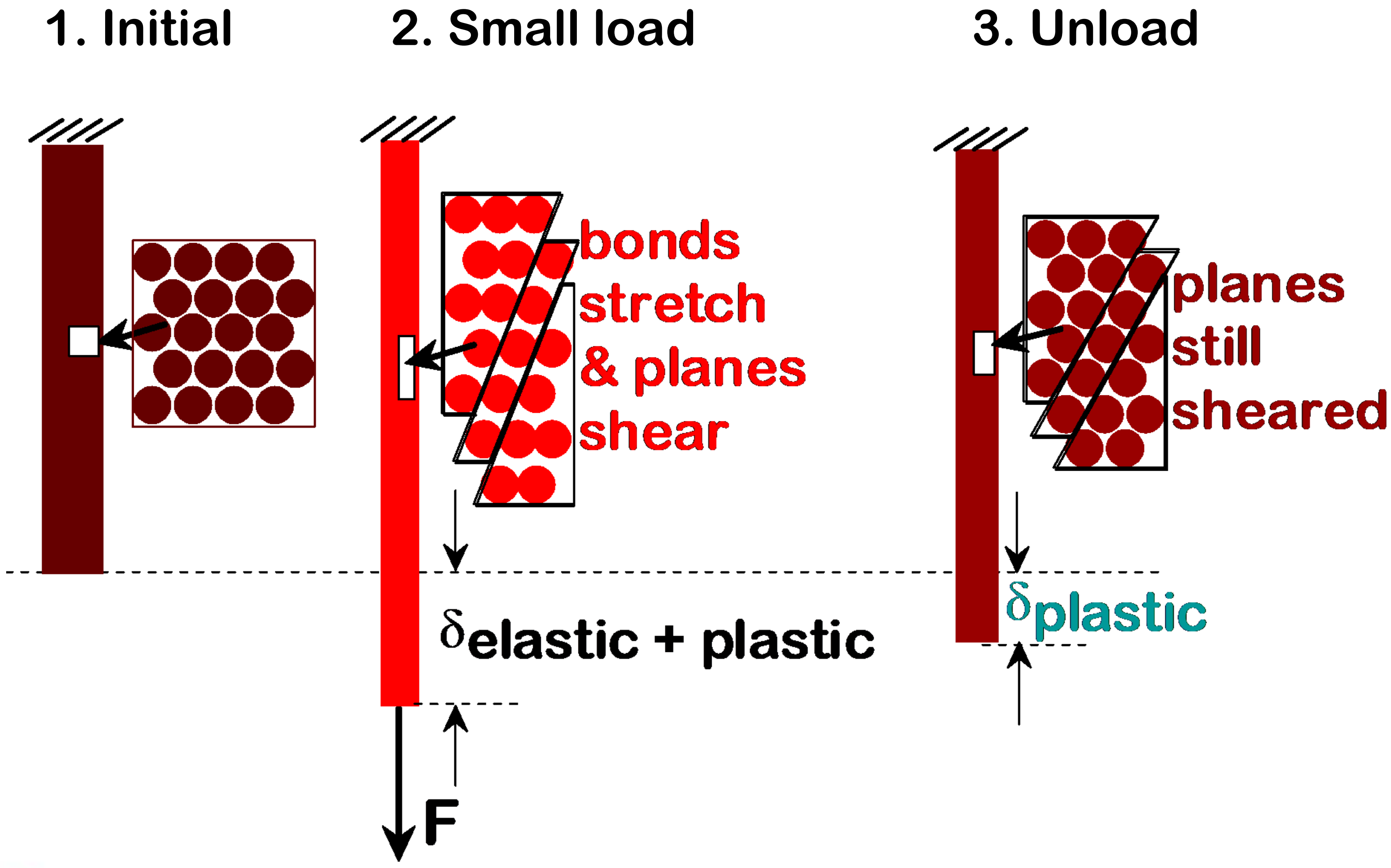
✓Elastic deformation (small forces)

Elastic means reversible!

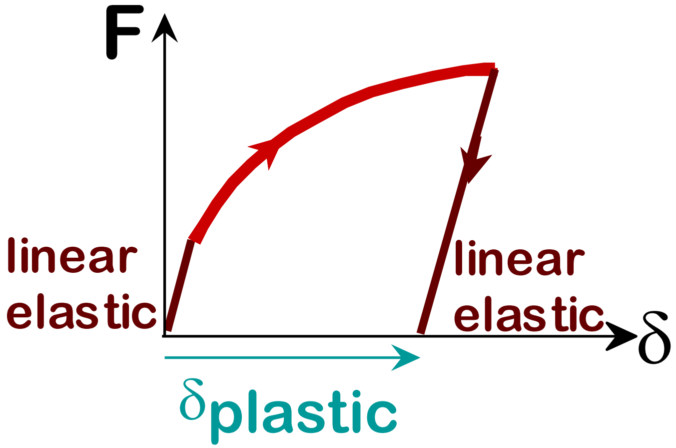




PLASTIC DEFORMATION (METALS)



Plastic means **permanent**!

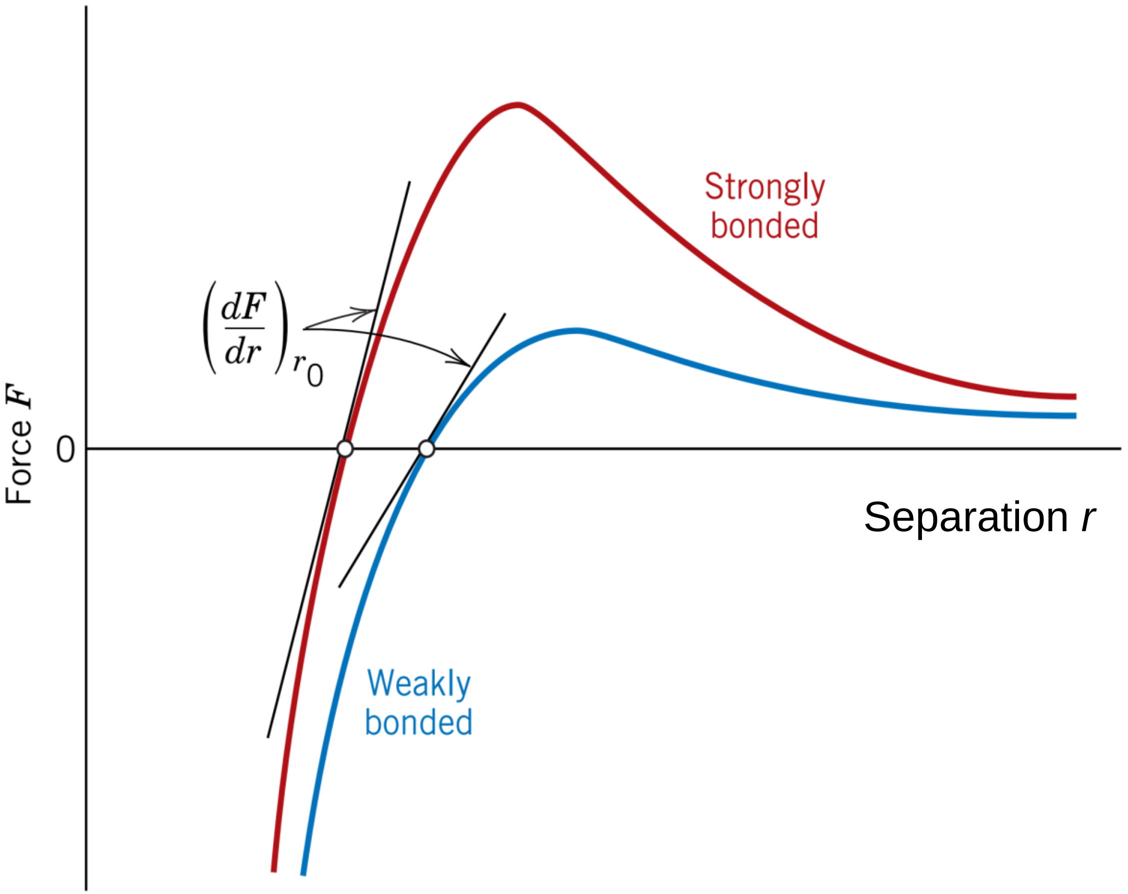


Elastic deformation – microscopic description

Strain is manifested as small changes in the interatomic spacing/stretching of bonds

- |E| is a measure of resistance to separation of adjacent atoms/ions/molecules (i.e. it is related to bonding forces)

$$E \propto \left.\frac{dF}{dr}\right|_{r_o}$$



Or differences in E are due to differences in bonding!

In other words microscopic (bonding) determines macroscopic (E)

Also as T increases, E generally decreases

Make similar observations for other “stress modes”

$$\tau = G\gamma$$

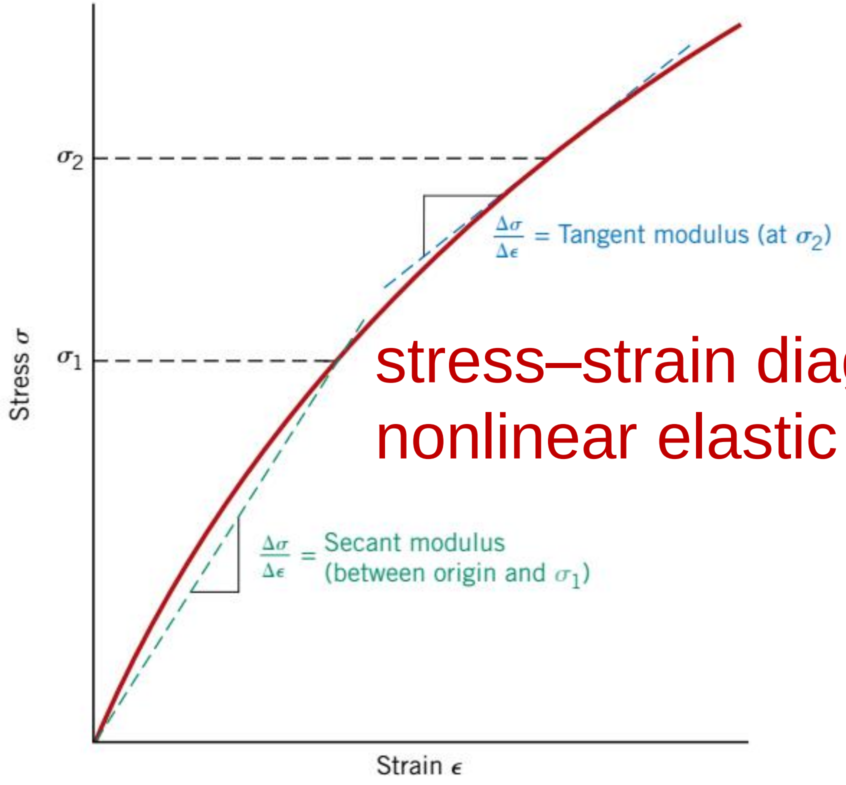
G is the *shear modulus*

Nonlinear Elastic Behavior

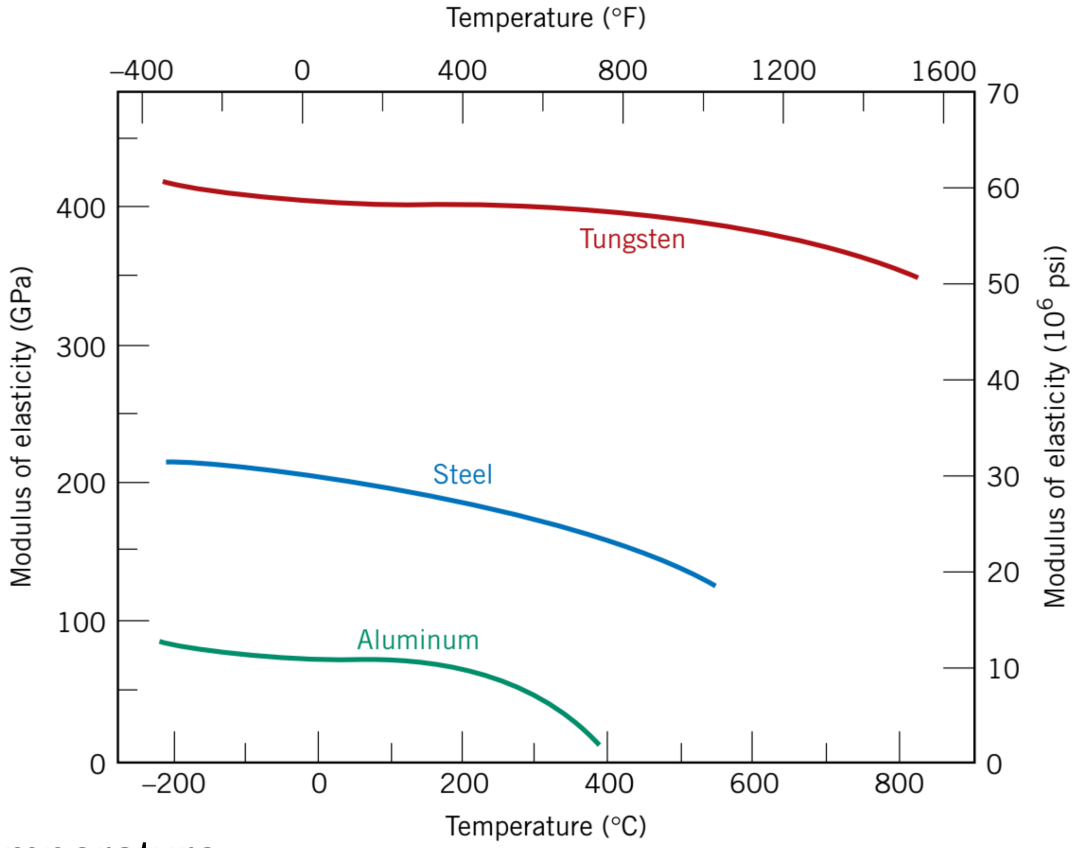
For some materials (i.e., gray cast iron, concrete, and mainly polymers) stress-strain plot is non-linear. What do you do (what is *E*)?

Two approaches

- Tangent modulus – slope of stress-strain curve at a specified stress
- Secant modulus – slope of a line drawn from zero stress to a specified stress



stress–strain diagram showing nonlinear elastic behavior



Modulus of Elasticity ~ Temperature