Chapter 6: Mechanical Properties

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 does permanent deformation occur? What materials are most resistant to permanent deformation?
- Toughness and ductility: What are they and how do we measure them?

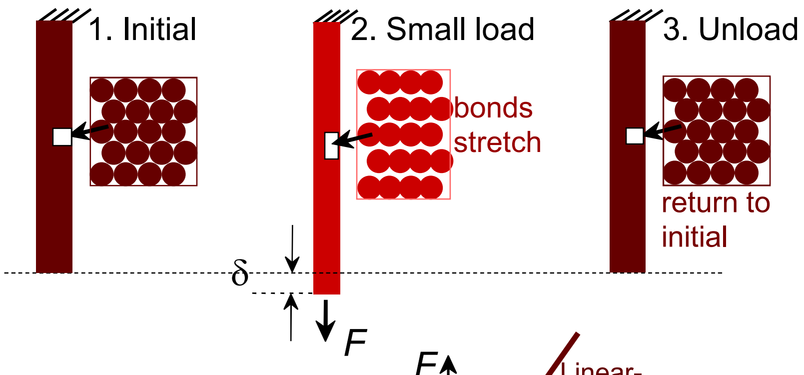
1

The mechanical behavior of a material reflects the relationship between its response or deformation to an applied load or force.

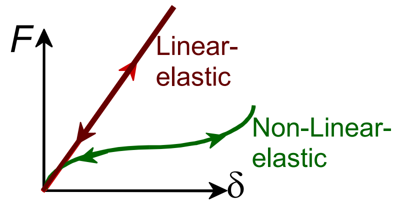
The mechanical properties of materials are determined by performing laboratory experiments that replicate as nearly as possible the service conditions (the nature of the applied load and its duration, as well as the environmental conditions).
•It is possible for the load to be tensile, compressive, or shear,
•Its magnitude may be constant with time, or it may fluctuate continuously.
•Application time may be only a fraction of a second, or it may extend over a period of many years.
•Service temperature may be an important factor.

2

Elastic Deformation

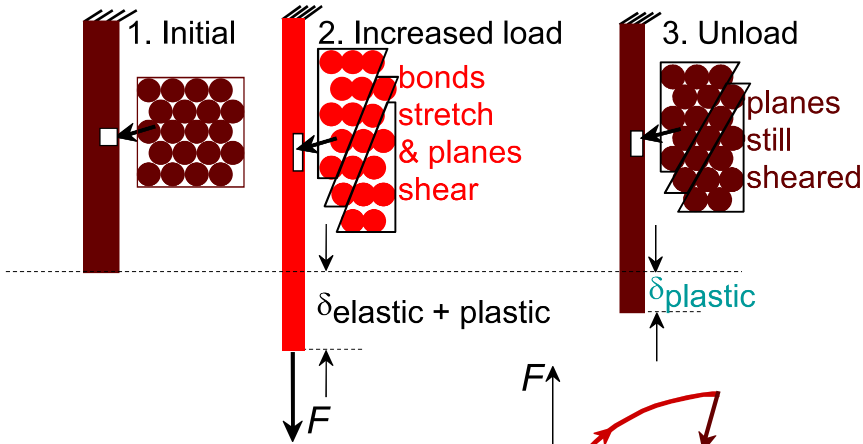


Elastic means reversible!

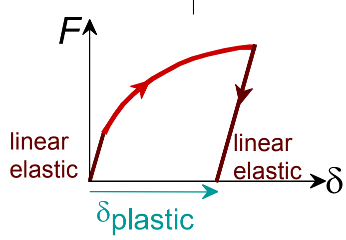


3

Plastic Deformation (Metals)



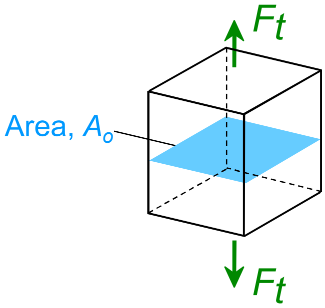
Plastic means permanent!



4

Engineering Stress

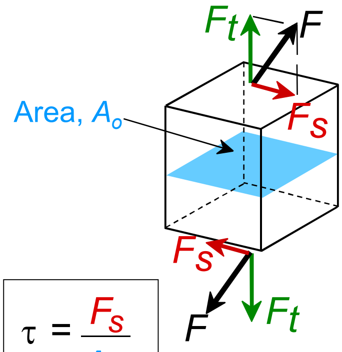
- Tensile stress, σ:



$$\sigma = \frac{F_t}{A_o} = \frac{lb_f}{in^2} \text{ or } \frac{N}{m^2}$$

original area before loading

- Shear stress, τ:

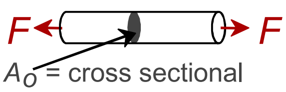


$$\tau = \frac{F_s}{A_o}$$

$\therefore$ Stress has units: N/m^2 or lb_f/in^2

Common States of Stress

- **Simple tension: cable**

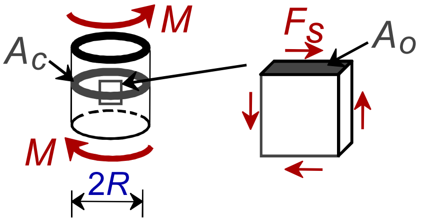


A_o = cross sectional area (when unloaded)

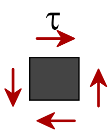
$$\sigma = \frac{F}{A_o}$$

Ski lift (photo courtesy P.M. Anderson)

- **Torsion (a form of shear): drive shaft**



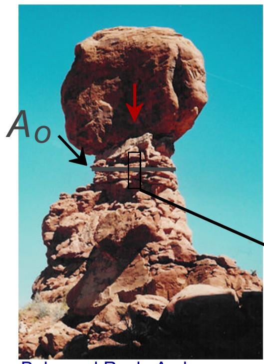
$$\tau = \frac{F_s}{A_o}$$



Note: $\tau = M/A_cR$ here.

OTHER COMMON STRESS STATES (i)

- **Simple compression:**



Balanced Rock, Arches National Park
(photo courtesy P.M. Anderson)

Canyon Bridge, Los Alamos, NM
(photo courtesy P.M. Anderson)

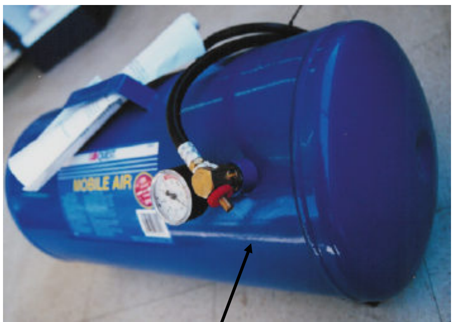
$$\sigma = \frac{F}{A_o}$$

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

7

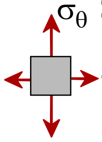
OTHER COMMON STRESS STATES (ii)

- **Bi-axial tension:**
- **Hydrostatic compression:**

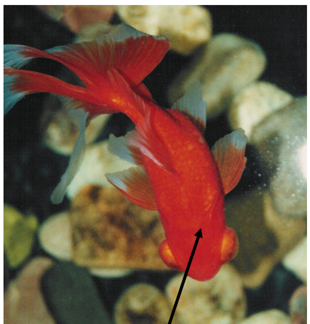


Pressurized tank
(photo courtesy P.M. Anderson)

$\sigma_\theta > 0$



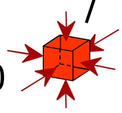
$\sigma_z > 0$



Fish under water

(photo courtesy P.M. Anderson)

$\sigma_h < 0$

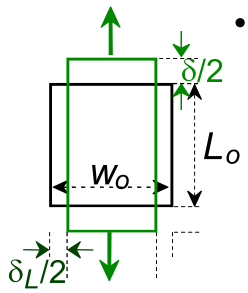


8

Engineering Strain

- **Tensile strain (longitudinal)** :

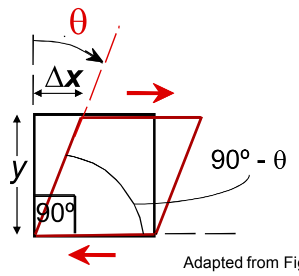
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral strain:**

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

- **Shear strain:**



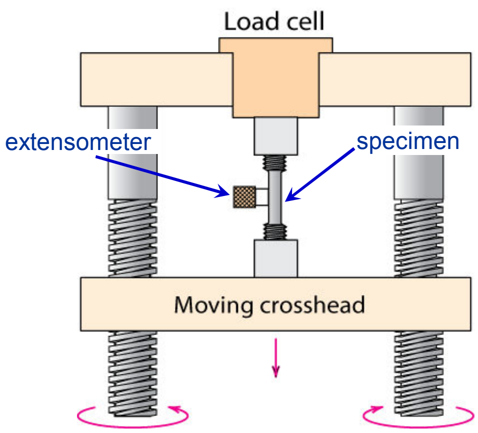
$$\gamma = \Delta x / y = \tan\theta$$

Strain is always dimensionless.

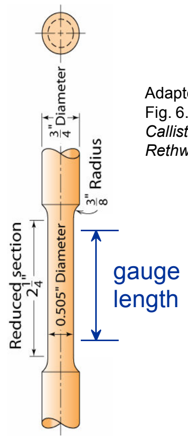
Adapted from Fig. 6.1(a) and (c), *Callister & Rethwisch 8e.*

Stress-Strain Testing

- **Typical tensile test machine**



- **Typical tensile specimen**



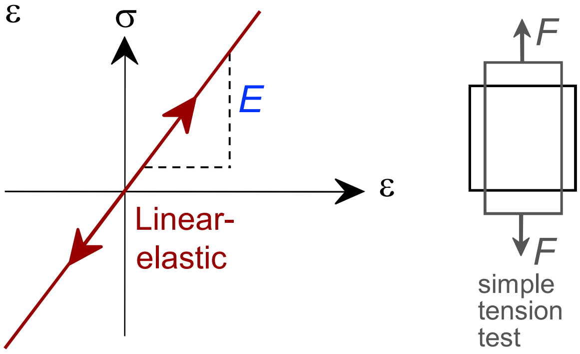
Adapted from Fig. 6.2, *Callister & Rethwisch 8e.*

Adapted from Fig. 6.3, *Callister & Rethwisch 8e.* (Fig. 6.3 is taken from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 2, John Wiley and Sons, New York, 1965.)

Linear Elastic Properties

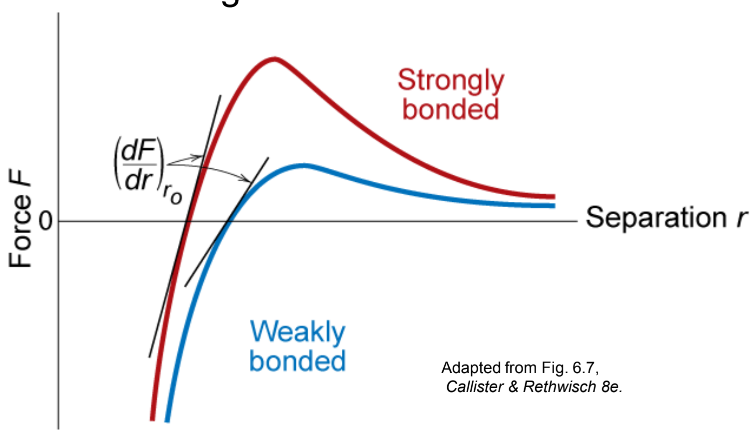
- **Modulus of Elasticity, *E*:**
  (also known as Young's modulus)
- **Hooke's Law:**

$\sigma = E\,\varepsilon$



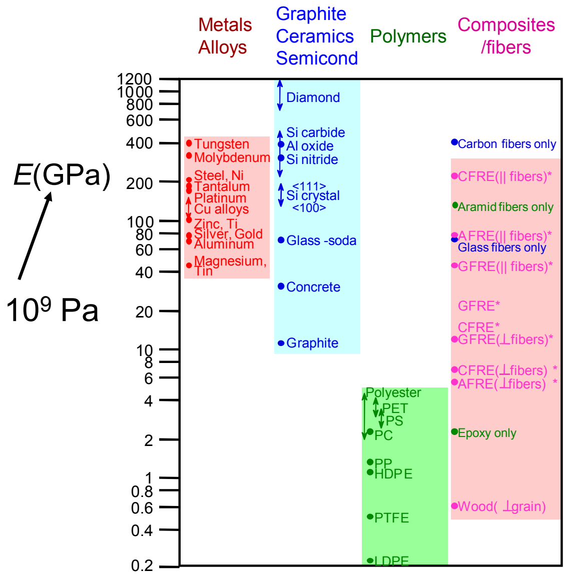
Mechanical Properties

- Slope of stress strain plot (which is proportional to the elastic modulus) depends on bond strength of metal



Adapted from Fig. 6.7,
Callister & Rethwisch 8e.

Young's Moduli: Comparison

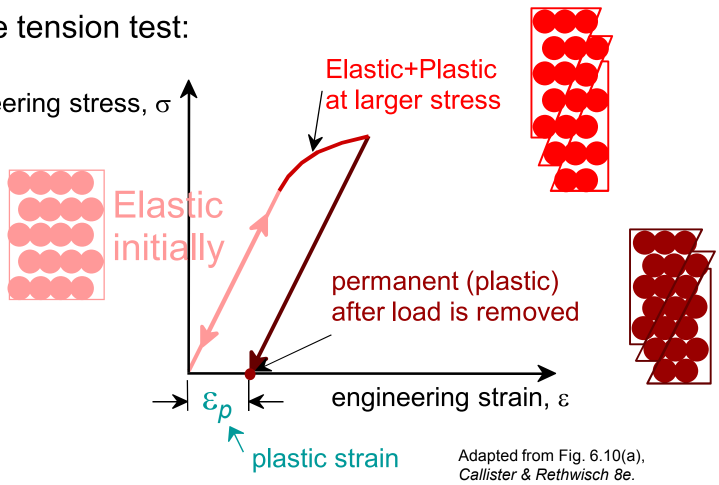


Based on data in Table B.2, *Callister & Rethwisch 8e.*
Composite data based on reinforced epoxy with 60 vol% of aligned carbon (CFRE), aramid (AFRE), or glass (GFRE) fibers.

13

Plastic (Permanent) Deformation

- Simple tension test:



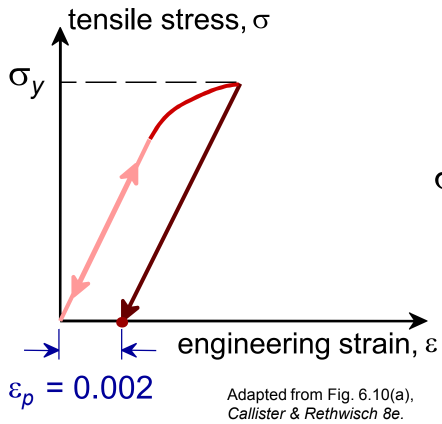
Adapted from Fig. 6.10(a), *Callister & Rethwisch 8e.*

14

Yield Strength, σ_y

- **Stress at which *noticeable* plastic deformation has occurred.**

when ε_p = 0.002

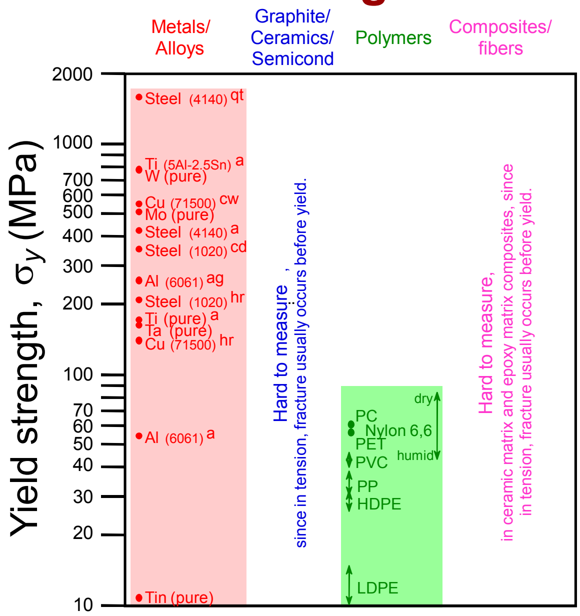


σ_y = yield strength

Adapted from Fig. 6.10(a), *Callister & Rethwisch 8e.*

15

Yield Strength : Comparison



Room temperature values

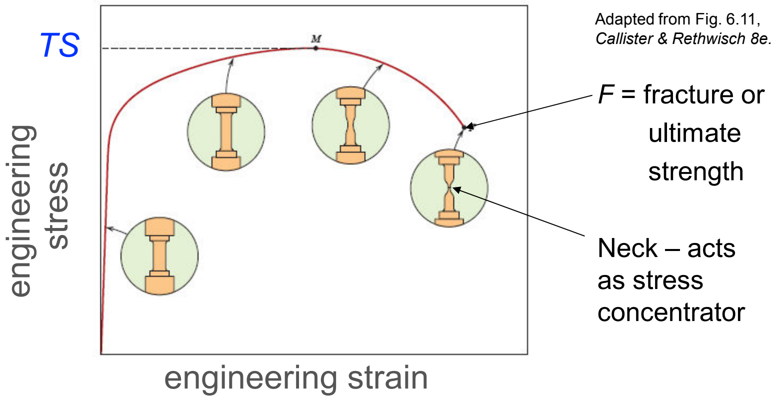
Based on data in Table B.4, *Callister & Rethwisch 8e.*

a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered

16

Tensile Strength, TS

- Maximum stress on engineering stress-strain curve.

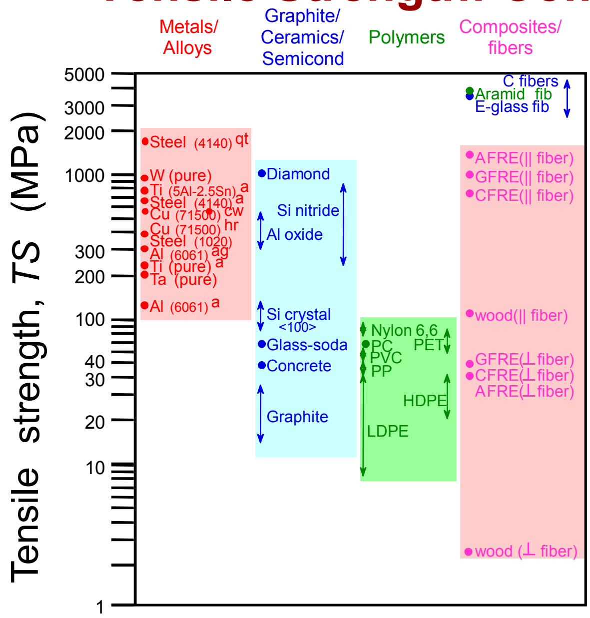


Adapted from Fig. 6.11, *Callister & Rethwisch 8e.*

- Metals: occurs when noticeable necking starts.
- Polymers: occurs when polymer backbone chains are aligned and about to break.

17

Tensile Strength: Comparison



Room temperature values

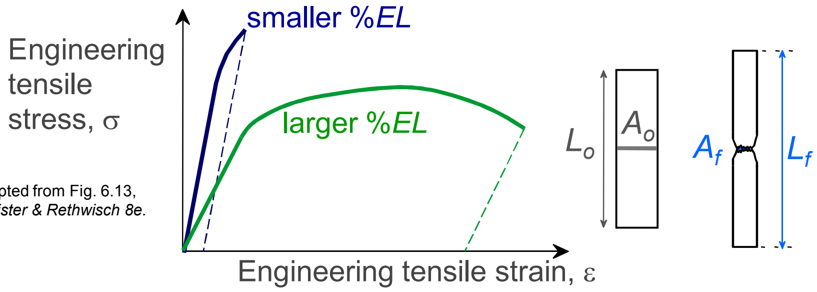
Based on data in Table B.4, *Callister & Rethwisch 8e.*

a = annealed
hr = hot rolled
ag = aged
cd = cold drawn
cw = cold worked
qt = quenched & tempered
AFRE, GFRE, & CFRE = aramid, glass, & carbon fiber-reinforced epoxy composites, with 60 vol% fibers.

18

Ductility

- Plastic tensile strain at failure: $\%EL = \frac{L_f - L_o}{L_o} \times 100$



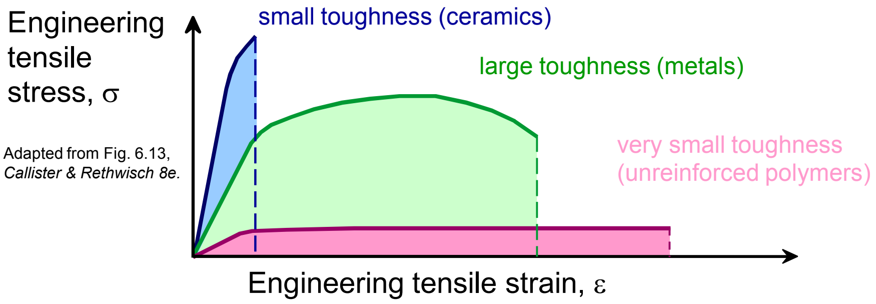
Adapted from Fig. 6.13, *Callister & Rethwisch 8e.*

- Another ductility measure: $\%RA = \frac{A_o - A_f}{A_o} \times 100$

19

Toughness

- Energy to break a unit volume of material
- Approximate by the area under the stress-strain curve.



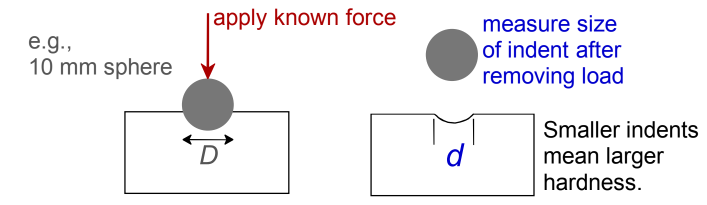
Adapted from Fig. 6.13, *Callister & Rethwisch 8e.*

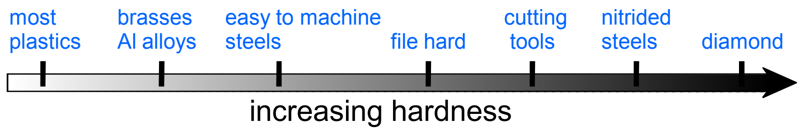
Brittle fracture: elastic energy
Ductile fracture: elastic + plastic energy

20

Hardness

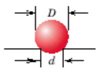
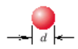
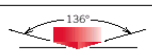
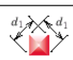
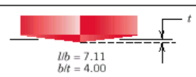
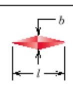
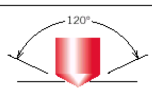
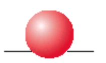
- Resistance to permanently indenting the surface.
- Large hardness means:
  -- resistance to plastic deformation or cracking in compression.
  -- better wear properties.





Hardness: Measurement

Table 6.5 **Hardness Testing Techniques**

Test	***Indenter***	***Shape of Indentation*** — ***Side View***	***Shape of Indentation*** — ***Top View***	***Load***	***Formula for Hardness Number***[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$ in. diameter steel spheres	 	 	60 kg, 100 kg, 150 kg (Rockwell); 15 kg, 30 kg, 45 kg (Superficial Rockwell)	

[a] For the hardness formulas given, P (the applied load) is in kg, while D, d, d_1, and l are all in mm.

Source: Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

Summary

- Stress and strain: These are size-independent measures of load and displacement, respectively.
- Elastic behavior: This reversible behavior often shows a linear relation between stress and strain. To minimize deformation, select a material with a large elastic modulus (E or G).
- Plastic behavior: This permanent deformation behavior occurs when the tensile (or compressive) uniaxial stress reaches σ_y.
- Toughness: The energy needed to break a unit volume of material.
- Ductility: The plastic strain at failure.