Chapter 3: Mechanical Properties of Materials

Chapter Objectives

✓ Understand how to measure the stress and strain through experiments
✓ Correlate the behavior of some engineering materials to the stress-strain diagram
Tension and compression test

https://www.youtube.com/watch?v=AFCA81ocFgo
https://www.youtube.com/watch?v=jbslR-6GVCs

Dog Bone Universal Testing Machine
~ Instron
~ SEE 300, TAM 324
~ ME 330

Typical steel specimen with attached strain gauge.

Electrical-resistance strain gauge

movable upper crosshead
tension specimen
load dial
motor and load controls

$L_o$: gage length
Stress-strain diagram

Uniaxial tension test:

- Specimen is stretched at a very slow, constant rate
- Measure distance $L$ and load $P$ at frequent intervals
- Convert $L$ and $P$ to engineering stress-strain data

$$\varepsilon = \frac{L - L_0}{L_0}$$

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

Note that two stress-strain diagrams for a particular material will be similar, but not identical, due to variability in:
- Material composition
- Specimen imperfections
- Rate of loading
- Ambient temperature
Characteristics of stress-strain diagram

**Elastic behavior (recoverable deformation):**
- **Reversible Deformation**
- Materials loaded in this region regain its original shape if load is removed
- The curve is a straight line throughout most of this region (stress is proportional to strain).
- Linear region is limited by the proportional limit \( \sigma_p \)
- Region formally ends after yielding

**Plastic behavior (permanent deformation):**
- Stresses above the elastic limit will cause the material to deform permanently
- **Yield strength** \( \sigma_y \): highest stress that the material can withstand without undergoing significant yielding
- **Ultimate strength** \( \sigma_u \): is the maximum value of engineering stress that the material can withstand
- **Necking** occurs after the ultimate strength is exceeded
- **Fracture (or rupture) stress** \( \sigma_f \): the value of stress at fracture

**Typical Ductile Material**

**Elastic Behavior**

\[ E \]

**Plastic behavior**

\[ E \]

**Strain hardening**

\[ E \]

**Unloading**

\[ E \]

**Necking**

- Rapid, localized reduction of cross-section locally, \( \sigma \) increases rapidly

- Final behavior we observe in a ductile material prior to rupture (fracture)

**Linearly elastic regime**

\[ [E] = [\sigma] = \frac{\text{force}}{\text{area}} \]

\[ \sigma_y \] = yield stress — found by 0.2% offset method
- unloadings after yielding also have slope = \( E \)

Upon reloading, we observe slope of \( E \)

In strain hardening, \( \sigma_y \) increases!

---

Only in ductile materials
Ductile materials

- Rupture occurs along a cone-shaped surface that forms an angle of approximately 45° with the original surface of the specimen

- **Shear is primarily responsible for failure in ductile materials**

- Axial loading: maximum shear stress occurs at 45°

- Ways to specify ductility:
  - % elongation = $100 \times \frac{(L_f - L_0)}{L_0}$
  - % area reduction = $100 \times \frac{(A_0 - A_f)}{A_0}$

- The **yield strength** $\sigma_Y$ is often defined as the stress at which unloading would produce a plastic or permanent strain of 0.002 (offset method)
**Strain-Hardening:**

- If a specimen of a ductile material is loaded into the plastic region and then unloaded, *elastic strain* is recovered as the material return to its equilibrium state.
- The *plastic strain* remains, resulting in *permanent deformation*.
- If material is reloaded, it will have a higher yielding point – *strain hardening*. The material has a greater *elastic region*, however is has reduced *ductility*.
Some Example Data: Loading and unloading of some structural metals

E is determined by the primary element of the alloy.

Steeles have one E value

Alumins have one different E value

Etc.
**Brittle materials**

- Material that exhibit little or no yielding before failure
- Absence of necking
- Rupture occurs along a surface perpendicular to the load
- Normal stress is primarily responsible for failure of brittle materials

---

**Concrete (brittle material)**

- Maximum compressive strength is substantially larger than the maximum tensile strength
- For this reason, concrete is almost always reinforced with steel bars or rods whenever it is designed to support tensile loads

---

![Compression causes material to buckling](image)
Hooke’s law
For small deformations (elastic region up to yield strength)

\[ \sigma = E \epsilon \]

For plastic deformation:
For the plastic region: \[ \sigma = K \epsilon^n \]

\( K \) = strength coefficient
\( n \) = strain hardening exponent

<table>
<thead>
<tr>
<th>Material</th>
<th>( \sigma_u )</th>
<th>( \sigma_y )</th>
<th>( E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>400 MPa</td>
<td>250 MPa</td>
<td>200 GPa</td>
</tr>
<tr>
<td>Al</td>
<td>110 MPa</td>
<td>95 MPa</td>
<td>70 GPa</td>
</tr>
<tr>
<td>Concrete (compression)</td>
<td>28 MPa</td>
<td>-</td>
<td>25 GPa</td>
</tr>
</tbody>
</table>
Which material has highest stiffness (Young’s modulus, $E$)?

$B$, steepest linear region

Which material is most ductile?

$C$, highest $\varepsilon$ before rupture

Which material is most brittle?

$A$, least yielding region (none)

Which material has the lowest yield strength $\sigma_y$?

$D$
Hooke’s law for shear stress and strain

$$\tau_{xy} = G \gamma_{xy}$$

Hooke’s law - linear relation between \(\tau\) and \(\gamma\) is usually determined using torsion experiments.

Modulus of rigidity or shear modulus

ONLY TWO OF THE THREE MATERIAL CONSTANTS ARE INDEPENDENT IN ISOTROPIC MATERIALS!

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

Shear modulus

[$G$] = force/area

[$E$] = force/area

[$\nu$] = 1

Ductile Material
**Poisson’s ratio**

**Undeformed configuration**

\[
P = 0 \quad L
\]

**Deformed configuration**

\[
P = 0 \quad L
\]

Axial (normal) strain 
\[
\varepsilon_x = \frac{\delta}{L}
\]

Poisson’s ratio: 
\[
\nu = -\frac{\text{lateral strain}}{\text{axial strain}}
\]

\(-1 < \nu < 0.5\)

\(\nu \approx 0.3\) for metals

Some materials do not have \(\nu < 0\)

\(\nu = 0.5\) \(\Rightarrow\) isochoric material \(\Rightarrow\) "volume-preserving"
**Isotropic vs. anisotropic materials:**

- Isotropic: material properties are independent of the direction
- Anisotropic: material properties depend on the direction
Repeated Loadings – Fatigue

- If stress does not exceed the elastic limit, the specimen returns to its original configuration.
- However, this is not the case if the loading is repeated thousands or millions of times.
- In such cases, rupture will happen at a stress lower than the fracture stress - this phenomenon is known as fatigue.