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

$L_0$: gage length

Typical steel specimen with attached strain gauge.
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

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):

- 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 $\sigma_{pl}$.
- Region formally ends after yielding ($\sigma_Y$).

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.
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 × \( \frac{L_f - L_0}{L_0} \)
  - % area reduction = 100 × \( \frac{A_0 - A_f}{A_0} \)

- 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

6061 Aluminum—2014

$E = 10,400$ ksi

50.6 ksi Yielding

Strain hardening

Unloading and reloading

0.2%

Axial strain, $\varepsilon_{ax}$
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
Hooke’s law

For small deformations (elastic region up to yield strength)

\[ \sigma = E \varepsilon \]

For plastic deformation:

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

- **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, $E$)?

Which material is most ductile?

Which material is most brittle?

Which material has the lowest yield strength $\sigma_Y$?
Hooke’s law for shear stress and strain

\[ \tau_{xy} = G \gamma_{xy} \]

Modulus of rigidity or shear modulus

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

\[ G = \frac{E}{2(1 + \nu)} \]
**Poisson’s ratio**

Undeformed configuration

![Deformed configuration image](image)

Deformed configuration

Axial (normal) strain

\[
\varepsilon_x = \frac{\delta}{L}
\]

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

\( 0 < \nu < 0.5 \)

Lateral strain

\[
\varepsilon_z = \varepsilon_y = -\nu \varepsilon_x
\]

Axial extension \( \rightarrow \) Lateral contraction
**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.

![Diagram showing stress amplitude vs. number of cycles for different materials (1045 steel and 2014-T6 aluminium).]