MAT 312
Material Characterization
Mechanical Testing

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Material Selection

• Procedure
  – Analysis of problem regarding material application
  – Translation of the material application requirements to material property values
  – Selection of candidate materials
  – Evaluation of candidate materials
  – Decision making

• Properties
  – Mechanical, thermal, chemical, electrical

• Constraints
  – Existing facilities
  – Compatibility
  – Marketability
  – Availability
  – Disposability and recyclability
Mechanical Testing of Materials

- Test type/loading
  - Tension
  - Compression
  - Hardness
  - Bending
  - Torsion

- Environmental conditions
  - Test ambient
  - Specimen

- Test specimen
  - Un-notched
  - Notched
    - Any stress raiser: Notch, hole, groove, cracks …

- Test standards
  - Industry
  - Company

- Test Equipment
Mechanical Testing of Materials

- Universal Testing Machines
  - Go back to early 1900s
  - Mechanical-screw-driven machine (electromechanical)
  - Servo-hydraulic machine

- Static or dynamic?
- Strain gage based
  - Load cells
  - Extensometer
Standard Test Methods

- **Mechanical testing**
  - Material properties as input for design procedure
  - Quality control
- **Test standards provide consistency, user-producer communication**
- **Professional societies:**
  - American Society for Testing and Materials - ASTM
  - International Organization for Standardization – ISO
  - European Norms- EN
  - TSE
Standard Test Methods

• Annual Book of ASTM standards covers significant number of standards for mechanical testing-about 10 volumes
• Test standards organized by class of material
  – Metals, concrete, plastics, rubber, glass...
### Table 4.1: Some of the Major ASTM Standards for Basic Mechanical Tests

<table>
<thead>
<tr>
<th>Class of Material (Volume in ASTM Standards)</th>
<th>Tension</th>
<th>Compression</th>
<th>Hardness</th>
<th>Impact</th>
<th>Bending</th>
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<tbody>
<tr>
<td>Metals (01.01, 02.02, and 03.01)</td>
<td>A 370</td>
<td>E 9</td>
<td>A 370</td>
<td>A 370</td>
<td>E 290</td>
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<tr>
<td></td>
<td>B 557</td>
<td>E 209</td>
<td>E 10</td>
<td>E 23</td>
<td>E 812</td>
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<td>E 8</td>
<td>E 18</td>
<td>E 208</td>
<td>E 55</td>
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<td>E 602</td>
<td>E 92</td>
<td>E 436</td>
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<td>E 646</td>
<td>E 384</td>
<td>E 604</td>
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<td></td>
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<td>E 448</td>
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<td>Concrete (04.02)</td>
<td>C 496</td>
<td>C 39</td>
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<td></td>
<td>C 78</td>
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<td></td>
<td></td>
<td>C 469</td>
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<td></td>
<td>C 293</td>
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<tr>
<td>Stone and rock (04.07 to .09)</td>
<td>D 2936</td>
<td>C 170</td>
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<td>C 99</td>
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<td></td>
<td>D 3967</td>
<td>D 2938</td>
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<td>C 120</td>
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<td>D 3148</td>
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<td>C 880</td>
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<tr>
<td>Wood and plywood (04.10)</td>
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<td>D 143</td>
<td>D 143</td>
<td>D 143</td>
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<td>D 3499</td>
<td>D 198</td>
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<td>D 3500</td>
<td>D 3501</td>
<td>D 3043</td>
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<td>Plastics (08.01 to .03)</td>
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<td>D 785</td>
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<td>D 2583</td>
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<td>D 1623</td>
<td>D 5420</td>
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<td>D 4812</td>
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<td>Rubber (09.01)</td>
<td>D 412</td>
<td>D 395</td>
<td>D 1415</td>
<td>D 1054</td>
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<td>D 575</td>
<td>D 2240</td>
<td>D 2632</td>
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<tr>
<td>Ceramics and glass (15.01 and .02)</td>
<td>C 565</td>
<td>C 133</td>
<td>C 730</td>
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<td>C 158</td>
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<td>C 749</td>
<td>C 695</td>
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<td>C 1273</td>
<td>C 773</td>
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<td>C 1275¹</td>
<td>C 886</td>
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<td>C 1341¹</td>
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<tr>
<td>Fibers and composites (15.03)</td>
<td>D 3039</td>
<td>C 364</td>
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<td>C 393</td>
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<td>D 3379</td>
<td>C 365</td>
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<td></td>
<td>D 3552</td>
<td>D 3410</td>
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<td></td>
<td>D 4018</td>
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</tbody>
</table>

Note: ¹Long fiber ceramic composite material.
Standard Test Methods

• Provide procedures to be followed in detail
  – Specimen description
  – Loading conditions
  – Values to report
  – Statistical analysis
Tension Test

- Pulling a sample of material in tension until fracture
- Specimens designed to avoid break where gripped
- Usually constant speed
  - Crosshead speed, mm/min
- Report stress-strain curve until failure
- Ideally recorded by dedicated transducers
  - Extensometer
  - Strain gages bonded on the specimen
Tension Test

• **Stress-strain behavior varies widely**
  – **Brittle behavior: without extensive deformation**-gray cast iron, some polymers (PMMA), glass
  – **Ductile behavior: failure following extensive deformation**-metals
Tension Test

- **Material properties are based on**
  - Mostly engineering stress-strain
  - Some true stress-strain

- **Elastic constants**
  - Elastic or Young’s modulus-slope of initial elastic line, \( E=(\sigma_B - \sigma_A)/(\varepsilon_B-\varepsilon_B) \)
  - Tangent modulus-tangent at the origin (if there is no well-defined linear region)
  - Poisson’s ratio
Tension Test

Figure 4.11  Initial portions of stress-strain curves: (a) many metals and alloys, (b) material with yield drop, and (c) material with no linear region.
Tension Test

- **Strength**
  - Ultimate - highest engineering stress prior to fracture
  - Fracture strength - stress at fracture
  - Yield strength - stress where departure from elastic behavior happens and contribution of plastic strain begins resulting in rapidly increasing deformation

- **Tensile strength at yield**
- **Tensile strength at break**
- **Usual priority** - assure that stresses are sufficiently small that yielding does not occur
Tension Test-criteria for yielding

• First departure from linearity-proportional limit,
  – Difficult to precisely locate- depends on judgment
  – Some material with gradually decreasing slope, no proportional limit identified

• Elastic limit-highest stress without permanent deformation
  – Difficult to determine, periodic unloading to check for permanent deformation
Tension Test-criteria for yielding

- Some metals exhibit nonlinearity followed by a dramatic drop in load (fig 4.11)
  - Upper yield point, $\sigma_{ou}$ - prior to the drop
  - Lower yield point, $\sigma_{ol}$ - prior to the subsequent increase

- Offset Method - offset yield strength
  - Intersection of the stress-strain curve and the straight line parallel to elastic slope $E$ or $E_t$, that is offset by an arbitrary amount
  - Offset amount for metals 0.2% strain
Tension Test-criteria for yielding

Figure 4.11 Initial portions of stress-strain curves: (a) many metals and alloys, (b) material with yield drop, and (c) material with no linear region.

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Tension Test-criteria for yielding

• For polymers offset yield strength also used

• Yield is at $d\sigma/d\varepsilon=0$, if there is early relative maximum $\sigma_{ou}$, usually followed by substantial plastic deformation (fig 4.10),
Tension Test-criteria for yielding

Figure 4.10  Engineering stress-strain curve and geometry of deformation typical of some polymers.

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Tension Test-Measures of Ductility

• **Definition:** Ability of a material to accommodate inelastic deformation without breaking

• **Measured by**
  - Engineering fracture strain or percent elongation, corresponds to the engineering fracture strength point

\[ \varepsilon_f = \frac{(L_f - L_i)}{L_i} \]
Tension Test-Measures of Ductility

- Elongation is the value at fracture
  - For polymers (ASTM standard): strain $\varepsilon_f$ at the instant of fracture
  - For ductile metals (ASTM standard): measured after it is broken using marks placed at a known distance apart prior to the test – plastic component of the strain or elongation $\varepsilon_{pf}$ (~ $\varepsilon_f$ for ductile metals)
  - For metals of limited ductility,
    \[ \varepsilon_{pf} = \varepsilon_f - \frac{\sigma_f}{E} \]
Tension Test-Measures of Ductility

• Also measured by percent reduction in area

\[ \% \text{RA} = 100\left(\frac{A_i - A_f}{A_i}\right) \]
Tension Test-Necking and Ductility

• If ductile, necking usually occurs
  – Deformation begins to concentrate in one region, area reduction higher than elsewhere
  – Strain becomes nonuniform

• With necking involved, percent elongation is sensitive to L/d or L/t as it is an average over a gage length, thus reduction in area is considered as more fundamental
Tension Energy Capacity

- Work done by the applied tensile load is equal to energy absorbed by the material, area under the stress-strain curve work done per unit volume
  \[ u = \int \sigma \, d\varepsilon \]
  Called tensile toughness of the material
  (ability of the material to absorb energy without fracture)
Figure 4.14  Areas under engineering stress-strain curves corresponding to resilience $u_r$ and tensile toughness $u_f$. 

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Tension Energy Capacity

• Within the region of elastic deformation, potential energy released upon unloading

• At the proportional limit, resilience (ability of the material to store elastic energy)

\[ u_r = \frac{\sigma_p^2}{2E} \]

Usually preferable to use offset yield strength

\[ u_r = \frac{\sigma_o^2}{2E} \]
Strain Hardening

- Increase in mechanical resistance with increasing strain following the yielding
- A measure of the strain hardening
  \[
  \frac{\sigma_u}{\sigma_o}
  \]
  Range considered average for metals 1.2-1.4
Trends in Tensile Behavior

- Materials vary widely regarding their strength and ductility
Effect of Temperature and Strain Rate

- In a temperature range where creep-related effects occur, strain rate temperature interaction exists
- Polymers of low Tg, for instance (larger creep effects occur even around RT), strain rate draws attention
- Generally speaking—for a given material at T range where creep-related strain-rate effects occur—
  - At a given T, increasing strain rate increases the strength, but decreases ductility
  - For a given strain rate, decreasing temperature increases strength, but decreases ductility
Effect of Temperature and Strain Rate

**Figure 4.18** Effect of strain rate on the ultimate tensile strength of copper for tests at various temperatures. (Adapted from [Nadai 41]; used with permission of ASME.)

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True Stress-Strain

- Engineering stress and strain appropriate when the changes in specimen dimensions are small, area for instance.
- For ductile materials, in particular, true stress-strain differs from engineering stress-strain.
- If necking occurs, correction may be needed.

\[ \tilde{\sigma} = \sigma \left( \frac{A_i}{A} \right) \]

\[ \tilde{\varepsilon} = \ln(1 + \varepsilon) \]
## Tension Test

### TABLE 4.6 MATERIALS PROPERTIES OBTAINABLE FROM TENSION TESTS

<table>
<thead>
<tr>
<th>Category</th>
<th>Engineering Property</th>
<th>True Stress-Strain Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic constants</td>
<td>Elastic modulus, $E$, $E_i$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio, $v$</td>
<td></td>
</tr>
<tr>
<td>Strength</td>
<td>Proportional limit, $\sigma_p$</td>
<td>True fracture strength, $\tilde{\sigma}_{FB}$</td>
</tr>
<tr>
<td></td>
<td>Yield strength, $\sigma_y$</td>
<td>Strength coefficient, $H$</td>
</tr>
<tr>
<td></td>
<td>Ultimate tensile strength, $\sigma_u$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Engineering fracture strength, $\sigma_f$</td>
<td></td>
</tr>
<tr>
<td>Ductility</td>
<td>Percent elongation, $100\varepsilon_f$</td>
<td>True fracture strain, $\tilde{\varepsilon}_f$</td>
</tr>
<tr>
<td></td>
<td>Reduction in area, $%RA$</td>
<td></td>
</tr>
<tr>
<td>Energy capacity</td>
<td>Resilience, $u_r$</td>
<td>True toughness, $\tilde{u}_f$</td>
</tr>
<tr>
<td></td>
<td>Tensile toughness, $u_f$</td>
<td></td>
</tr>
<tr>
<td>Strain hardening</td>
<td>Strain hardening ratio, $\sigma_u/\sigma_y$</td>
<td>Strain hardening exponent, $n$</td>
</tr>
</tbody>
</table>

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Compression

• Behavior in compression may be substantially different
  – Concrete
• Similar test arrangement except the direction of loading
• Specimen dimensions
  – Too small: end effects
  – Too long: buckling
  – L/d=3 for ductile materials
  – L/d=1.5-2 for brittle
Compression

Figure 4.26 Stress-strain curves for plexiglass (acrylic, PMMA) in both tension and compression. (Adapted from [Richards 61] p. 153; reprinted by permission of PWS-Kent Publishing Co., Boston.)
Hardness Test

• Hardness is the property of a material that enables it to resist plastic deformation, usually by penetration. However, the term hardness may also refer to resistance to scratching, abrasion or cutting.

• Several types
  – Indentation hardness: pressing of a hard indenter against the sample with a known force
  – Scleroscope hardness test: rebound of a hammer with diamond tip
  – Mohs hardness: Scratching, matter of judgment, scaled between 1-10, (10 for diamond)
Indentation Hardness Test

• Surface resistance to indentation/penetration that results from plastic deformation beneath the indenter
• Differ by type and geometry of indenter, amount of force, but measure the size/depth of an indentation
  – Brinell harness test: sphere indenter of 10 mm in dia,, varying load, measure the size of indentation
  – Rockwell hardness test: using different scale (various sized indenter, different loads)
  – Vickers hardness test: diamond pyramid used as indenter
  – Shore Durometer hardness test (polimers, rubber)
Indentation Hardness Test

- Brinell harness test: sphere indenter of D, load F, measure the size of indentation $D_i$
Indentation Hardness Test

- Vickers harness test: square based pyramid diamond indenter, load $F$, measure the size of indentation $D_i$

\[
HV = \frac{2F \sin \frac{136^\circ}{2}}{d^2}
\]

$HV = 1.854 \frac{F}{d^2}$ approximately

http://www.gordonengland.co.uk/hardness/
Indentation Hardness Test

• Rockwell hardness test: measures the depth of indentation

\[ HR = E - e \]

http://www.gordonengland.co.uk/hardness/
Indentation Hardness Test

- Microhardness test: very similar to that of the standard Vickers hardness test, except that it is done on a microscopic scale with higher precision instruments. Vickers diamond pyramid or the Knoop elongated diamond pyramid. Use projected area A, \( KHN = \frac{F}{A} \)

http://www.gordonengland.co.uk/hardness/
Indentation Hardness Test

• Shore Durometer hardness Test: to determine the relative hardness of soft materials, usually plastic or rubber

Notch-impact Tests

- Measure the resistance of a material to sudden fracture in the presence of stress raiser or flaw
- Energy required to break the sample is determined from an indicator measuring how high the pendulum swings after breaking the sample
- Simple, quickly compare materials,
Notch-impact Tests

For polymers and plastics

Bending (Flexure) Tests

• Tensile strength of brittle materials that are difficult to grip without cracking, glass...

• Laminated materials: interlaminar strength

• Meaningful for materials of linear stress-strain behavior until fracture

\[
\sigma = \frac{Mc}{I}
\]

\[
\sigma_{fb} = \frac{3L}{8tc^2} P_f
\]
Bending (Flexure) Tests

- Elastic modulus may also be obtained
- Maximum deflection using linear-elastic analysis

\[ v = \frac{PL^3}{48EI} \]

\[ E = \frac{L^3}{48I \left( \frac{dP}{dv} \right)} \]

**Figure 4.39** Loading configuration for (a) three-point bending and (b) four-point bending. The deflection of the centerline of either beam is similar to (c).
Torsion Tests

- Test of round bars subject to torque
- Shear modulus, $G$ is determined
- Fracture of brittle materials: at 45 to both specimen axis and surface, planes of maximum tension
- Fracture of ductile materials: planes of maximum shear
Torsion Tests

Figure 4.40  Typical torsion failures showing brittle behavior (above) in gray cast iron, and ductile behavior (below) in aluminum alloy 2024-T351. (Photo by R. A. Simonds.)

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