Material Selection Tutorial

- Selecting an appropriate material is a critical part of almost all engineering designs
- There are many factors to consider
  - Strength, stiffness, durability, corrosion, cost, formability, etc
- Methods
  - Experience: how do you get it? limiting
  - Ashby selection charts
    (http://www-materials.eng.cam.ac.uk/mpsite/DT.html)
  - Quantitative ranking of options (described here)
Ashby Material Selection Chart

http://www-materials.eng.cam.ac.uk/mpsite/tutorial/non_IE/selchart.html
Quantitative Ranking of Options for Material Selection*

- **Objective**: develop a rational method to select the best material for an application based upon known material parameters and the requirements of the application

- Use a 5-step method
  1. Select a quantity, Q, to minimize or maximize
  2. Classify the variables
  3. Determine the relationship between the geometry variable, the requirements, and material properties
  4. Determine Q as a function of requirements and material properties
  5. Rank candidate materials based upon function $f_2$

* Based on N.E. Dowling, *Mechanical Behavior of Materials*, section 3.8
Step 1: Select a quantity, Q, to minimize or maximize

- Mass (weight), m
- Cost, C

are the most common and the only ones that we will consider
Step 2: Classify the variables

• Requirements – variables that have prescribed values that will not change
• Geometry – variables that define the dimensions of the component and depend implicitly upon the material properties
• Material Properties – variables used to define the material in terms of physical behavior, mechanical behavior, and cost
Step 3: Determine the relationship between the geometry variable, the requirements, and material properties

- **Strength**
  - Bar, axial stress
  - Beam, flexural stress
- **Stiffness**
  - Bar, deformation
  - Beam, deflection
Step 4: Determine $Q$ as a function of requirements and material properties

- $Q = f_1(\text{requirements}) \ast f_2(\text{material props})$
Step 5: Rank candidate materials based upon function $f_2$

- If both weight and cost are important then separate rankings can be generated and results combined.
- Calculate geometry variable after ranking materials:
  - Adjustments may be necessary if calculated dimensions are impractical (either too large or too small).
- There may be multiple requirements such as strength and serviceability:
  - Often material can be selected based on strength and then the serviceability requirements checked.
Sample Problem

- We must bridge a gap of $L = 8'$
- The bridge must have a width of $b = 4''$
- A load $P = 300$ lb can be applied at any point
- There must be a safety factor $X = 1.5$ for strength
- The deflection, $v$, must not exceed $1''$
- Weight (mass) and cost have equal importance

OBJECTIVE: select the best candidate material from…

AISI 1020 steel    AISI 4340 steel
7075-T6 aluminum   Ti-6Al-4V (titanium alloy)
Polycarbonate      Loblolly pine
GFRP (glass fiber reinforced polymer)
CFRP (carbon fiber reinforced polymer)
Step 1: Select a quantity, \( Q \), to minimize

Here, mass and cost have equal importance

- Mass, \( m \)
- Cost, \( C \)

Select \( Q \) to be the sum of the normalized mass and cost

- \( Q = \frac{m}{\min(m)} + \frac{C}{\min(C)} \)
Step 2: Classify the variables

- Requirements: $L = 8'$, $b = 4''$, $P = 300$ lb, $X = 1.5$, $v = 1''$
- Geometry: restrict analysis to a rectangular cross-section, $h = \text{height}$
- Material Properties (need step 3 & 4 results here): $ho = \text{mass density}$, $E = \text{Young’s modulus}$, $S = \text{strength}$, $C_m = \text{cost index}$
Step 3: Determine the relationship between the geometry variable, the requirements, and material properties

• We have a simply supported beam with a rectangular cross-section
• The worst case occurs when the concentrated load, $P$, is applied at the center
Strength – elastic flexural formula shows the maximum stress occurs at the extreme fibers of the beam at midspan

\[ \sigma = \frac{Mc}{I}, M = PL/4, c = h/2, I = bh^3/12 \]

\[ \sigma = \frac{PLh}{4} \cdot \frac{12}{2bh^3} = \frac{3PL}{2bh^2} \]

\[ S = X\sigma = \frac{3PLX}{2bh^2} \Rightarrow h = \left[ \frac{3PLX}{2bS} \right]^{1/2} \]

Deflection – from integration, is found to be maximum at midspan

\[ \nu = \frac{PL^3}{48EI} = \frac{12PL^3}{48Eb^3} = \frac{PL^3}{4Eb^3} \Rightarrow h = \left[ \frac{PL^3}{4Eb^3} \right]^{1/2} \]
Step 4: Determine Q as a function of requirements and material properties – strength basis

Try using strength as the basis for material selection and then check deflection

\[ m = \rho bhL = \rho bL \left[ \frac{3PLX}{2bS} \right]^{\frac{1}{2}} = \left[ \frac{3}{2} PL^3 Xb \right]^{\frac{1}{2}} \left[ \frac{\rho}{S^{\frac{1}{2}}} \right] \]

\[ C = C_m m = \left[ \frac{3}{2} PL^3 Xb \right]^{\frac{1}{2}} \left[ \frac{\rho C_m}{S^{\frac{1}{2}}} \right] \]
Step 5: Rank materials based upon function $f_2$ – strength basis

Use spreadsheet to determine rankings

Selection Table - strength basis (check deflection)

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (slug/in3)</th>
<th>Strength (psi)</th>
<th>Cost Index</th>
<th>$f_2$ for mass</th>
<th>Norm Mass</th>
<th>Mass Rank</th>
<th>$f_2$ for cost</th>
<th>Norm Cost</th>
<th>Cost Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 1020 steel</td>
<td>8.87E-03</td>
<td>37708</td>
<td>1</td>
<td>4.57E-05</td>
<td>9.34</td>
<td>8</td>
<td>4.57E-05</td>
<td>6.01</td>
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</tr>
<tr>
<td>AISI 4340 steel</td>
<td>8.87E-03</td>
<td>159971</td>
<td>3</td>
<td>2.22E-05</td>
<td>4.53</td>
<td>7</td>
<td>6.65E-05</td>
<td>8.75</td>
<td>3</td>
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<tr>
<td>7075-T6 aluminum</td>
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<td>68020</td>
<td>6</td>
<td>1.16E-05</td>
<td>2.38</td>
<td>4</td>
<td>6.98E-05</td>
<td>9.17</td>
<td>4</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>5.05E-03</td>
<td>171864</td>
<td>45</td>
<td>1.22E-05</td>
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<td>5.49E-04</td>
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</table>

Material Selection - 15
Step 4: Determine Q as a function of requirements and material properties – deflection basis

Try using deflection as the basis for material selection and then check strength

\[
m = \rho bhL = \rho bL \left[ \frac{PL^3}{4Ebv} \right]^{\frac{1}{3}} = \left[ \frac{PL^6b^2}{4v} \right]^{\frac{1}{3}} \left[ \frac{\rho}{E^{\frac{1}{3}}} \right]
\]

\[
C = C_m m = \left[ \frac{PL^6b^2}{4v} \right]^{\frac{1}{3}} \left[ \frac{\rho C_m}{E^{\frac{1}{3}}} \right]
\]
Step 5B: Rank materials based upon function $f_2$ – deflection basis

Use spreadsheet to determine rankings

Requirements
- $L$ (in) = 96
- $P$ (lb) = 300
- $b$ (in) = 4
- $X = 1.5$
- $v$ (in) = 1

Selection Table - deflection basis (check strength)

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (slug/in³)</th>
<th>Strength (psi)</th>
<th>Cost Index</th>
<th>$f_2$ for mass</th>
<th>Norm Mass</th>
<th>Mass Rank</th>
<th>$f_2$ for cost</th>
<th>Norm Cost</th>
<th>Cost Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 1020 steel</td>
<td>8.87E-03</td>
<td>37708</td>
<td>1</td>
<td>2.87E-05</td>
<td>6.08</td>
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<td>4.06</td>
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<tr>
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<td>2.85E-05</td>
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<td>7075-T6 aluminum</td>
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<td>68020</td>
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<td>8.85E-04</td>
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<td>Polycarbonate</td>
<td>1.35E-03</td>
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<td>4.06</td>
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<td>9.58E-05</td>
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<td>Lobolly pine</td>
<td>5.73E-04</td>
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</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>$Q$</th>
<th>Combined Rank</th>
<th>Depth, h (in)</th>
<th>Modulus (psi)</th>
<th>Deflection (in)</th>
<th>Stress (psi)</th>
<th>Safety Factor</th>
<th>Check Strength</th>
</tr>
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<tbody>
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<td>AISI 1020 steel</td>
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<td>7075-T6 aluminum</td>
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</table>
Sample Problem Results

• Material selection based only on strength results in the deflection criterion being violated
• Material selection based only on deflection results in the strength criterion being satisfied
• We can say that deflection governs this design
• Pine is best, 1020 steel is second best, CFRP is worst