Material Design Applications

Learning Objectives

Become aware of methods for tailoring the material properties to achieve design objectives.
Question for the Semester …

We imagine a future in which geographically distributed engineers collaboratively develop, build, and test solutions to design-manufacture problems encountered in the product realization process.

We recognize that solutions evolve over time. Accordingly, we expect you to build on what has been done before.

In this context, we want you to provide a method to support the realization of products for a global marketplace through distributed design and manufacture.

How should the P&B systematic design method be personalized and augmented to support the realization of products for a global marketplace in a distributed environment?

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Personalized – made usable for realizing all types of systems
Augmented – made usable for designing for a global marketplace and a distributed environment
Steps to Answer the Q4S

Part 1
• Describe your world of 2020
  – Increasing complexity of product requirements
  – Material Design dominates

Part 2
• Understand your world of today
  – Material Selection dominates

Part 3
• In the context of the preceding postulate your method; one that you will be able to evolve into the methods required in your world of 2020
Scaffolding to Answer the Q4S

- **Internalize** P&B (A1)
- **Critically evaluate** answers to the Q4S proposed by others (A2)
- **Identify** the characteristics of the world of 2020 and the requirements list for your method for 2020 (A2)
- **Learn how to verify** your personalized and augmented method for 2020 (A3)
- **Identify** a base method plus verification strategy for your answer to the Q4S and a method for verification (A4, Mid-Term)
- **Develop** the base method you have identified to meet the requirements for the method (A5 – A7)
- **Postulate** how you will design sustainable engineering systems for a global marketplace. (Answer to Q4S)
Learning Objectives for Lectures 25-26:

- Materials design in the context of multiscale design
- Application of multiscale design materials design techniques in product design examples
- Materials design in your augmented P&B and in the world of 2020

Lecture Schedule

- Lecture 21 (11-2) – Mass Customization
- Lecture 22 (11-3) – Design for X
- Lecture 23 (11-9) – Designing Customizable Products and Processes
- Lecture 24 (11-10) – Robust Design
- Lecture 25 (11-16) – Multiscale Design – Background and Motivation
- Lecture 26 (11-17) – Multiscale Design – Examples
The Big Picture…

Today we will discuss...

- A simple beam, designed three ways
  - Material-Driven Design
  - Material Selection
  - Material Design
  - Goal: Learn how to apply material design to a simple problem

- Multi-Scale Design of Fan/Shaft Assembly
  - Goal: Learn how to apply material design to a complex problem

- Back to the bread example
  - Goal: Connect Lecture 26 to Lecture 25

Key … Learn how to apply methods for material design to engineering problems
Consider a simple cantilever beam supporting a load at the free end.

**Design Requirements:**
- Support a load of 10 N at free end
- Span 2 meters in length
- Square cross-section
- Maximum allowable deflection of 1 cm

**Goal:** Minimize Weight
Cantilever Beam - Equations

Mass of the beam
- \( a \) = height of cross-section
- \( \rho \) = density
- \( L \) = beam length

\[
m = \rho a^2 L
\]

Maximum Deflection (free end)
- \( F \) = applied load
- \( E \) = modulus of elasticity

\[
\delta_{\text{max}} = -\frac{8FL^3 + 3\rho ga^2 L^4}{2Ea^4}
\]

Safety Factor, S.F.
- \( \sigma_{\text{yield}} \) = yield stress

\[
S.F. = \frac{\sigma_{\text{yield}}}{6L(F + \rho g/2)/a^3}
\]

Caution: These equations assume constant material properties throughout the beam!!!
In material-driven design, the product is chosen at the beginning of the design process based on familiarity, availability or previous success.

We will choose iron for this example because it is readily available and familiar.
Cantilever Beam – Material-Driven Design

Iron

\[ \rho = 7000 \text{ kg/m}^3 \]

\[ E = 211 \text{ GPa} \]

\[ \text{Yield strength} \]

\[ L = 2 \text{ m} \]

\[ F = 10 \text{ N} \]

\[ \text{Area} = a^2 \]

\[ \delta_{\text{max}} = 0.01 \text{ m} \]

\[ m = 13.2 \text{ kg} \]

\[ \text{S.F.} = 3.8 \]

Design Process

\[ a = 3 \text{ cm} \]

\[ m = 13.2 \text{ kg} \]

\[ \text{S.F.} = 3.8 \]

\[ \delta_{\text{max}} = 0.03 \text{ m} \]

\[ \sigma_y \]

\[ m = \rho a^2 L = 13.2 \text{ kg} \]
Using material selection for design, the product is chosen *during the design process* from a vast *material database* based on *product requirements*.

**Goal:** minimize mass
Method for material selection in product design as detailed in *Materials Selection in Mechanical Design*, by Michael F. Ashby

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**Material Selection**

All Materials

Screening: apply property limits
Ranking: apply material indices

Subset of Materials

Supporting information: handbooks, specialized software, expert systems, www

Prime Candidates

Local Conditions

Final Material Choice

Steps for Material Selection

**Defined in Problem Statement:**

1. **Identify the property limits imposed by the product design.**
   
   No property limits imposed by problem statement.

2. **Identify the form (basic geometry) of the part.**
   
   Cantilever beam, square cross-section

3. **Detail the function (load requirements) of the part.**
   
   Finite load at the free end, distributed load due to weight.

4. **Write objective function(s).**
   
   Want to minimize weight $\rightarrow$ minimize MASS

**Next Steps:**

5. **Develop material index based on loading conditions and objective function(s).**

6. **Use material property charts to identify and rank a subset of possible materials.**
Cantilever Beam – Material Selection

Material index, M: High M → Low mass

- Diamond
- Aluminum
- Beryllium Alloys
- Carbon Fiber
- Wood

Young's Modulus, $E$

Density, $\rho$

$$M = \frac{\sqrt{E}}{\rho}$$
Cantilever Beam – Material Selection

Prime Candidates:

Wood
- Pro: Low Density
- Con: high variability, degrades quickly (rots)

Diamond
- Pro: Highest possible strength
- Con: Expensive!

Carbon Fiber
- Pro: High strength-to-weight
- Con: Expensive!

Beryllium Alloys
- Pro: Very high strength-to-weight
- Con: Expensive, health hazards.

Aluminum
- Pro: Well known and readily available
- Con: not lowest density

Final Material Choice
Cantilever Beam – Material Selection

L = 2 m
F = 10 N
Area = \( a^2 \)
\( \delta_{\text{max}} = 0.01 \text{ m} \)

Material Database

Material Selection

Product Layout (dimensions)

\[ \delta_{\text{max}} = -\frac{(8FL^3 + 3\rho ga^2 L^4)}{2Ea^4} \Rightarrow a = 0.036 \text{ m} \]

\[ m = \rho a^2 L = 6.93 \text{ kg} \]

S.F. = \[ \frac{\sigma_y}{\left(\frac{6L(F + \rho g/2)}{a^3}\right)} = 11.32 \]

Aluminum

a = 3.6 cm
m = 6.93 kg
S.F. = 11.32
Materials design is the process of **tailoring material properties** to meet the **requirements** of specific design problems\(^1\).

This is a paradigm shift!

Material Design adds significant complexity to analysis models, but superior performance can be achieved!

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Cantilever Beam – Material Design

Methods of tailoring material properties

Material Composition

- Alloys

- Composites

Topography Design

- Mesostructure

- Processing

- Thermal
  - Annealing
  - Case Hardening
  - Tempering
  - Quenching
  - Differential Hardening

- Surface
  - Cold Rolling
  - Shot Peening

Cantilever Beam – Material Design

We have chosen **alloying** because of the simplicity of analysis.

In this case, the material properties \((E, \rho, \sigma_{yield})\) vary with position \((x)\) along the beam.
Cantilever Beam – Material Design

For analysis, we need a relationship between alloy composition and material properties.

We assume a simple linear relationship of alloy properties based on the volume fraction of the alloy.

\[ X_{\text{alloy}} = (v_f) X_A + (1 - v_f) X_B \]

If \( v_f = 1 \), the properties of the alloy are the same as the properties of material A.
If \( v_f = 0 \), the properties of the alloy are the same as the properties of material B.
Using the linear relationship, we determined the following relationships for $E$, $\rho$, and $\sigma_{\text{yield}}$

\[
E_{\text{alloy}} = (\nu f)E_A + (1 - \nu f)E_B
\]

\[
\rho_{\text{alloy}} = (\nu f)\rho_A + (1 - \nu f)\rho_B
\]

\[
\sigma_{y,\text{alloy}} = (\nu f)\sigma_{y,A} + (1 - \nu f)\sigma_{y,B}
\]
The beam was modeled in COMSOL as 10 discrete segments that could have independent material properties. The volume fraction ($v_f$) in each segment is the control variable that we can vary to achieve our design requirements, as well as the beam width ($a$), which is held constant for all segments. The total length ($L$) of the beam is 2 meters. The volume fractions for each segment are $v_f_1$, $v_f_2$, $v_f_3$, $v_f_4$, $v_f_5$, $v_f_6$, $v_f_7$, $v_f_8$, $v_f_9$, and $v_f_{10}$.
A compromise Decision Support Problem (cDSP) was used to choose the best values for the control variables.

**Given:**
- Material property equations
- Loading conditions
- Beam length (L)
- Alloying metals

**Find:**
- Volume fraction \( (v_f) \) in each segment
- Beam width \( (a) \)

**Satisfy:**
- **Constraints:** maximum deflection, yield stress
- **Bounds:**
  - \( 0 \leq v_f \leq 1 \)
  - \( 0.005 \leq a \leq 0.25 \text{m} \)
- **Goals:** minimize weight

**Minimize:**
- Deviation from target weight
Cantilever Beam – Material Design

Product Requirements

L = 2 m
F = 10 N
Area = a²
δ_{max} = 0.01 m

Design Process

cDSP

Material Model
Performance Model

Product Material

a = 0.027
m = 6.46
S.F. = 14.61

Alloy composition in each segment

<table>
<thead>
<tr>
<th>Segment</th>
<th>Volume Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
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<tr>
<td>4</td>
<td>0.4</td>
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<td>5</td>
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<td>6</td>
<td>0.7</td>
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<tr>
<td>8</td>
<td>1.0</td>
</tr>
<tr>
<td>9</td>
<td>0.0</td>
</tr>
<tr>
<td>10</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Steel
Aluminum
### Cantilever Beam – Comparison

<table>
<thead>
<tr>
<th>Material-driven Design</th>
<th>Material Selection</th>
<th>Material Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material(s)</td>
<td>Iron</td>
<td>Aluminum</td>
</tr>
<tr>
<td>width (a), m</td>
<td>0.031</td>
<td>0.036</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>13.19</td>
<td>6.93</td>
</tr>
<tr>
<td>Safety Factor</td>
<td>3.87</td>
<td>11.32</td>
</tr>
</tbody>
</table>

As compared to material-driven design, Material Selection yields:
- Larger cross-section
- Much smaller mass
- Larger safety factor

Material Design yields:
- Smallest cross-section
- Smallest mass
- Largest safety factor
Let’s stop for a moment to reflect on what we have learned from these examples.

What are you taking away?

• ...
• ...
• ...
• ...
• ...
• ...
The Big Picture...

Today we will discuss...

- A simple beam, designed three ways
- Material-Driven Design
- Material Selection
- Material Design

Multi-Scale Design of Fan/Shaft Assembly

Back to the bread example

Key... Learn how to apply methods for material design to engineering problems.
Multiscale design must account for interactions between scales (or levels of hierarchy).

In the preceding beam example, there were two levels of hierarchy involved: part level and material level.
Consider the design of a multi-scale system of fans for ventilation.

Multiscale design of fan/shaft assembly
What types of interactions occur in assemblies of parts?

- **Geometry**: parts must mate, fit inside, fit around other parts
- **Loads**: one part applies a load to another part (weight, torque, friction, etc.)
- ?

What other interactions might there be?

How do we account for these interactions?
Let’s consider the interactions between the fan blade and the shaft...

**Fan Blade Model**
- Geometry
- Material Model
- Interaction Model (Fluent, GAMBIT, COMSOL)
- Performance Requirements, External Loads
- Fan Performance (Deflection, stress, etc.)

**Shaft Model**
- Geometry
- Material Model
- Interaction Model (COMSOL)
- Performance Requirements, External Loads
- Shaft Performance (Deflection, stress, etc.)
Fan/Shaft Assembly Model

- Fan Blade Model
  - Material Model
    - Interaction Model (Fluent, GAMBIT, COMSOL)
  - Performance Requirements, External Loads
  - Geometry

- Shaft Model
  - Material Model
    - Interaction Model (COMSOL)
  - Performance Requirements, External Loads
  - Geometry

Interaction Model

- Fan Performance (Deflection, stress, etc.)
- Shaft Performance (Deflection, stress, etc.)

Assembly Performance
Multiscale Fan/Shaft Design Steps

- Develop Part Models with Material Model inputs
  - Shaft (COMSOL)
  - Fan blade (GAMBIT, Fluent, COMSOL)

- Develop the interaction model between the fan and shaft components

- Extend models to include motor and duct design as well as additional interactions
Modeling Fan Blade Performance

Fan Blade

Airflow towards blade

Airflow due to rotation

Deflection

Von Mises Stress Distribution
Multiscale Fan/Shaft Design

Current Status:
- Models in development
  - Shaft (COMSOL)
  - Fan blade (GAMBIT, Fluent, COMSOL)

Future Work:
- Develop the interaction model between the fan and shaft components
- Extend models to include motor and duct design as well as additional interactions
The Big Picture…

Today we will discuss…

☑️ A simple beam, designed three ways
  ☑️ Material-Driven Design
  ☑️ Material Selection
  ☑️ Material Design

☑️ Multi-Scale Design of Fan/Shaft Assembly

☑️ Back to the bread example

Key … Learn how to apply methods for material design to engineering problems
Multi-Scale Design of Bread with Sandwich Applications

Let’s return to our bread example…
How is this bread part of a multi-scale system?

Diet

- Meal 1
- Snack 1
- • • • •
- Meal n
- Snack n

- Apple
- Drink

Sandwich

- Chips
- Bread
- Meat
- Cheese
- Veggies
- Condiments
If we were to create a part model for the bread, it might look something like this:

How can the processing, structure, and performance models for bread be developed?
### Lecture 26: Materials Design Applications

#### Learning Essay Themes

**Speculate the influence and importance of materials in the world of 2020...**

<table>
<thead>
<tr>
<th>Question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>What are the drivers of designing new materials? Where should material selection / materials design be added to P&amp;B?</td>
<td></td>
</tr>
<tr>
<td>How can a designer choose between material selection and materials design?</td>
<td></td>
</tr>
<tr>
<td>What design tools are necessary for materials design?</td>
<td></td>
</tr>
<tr>
<td>What is the role of materials design in the multiscale product design process?</td>
<td></td>
</tr>
<tr>
<td>How do we incorporate robustness in the materials design process?</td>
<td></td>
</tr>
</tbody>
</table>
Summary

Today, we discussed:

- A simple beam, designed three ways
  - Material-Driven Design
  - Material Selection
  - Material Design
- Multi-Scale Design of Fan/Shaft Assembly
- Back to the bread example

What are you taking away?... How will you use this in your A2Q4S?

•
•
Hannah and I would like to thank:
- Emad Samandiani
- Greg Mocko
- Jitesh Panchal

References:

