MTRL 280 Material Selection

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The Design Process

What is design?

Design is the process of translating a new idea or a market need into the detailed information from which a product can be manufactured.

The Need Statement

Any design process starts with a need statement. A need statement must be solution neutral which means it should not convey how a problem can be solved. "A device is required to perform the following set of design requirement" would be an example of a need statement.

Types Of Design

- Original Design: A new idea or a new working principle

- Adaptive Design: Redesign of existing product that seeks improvement in performance

- Variant Design: Change of dimension or detailing without a change of function or method of achieving it.

Material Information

Structural Property

Structural properties are properties that changes with the dimension, geometry, and shape of an object. Design is usually specified with structural properties.

- Force at Failure(N): How much force is required to break the object under force.

- Stiffness(N/m): How much deformation there is when a force is applied. This is a structural property because it depends on the geometry and size of the object. Ex. Increasing the thickness of an object also increase its stiffness.

- Electrical Resistance(Ω)

Material Property

Material Properties are properties that does not change with the dimension, geometry, and shape of an object. It has been normalized.

- Failure Stress (N/m^2): Stress at failure

- Elastic Modulus (N/m^2): measures how much a subject deforms when a stress is applied to it.

- Resistivity (Ωm)

- Strength(σ_f)

*There is usually a complementary material property for a structural property.

Strength
Strength is defined differently for different material.

- Metal: The stress at which the stress-strain curve for axial loading deviates by 0.2% from the linear elastic line. (find 0.2% on strain axis then draw a line parallel to Young's Modulus, the intersection between the drawn line and the actual curve is the strength)

- Polymer: The stress at which the stress-strain curve becomes non-linear.

- Ceramics and Glasses: Depends on the mode of loading, for tension - fracture strength(σ_t), for compression - crushing strength (σ_c). Strength can also be measured in bending - flexure strength or modulus of rupture.

Toughness
Area under the stress-strain curve, the amount of energy required to fracture or the amount of energy stored while the material plastically deform.

Fracture Toughness
How resistant(amount stress) a material is to propagation of an existing crack.
*Ceramics have low fracture toughness(cracks in concrete) and low toughness(easy to fracture); polymers have high toughness(not easy to fracture) and low fracture toughness (easy to break once there is a crack in it), think of tapes.

Thermal Conductivity
The rate at which heat is conducted through a material when temperatures are fixed. It is a measure of whether heat transfers quickly(high) or slowly(low).

Thermal Diffusivity
It is the rate of an object with non uniform temperature reaches thermal equilibrium. It is a measure of whether the object heats up fast(high) or slowly(low).

Mechanical Loading

- Tie - in tension

- Beam - in bending

- Shaft - in torsion

- Column - in compression

Material Property Chart

A graph containing 2 material properties on the two axes.

Material Selection Steps

The first step in material selection is to define the function, objective, constraint, and free variables from the design requirement.

- Function: what the component must be able to do

- Objective: a parameter to optimize (maximize or minimize)

- Constraint: the condition the design must meet (hard or soft)

- Free Variable: what can be changed by the designer (material is always a free variable)

The second step in material selection is to screen and rank the materials that can be used for the design.

Screening

- Engineering Design must be unbiased, therefore all materials are equally possible initially.

- Constraints can be used to screen material.

Ranking

Ranking is to rank the remaining materials after screening base on their performance. Constraints and objectives are usually coupled through a free variable. The Constraints are used to eliminate the free variable in the objective equation. The resulting parameter to be maximized(optimized) is a material property that is refer to as the materials index. The objective equation can usually be separated into a functional, a geometry, and a material part. Always isolate for free variable in the constraint equation and substitute into the objective equation.

Shape Factor (ϕ)

Measure of improvement in performance by changing shape. It is the ratio between the stiffness of a given shape and a reference shape. Shape factor does not depend on size. The higher the shape factor, the better the shape performs compare to the reference shape. The reference shape is often a solid square.

Shape Factor in Bending

$$S = \frac{EI}{L^3}$$

$$I_{ref} = \frac{A^2}{12}$$

$$\phi_{Bending}^{Elastic} = \frac{S}{S_{ref}} = \frac{I}{I_{ref}} = 12\frac{I}{A^2}$$

Limits To Shape Factors

1. Empirical Limits

   - Imposed by manufacturing Constraints
   - Difficulty or expensive to make a given shape
   - Limitations may be intrinsic to material

2. Competing Failure Mechanism

   - New mode of failure may be more dominant
   - Reduce wall thickness lead to buckling...

Hybrid Material

Hybrid material is designed to fill the holes on the material property chart. It is a combination of two or more materials in a predetermined configuration, relative volume, and scale, optimally serving a specific purpose.

Types of Hybrid Material

1. Composite - made up of 2 materials, one for matrix and the other for reinforcement.

2. Sandwich - made up of 2 materials, one is the core, one is the outer surface.

3. Lattice - similar to form, but with a highly tailored order of material.

4. Segment - comprised of structural units of material that can be combined in either 2D or 3D.

Property of a Hybrid Material

There are 4 average behavior a hybrid material can have depending on how the hybrid material is designed.

1. Greatest Of Both - hybrid with the best properties of both components

2. Rule Of Mixture - weighted average of the properties of the two material base on their volume fraction

3. Harmonic Means - when the property is more dominated by the weaker one of the components

4. Least Of Both - hybrid with the weakest properties from one of the components

Density
Density of a hybrid material obeys the rule of mixture such that it solely depends on the volume fraction of the components.

$$\rho = V_{f1}\rho_1 + V_{f2}\rho2$$

Elastic Modulus
Elastic Modulus of a hybrid material not only depends on the volume fraction, but also the configuration(orientation, direction...) of the hybrid material. In this case, to predict the hybrid material's property, a lower bound and a higher bound of the elastic modulus are found instead of calculation every single combinations.

The upper bound estimate is given by when 2 materials are 2 fibers oriented parallel to the direction of loading. where the deformation of the first component is equal to the deformation of the second.

$$\epsilon_{hybrid} = \epsilon_1 = \epsilon_2$$

The stress for the hybrid material is therefore,

$$\sigma_{hybrid} = \sigma_1 V_{f1} + \sigma_2 V_{f2}$$

The upper bound estimate of the elastic modulus is then,

$$E = \frac{\sigma}{\epsilon} = V_1 E_1 + V_2 E_2$$

The lower bound estimate is given by when 2 materials are 2 fibers are oriented perpendicular to the direction of loading. The stress in the two materials must be the same.

$$\sigma_{hybrid} = \sigma_1 = \sigma_2$$

The strain parallel to the loading direction must only sum to give the imposed strain.

$$\epsilon_{hybrid} = V_{f1}\epsilon_1 + V_{f2}\epsilon_2$$

The lower bound estimate of the elastic modulus is then,

$$\frac{1}{E} = \frac{V_{f1}}{E_1} + \frac{V_{f2}}{E_2}$$

Sandwich Panel

Sandwich panel can be used as a light stiff panels in bending. Since most materials that has a low density also has a low elastic modulus. To achieve both objectives, notice that for a body in bending, most of the load is carried by the surface material => high modulus material for the surface, low density material for the core.

The modulus of a sandwich panel depends on the overall bending and from shear of the core, it is also sensitive to the volume fraction of the components.

Types Of Failure For A Sandwich Panel

1. Core Shear

2. Face Yield

3. Face Buckling

Potential of Lattice Structure

Stretch Dominated Lattices - perform better than foam because of highly order cell wall.

1 Multiple Constraints

When there are 2 constraints(two material indices), which constraint dominates? Find the constraint that is more limiting such that when that constraint is met, the other constraint is also met.

Strategy

1. Make a preliminary short list of materials by consecutive application of materials indices and material property charts.

2. From the initial list, make a table and calculate the free variable, objective

3. For each material, look at the prediction of the free variable/objective and pick the one that is most limiting.

4. From the table, pick the best material.

However, we cannot be sure that the initial screening did not screen out good potential material. Computer software is used to graph all material's variables with respect to different constraints and compare which material is best.

Compound Objectives

When they are competing objectives, one must look for trade offs. In Figure 1, a "trade off surface" is defined, which is a short list of possible, optimal solutions(Pareto Set). Alternatively, one of the objective can be turned into the constraint where the maximum value for an objective is fixed.
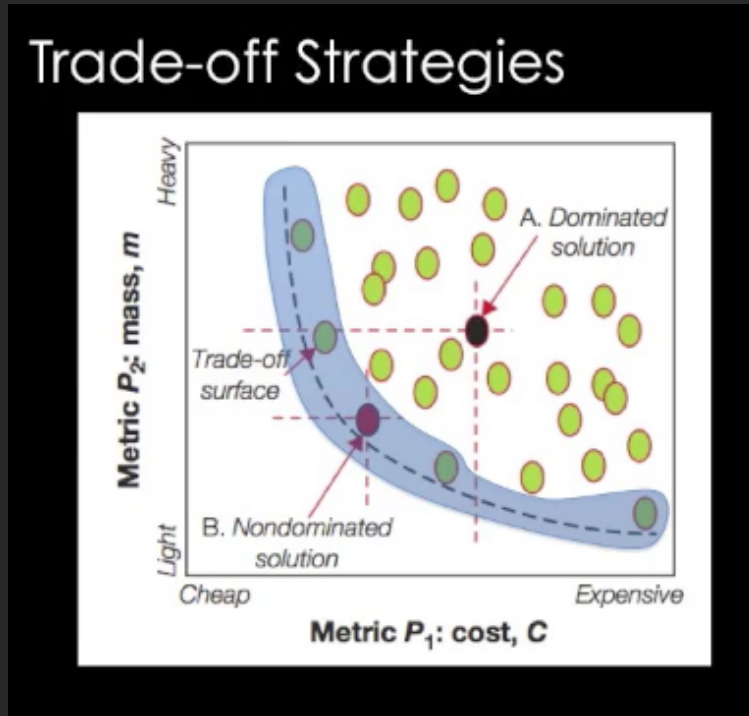

Figure 1: Cascode Amplifier

Penalty Function

Using tradeoff surfaces helps us to narrow down to a set of good possible solutions; however, there is no way to quantitively compare how good the different solutions are within the Pareto set. A penalty function compares different options from the Pareto set.

A penalty function is a linear combination of all objectives.

$$Z = \alpha_1 P_1 + \alpha_2 P_2 + ...$$

where alpha is a exchange constant that measures the rate of change of the penalty function with respect to each objective.

$$\alpha_i = \frac{\delta Z}{\delta P_i}$$

Example

Let Z be a penalty function for mass and cost.

$$Z = C + \alpha m$$
$$m = -\frac{C}{\alpha} + \frac{Z}{\alpha}$$

Different Z can be plotted on the graph of 2 objectives, and the best option will lie in the bottom left corner where Z is at a minimum.

Exchange Constant

Obtaining the exchange function is difficult. It can be found based on engineering criterial or market research, or political or socio-economic policy. The exchange function does not have to be a constant.