# StM1 Materials Selection Lab

## 1. Introduction

There are many materials you can choose from as an engineer to build your structure. This lab deals with how you choose a suitable material based on a set of requirements and constraints. A simple method is to look atexisting designs and find suitable materials that way. But here we aim to give you a different, more robust way of choosing materials by making you think about what the ideal properties of a material would be for a given application. This means that instead of looking at previous solutions you will learn to think of new materials for the future.

During this 1-hour lab you will first familiarize yourself with the CES EduPack software (20min). Then, you will derive material performance indices (20min) and learn how to present them in Ashby plots (20min). After this lab, your task is to do the material selection process for a lighter-than-air aircraft and write a group report about this. A template for the report is available on Blackboard.

*Learning Objectives:*

- Prepare Ashby plots using the CES EduPack software for different materials and properties.
- Assemble a set of relevant material performance indices for various structural applications.
- Assess suitable materials for different structural applications.

## 2. Introduction to CES EduPack 2017

CES Edupack provides a database of material properties and has interactive functions to compare many properties of different materials. It was developed on the work of Professor Mike Ashby who has written excellent books and papers on materials selection in mechanical design [1]. CES Edupack allows to easily apply his methods and compare different materials.

In many engineering problems, a trade-off must be made between multiple criteria and the same holds for materials selection. So-called Ashby plots are an effective way to compare materials, where material properties such as strength and density are plotted against each other as shown in Figure 1 below.

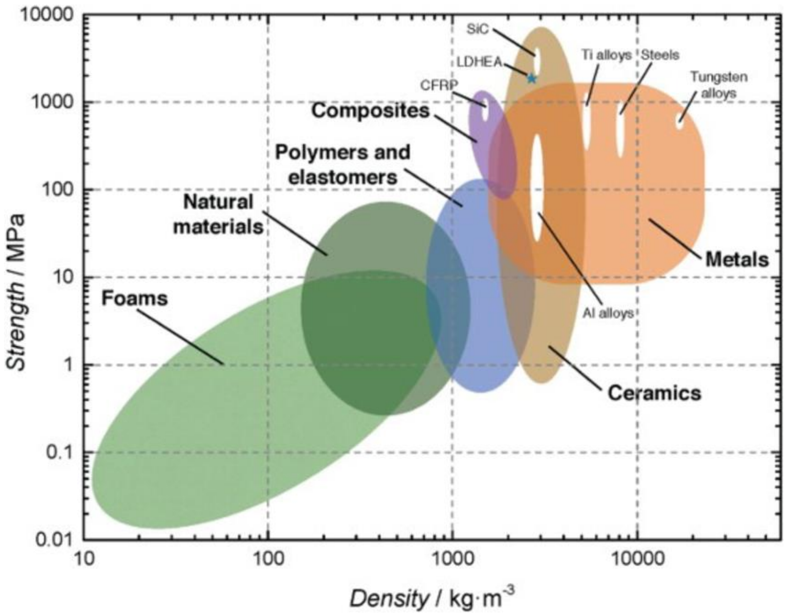



**Figure 1:** Ashby plot of strength versus density for engineering materials.

The first task of this lab is to create your own Ashby plot using the CES EduPack software. Follow instructions 1 to 7 on the CES Edupack tutorial PDF and have a look at the different materials.

# 3. Derivation of material performance indices

As an engineer, you are often faced with questions like the ones below:

- How suitable is a carbon fibre-epoxy beam in resisting impact loads?
- What material provides the best compressive strength for a given density and cost?
- What material is the cheapest and can still be used at 500 °C and maintain its shape?

How do you answer these questions given the many (>4000) engineering materials available, and many more composite and variations of them? We can make a guess and compare mechanical properties directly, but we lose important details for the specific function it needs to fulfil. Or, we can do a full analysis for each material in that given function but that will cost a lot of time (and money). An efficient method is needed to make a quick selection to answer the following question:

***How well does a material behave for a given structural function?***

And this is done using material performance indices. A material performance index is derived from a structural element (i.e. a beam, a damper, an impact absorber) which fulfils a certain function (carry loads, damp vibrations, absorb energy). How well a structural element performs in its function depends on three things:

1. The functional requirement(s): *what does it need to do?*
2. The geometry: *what is its shape?*
3. The material properties: *what are the material properties?*

Often the functional requirement, the geometry and material properties do not depend on each other. That means we can set up an equation and separate the materials requirements which is called a material performance index. Let's derive a material index for a beam in bending, for instance the spar beam of a commercial aircraft:

**Table 1:** Design requirements for a spar of a commercial aircraft

| | |
|---|---|
| **Function** | Wing spar; resist bending |
| **Constraints** | Length $L$ is a geometric constraint linked to the wing span<br>Beam must support load $F$ without exceeding a specified deflection. Hence requires a minimum bending stiffness of $S$ |
| **Objective** | Minimize mass $m$ |
| **Free variables** | Cross-section area $A$<br>Choice of material |

**Step I:** Let's look at the objective first, what is the mass $m$ of the beam given a certain length $L$ and cross-sectional area $A$, for a given density ρ?

| | |
|---|---|
| $m = A * L * \rho$ | Equation (1) |

**Step II:** The function of the beam is to resist bending without deflecting too much, write down the equation for the bending deflection of the beam below

| | |
|---|---|
| $\delta = \frac{FL^3}{3EI}$ | Equation (2) |

**Step III:** This is the most challenging part, we need to combine Equation (1) and Equation (2) to see what material property we need maximize to obtain the minimal weight. The trick here is to realize that the second moment of inertia $I$ scales with $A^2$ . So we can replace $I$ in Equation (2) with: $C_1 A^2$, where $C_1$ is some constant is independent of the material property. Now combine the two equations and obtain an expression for $m$ in terms of the bending deflection and other properties.

| | |
|---|---|
| $\delta = \frac{FL^3}{3EC_1A^2} \rightarrow A = \sqrt[2]{\frac{FL^3}{3EC_1\delta}}$ <br> $m = A * L * \rho \rightarrow m = \left(\frac{FL^3}{3EC_1\delta}\right)^{\frac{1}{2}} L\rho$ | Equation (3) |

**Step IV:** The last step is rearranging Equation (3) into constants, functional constraints, geometric constraint and material properties.

| | |
|---|---|
| $m = C_2 \left(\frac{F}{\delta}\right)^{\frac{1}{2}} (L)^{\frac{5}{2}} \left(\frac{\rho}{E^{1/2}}\right)$ | Equation (4) |

This will give you the material performance index for a light and stiff beam:

| | |
|---|---|
| $M = (E^{1/2} / \rho)$ <br> Min (m) $\rightarrow$ max $(E^{1/2} / \rho)$ | Equation (5) |

The derivation of material performance indices is not always trivial. It has, however, been done for many cases already which are documented in text books and on the CES Edupack software. Now, let's see how we can plot that on our Ashby chart. Let's take our material performance index:

$$M = E^{1/2}/\rho$$

The Ashby chart is on a logarithmic scale, so we need to take the logarithms on both sides:

$$\log (M) = \log (E^{1/2}) - \log (\rho)$$
$$\log (E^{1/2}) = \log (\rho) + \log (M)$$
$$\log (E) = 2 \log (\rho) + 2 \log (M)$$

This shows that the materials with the same value of $M$ lie on a line on the log(E) vs. log (ρ) graph with slope 2. And the higher values of $M$ are found with the highest lines on the log(E) vs. log (ρ).

Go back to the CES Edupack tutorial PDF and follow steps 8 to 14.

The loads applied to most structures can typically be decomposed into axial, bending and torque. It is also important to note their efficient cross-sectional shapes that can carry these loads, eg: *I* section for bending and hollow shaft for torque. A ratio of the effective stiffness for the loading of the shape to a reference cross section is used to measure the efficiency of the shape and defined as the shape factor, φ.

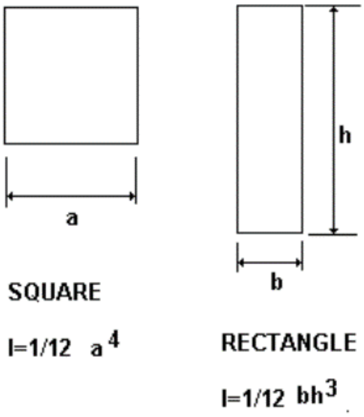



**Figure 2:** Second moment of inertia for square and rectangular sections

In the case of wing spar assuming two cross-sections with same cross-sectional area, *A* and made of material with Young's modulus, *E*.

Then for a component subjected to bending, shape factor is the ratio of the bending stiffness of rectangular beam S to the reference bending stiffness of the square cross-section S*

| | |
|---|---|
| $\phi = S/S^*$ | Equation (6) |

The bending stiffness, $S^*$ and S

| | |
|---|---|
| $S = EI/L^3$ <br> $S^* = \frac{EI_0}{L^3} = E\frac{A^4}{12\,L^3}$ | Equation (7) |

Therefore, the shape factor

| | |
|---|---|
| $\phi = \frac{12I}{A^2}$ | Equation (8) |

Now to obtain material-shape performance index of the rectangular cross-section, apply in equation (2) and derive the modified equation (5) in the form:

| | |
|---|---|
| $m = C_2\left(\frac{F}{\delta}\right)^{\frac{1}{2}}\ (L)^{\frac{5}{2}}\ \left(\frac{\rho}{(\phi E)^{1/2}}\right)$ | Equation (9) |

To represent the effect of shape graphically rearrange the modified material performance index

| | |
|---|---|
| $M = \frac{(\phi E)^{1/2}}{\rho} = \frac{(E/\phi)^{1/2}}{\rho/\phi} = E^*/\rho^*$ | Equation (10) |

Plot (E*, ρ*) on the Ashby plot (Figure 1) to compare it with other shape-material combinations. A similar derivation can be applied to the shape factor for torqued components.

Shape factor is critical as each material is limited by the manufacturing process to be formed into certain shapes. For example, it is difficult to form a thin walled hollow section using wood on the other hand Aluminium hence improving the performance index.

**Important note:** Shape factor does not change if the shapes are being scaled (Figure 5).

# 4. Material selection for lighter-than-air aircraft

The Phoenix aircraft (Figure 3) is a prototype, unmanned, lighter-than-air blimp which can move up and down by changing its volume. This vertical motion is converted into horizontal motion by the wings such that a forward movement is possible without a propeller. This allows the aircraft to efficiently cover distances and stay up in the air for a long time. The ultra-endurance performance of the Phoenix aircraft gives it the edge for a variety of applications such as surveillance missions or communication solutions.

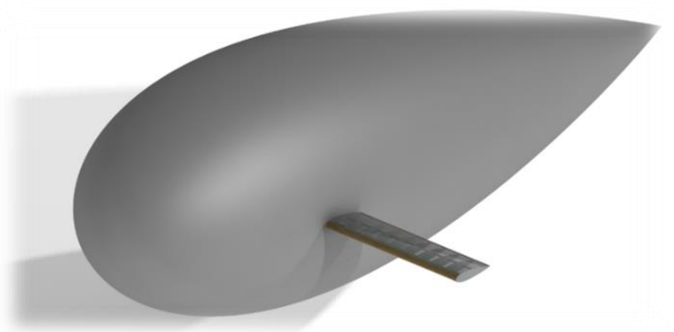


**Figure 3:** Early design concept of lighter-than-air Phoenix aircraft

The aircraft currently is in an early-design phase with a simple wing structure consisting of two spar beams, ten ribs, a leading-edge curved plate and a trailing edge rod. The wing span is 3m and the chord length is 1m. The skin is made from a polyester film which is shrunk around this structure. A schematic overview of the wing structure is shown in Figure 4 and a demonstrator was made with laser cut MDF ribs and hardwood dowel rods. The design needs to be changed as the goal is to have a maximum weight of 3kg for the wings.

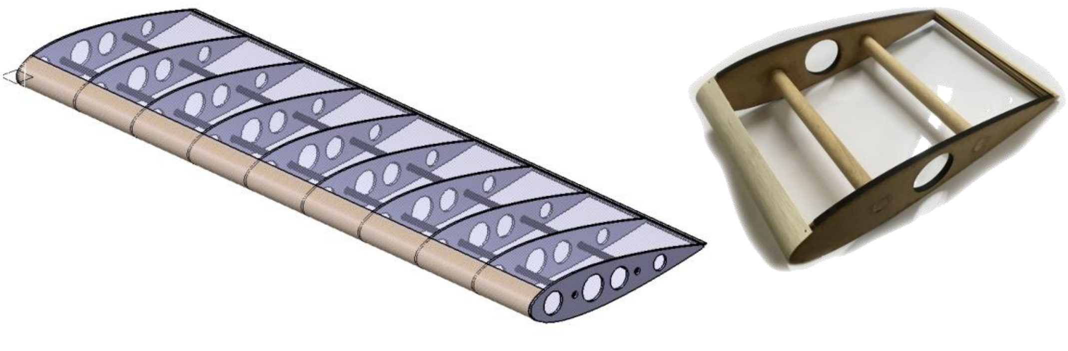


**Figure 4:** Wing design showing two spar rods, ribs and LE

The spars resist bending, and the wing ribs are loaded with the so-called Brazier load when the wing is subjected to bending. The Brazier load tries to flatten the ribs and causes a compressive force as shown in Figure 6.

For the wing spars, the shape is not determined yet which means the shape factor depends on the geometry of the spar. The exact dimensions are unknown yet, so to help you choose a material you can assume the standard shape factors shown in Figure 5. They give a ballpark figure for the shape factor of the cross section.

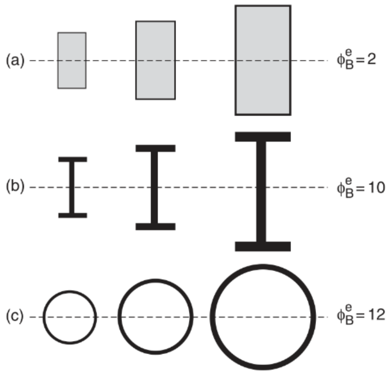



**Figure 5:** Shape factors of different cross sections

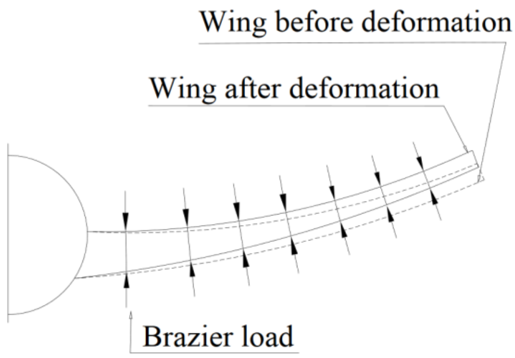



**Figure 6:** Schematic representation of Brazier loading

Your assignment is to investigate different materials for the spars and the ribs of the wing. You need to write a report documenting the material selection process and how the current wooden demonstrator may be improved. To do this, you will use CES Edupack 2017 and the material selection process explained to you in the lectures.

Your tasks are:

- Perform the material selection process for the spars
  - Set up function, constraints, objective and free variables for the spars.
  - Derive/choose suitable material performance indices to compare materials
  - Implement shape factor for; an I-beam and a hollow tube.
  - Show Ashby plots and discuss material options with respect to current hardwood design.
- Perform the material selection process for the ribs
  - Set up function, constraints, objective and free variables for the rib.
  - Derive/choose suitable material performance index.
  - Show Ashby plots and discuss material options with respect to current MDF design.

To help you, the design requirements are given in Table 2 and 3, but you need to think about the main constraints for each part. There are many constraints you could define for each part in an aircraft, from chemical resistance to electrical conductivity. For this assignment, however, you need to define one structural constraint per part and show an accompanying Ashby plot with the material performance index in the results section. This will give you a (pre)selection of materials. In your discussion, you can discuss secondary constraints and assess which material seems most suitable.

**Table 2**: Design requirements for wing spars

| | |
|---|---|
| **Function** | Resist bending |
| **Constraints** | …………… |
| **Objective** | Minimize mass *m* |
| **Free variables** | Choice of material<br>Choice of cross section (solid, I-beam, hollow tube) |

**Table 3** Design requirements for wing ribs

| | |
|---|---|
| **Function** | Maintain aerodynamic shape |
| **Constraints** | ……………. |
| **Objective** | Minimize mass *m* |
| **Free variables** | Choice of material |

# 5. Closing comments

Here are a few tips:

- This assignment is on material selection process, make sure you clearly show this process in your report: state your assumptions and clearly show the arguments that help you make your material selection
- You may find materials in your results that you might find unsuitable or you think won't work. Use your discussion to mention reasons (other requirements/constraints) why some materials may be unsuitable and how you would improve the material selection process to take those requirements into account.
- Quick link to Ashby's book on Material Selection at UoB library: https://goo.gl/EZArxo

# References

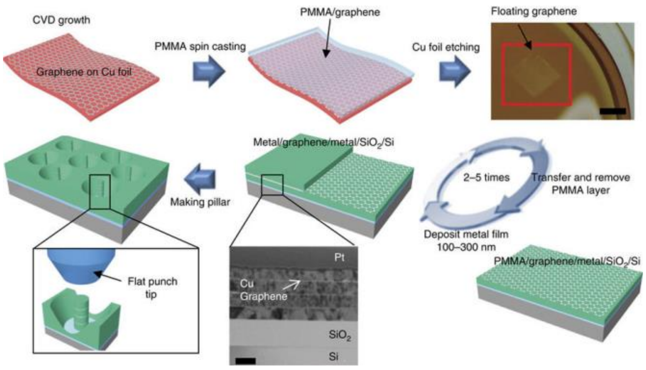
[1] M. F. Ashby, *Materials selection in mechanical design*, 3rd ed. Oxford: Elsevier Butterworth-Heinemann, 2005.

# Appendix I: Some interesting developments

A material that has properties not found in nature? Impossible right? Yes and no…Metamaterials are materials that have engineered microstructures (like repeating nanopatterns) and exhibit properties on the macrolevel that are not found in nature. It is where structures and materials intertwine, some cool examples:

**Ultra-high-strength metamaterial developed using graphene**

A new metamaterial has been developed exhibiting hundreds of times greater strength than pure metals.




To maximize the increase in strength imparted by the addition of graphene, the KAIST research team created a layered structure of metal and graphene. Using CVD (Chemical Vapor Deposition) the team grew a single layer of graphene on a metal deposited substrate then deposited another metal layer and repeated the process to produce a metal-graphene multilayer composite material that, achieving a world first in doing so, utilized single layer of graphene.

Micro-compression tests within Transmission Electronic Microscope and Molecular Dynamics simulation effectively showed the strength enhancing effect and the dislocation movement on an atomic level. The mechanical characteristics of the graphene layer within the metal-graphene composite material successfully blocked the dislocations and cracks from external damage from traveling inwards. Therefore, the composite material displayed strength beyond conventional metal-metal multilayer materials.