16.001 - Materials & Structures

Unified Materials and Structures Lab 1

Instructor: Raúl Radovitzky
Teaching Assistant: Grégoire Chomette
Department of Aeronautics & Astronautics
M.I.T.

Contents

1 Overview

In this laboratory, you will get hands on experience with engineering materials and structures through

- Material tensile strength testing (Material Tensile Testing Lab)
- Measuring loads within members of a Howe truss (Truss Lab)

The material tensile testing lab is framed like a detective exercise, where you are required to identify four unknown materials from a larger list of 25 materials (see Appendix A) based on your analysis of data obtained from the tensile testing. The truss lab is focused on comparing theoretical predictions with experimental data for a Howe truss structure. This lab complements the theory lectures in Unified Materials & Structures.

1.1 Measurable Outcomes:

The measureable outcomes of this lab are as follows:

- MO1: To determine Young's Modulus, yield strength, ultimate strength, and elongation at failure for an unknown material from data obtained from material tensile strength testing
- MO2: To uniquely identify a material by using experimentally obtained values for its material properties along with Ashby charts and materials databases
- MO3: To determine the loads acting upon a physical structure using load cells
- MO4: To contrast and compare theoretical versus experimental loads and displacements for a simple "planar" truss structure

2 Material Tensile Testing Lab

In this lab, you will perform tensile testing on four different dogbone shaped specimens, each made of a different material. The testing will be done using a Zwick machine (a more popular machine brand is Instron which is not available to us for this test). This machine will apply a tensile load to the specimen and increase it steadily until the material fails. During the process, the force applied is measured by a *load cell* and the elongation displacement is measured by sensors which know the location of the device loading surfaces with high precisions. The data is recorded by specialized software throughout the duration of the test.

An example of a material dogbone specimen is shown in Figure 1. A separate test will be performed for each specimen. Based on the data you obtain from the tests, you must determine which four materials the provided dogbones are made up of. These four materials are included as a subset of the master list of materials provided in Appendix A.

Figure 1: A Dogbone Specimen on which tensile testing will be performed

2.1 Directions for Tensile Testing

The directions for the lab are as follows:

1. Pickup a set of four material dogbone samples from the lab instructor, and use the provided calipers and weights scales to determine the dimensions, volume, and density of the material samples.

2. Once you are done, the lab instructor will place your sample in the Zwick machine, and run the program to perform the tensile test, until the dogbone fails. The tensile test will be performed for each of the four dogbone samples, resulting in load-displacement data for each of the four samples. You will need to convert this data to a stress-strain curve, identify several important parameters, and ultimately determine which dogbone corresponds to which material.

3. Take the raw data from your test session at the end of the test. **The computer used to run the Zwick and store the raw data is not connected to the internet, so please bring a USB**.

During the tensile testing, you may want to take note of any ”special” events occurring during the test session. The material samples will be stressed to different points along their stress-strain curve, so it may be helpful to correlate any physical observations you make during the test to points in the data you receive afterwards.

2.2 Safety Instructions for Tensile Testing

Please acknowledge the following safety procedures:

- Safety glass are located outside of the testing lab, and inside as well. Please make sure to wear one upon entering and performing the tensile tests.

- Be sure to wear close-toed shoes and long pants to enter the lab

- Follow the instructions of the laboratory instructor.

3 Truss Lab

In this lab, we will load two Howe trusses and compare the theoretically predicted and experimentally observed loads experienced by three of the truss members (Members 5, 6, and 7 in Figure 3). A schematic of our Howe truss (consisting of two geometrically identical trusses) is shown in Figure 2, with dimensions given.

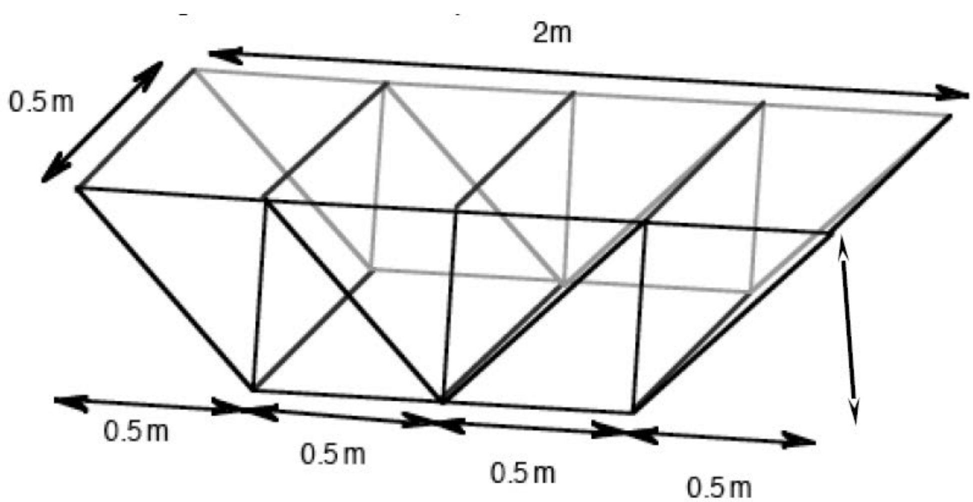


Figure 2: Howe Truss Geometry

The lab setup for the Howe truss in this lab is shown in Figure 3. Our particular truss geometry consists of four bays of the same length. The height of each bay is equal to its length of 0.5 meters. The intervening members have the same length as the length of each bay (0.5 meters). Additionally, the overall span is 2 meters. Testing will be performed on two different trusses; one made of steel and one made of aluminum.

The lab will take place in the AeroAstro Building 33 Hangar. The lab will be performed in groups of four to five students over the one hour period, with two groups present for each lab session. For the first half of the period, one group will perform testing on the steel truss while the other performs testing on the aluminum truss. Afterwards, the groups will perform testing on the other truss, so that data is obtained for both the aluminum and steel truss.

The truss systems utilized in this test are configured so that the "planar truss" assumption used in the model holds. The following assumptions can be made about the actual truss configuration:

1. The system is simply supported by a pin and a roller (no static indeterminacy).
2. The load that the structure must support is evenly distributed between each of the two 2D-trusses. Thus, for each two-dimensional truss, the applied load P is modeled as a point load, equal to half of the total load $2P$, concentrated at the joint at the mid-span of the truss.

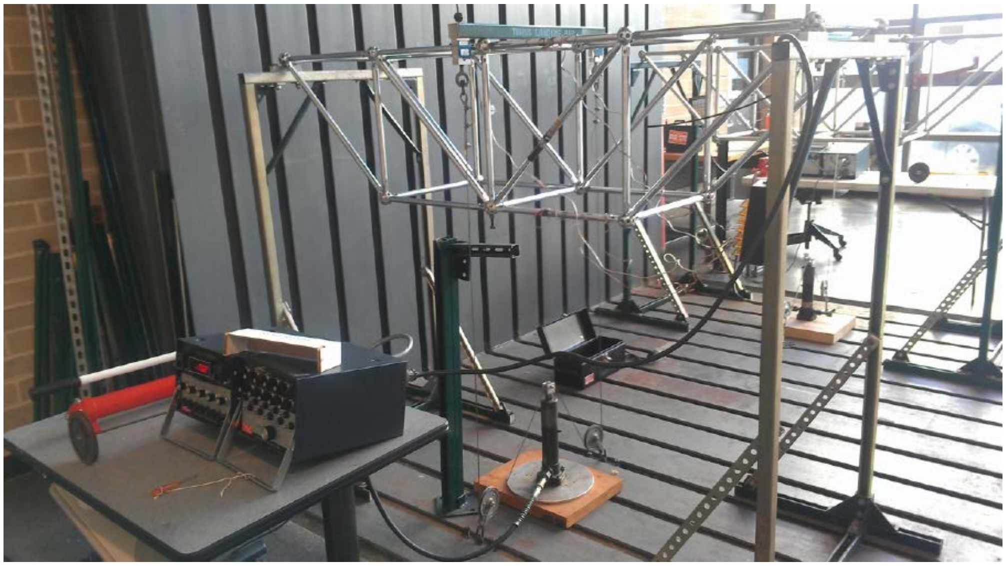


Figure 3: Howe Truss Lab Setup

3. The normal assumptions associated with "idelalized planar (two-dimensional) trusses":
   (a) All bars are straight
   (b) Bar joints are frictionless pins
   (c) Bars have no mass
   (d) All loads and reactions are applied at the joints
   (e) Loads in truss members are aligned with the member axis, and thus, carry only axial forces

The idealized configuration of our truss experiment is shown in Figure 3.

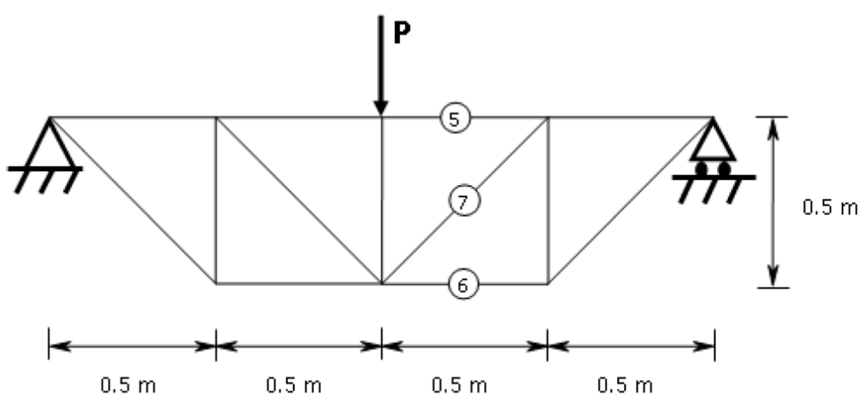


Figure 4: Idealized Howe Truss Configuration. The internal forces in members 5, 6, and 7 will be measured and compared to theoretical predictions.

3.1 Directions for Truss Lab

The directions for this lab are as follows:

1. **Before the lab:** Perform a hand calculation to determine the expected loads in Members 5, 6, and 7 as shown in Figure 3 (hint: use the method of sections for truss analysis). Your loads should be represented as a function of the applied load P. Note that we will follow the standard convention where positive loads correspond to members in tension, and negative loads correspond to those in compression. Record these predicted loads and bring them to your scheduled truss lab test session.

   We also recommend that you bring a laptop to the lab. This will allow you to perform your analysis in real time and record your data in a spreadsheet.

2. A TA or instructor will be present at the lab and will give you a summary of the operation of the setup, and will then instruct your group on how to check the calibration of the load cells.

3. Make sure that all the read outs in all of the acquisition channels are at zero when the truss is unloaded.

4. Apply up to **five different load levels** on each truss setup (the values of these loads are up to you but should NOT exceed the maximum allowable load indicated in the lab).

   Your task is to record the applied load at each level and the resulting loads in Members 5, 6, and 7, as well as the corresponding vertical displacement of the truss. Additionally, you are to apply each load level for a total of five different trials. Thus, you should have 25 different trials (5 trials for each load level). These trials should be performed on BOTH the aluminum and steel trusses.

5. Data analysis and comparison with model: groups must share the recorded data. Each student must make sure they have a complete set of data after the test. Perform a post-experiment analysis of the data as follows in the next section.

Please provide the following deliverables, labeling axes and provide legends where appropriate for plots:

1. For each sensor 5, 6, and 7, create a plot of the measured load vs. applied load. On the same figure, plot the results for all five tries in each truss. Use one color/line style for the aluminum truss results and another for the steel truss results. Include a legend.

2. In each of the three figures, add a plot of the theoretical values of the loads on the respective bar as a function of the applied load (use a different color/line style).

3. Include this figure in your report and comment of the observed variability of the results across the different tries and for the two different trusses. Should the two trusses give the same results? Why or why not? Do you observe any type of systematic experimental errors? What about random errors? What is the order of the experimental error you observe for each sensor in the two trusses?

4. Compare the experimental results with the theory predictions. Quantify the discrepancy between model and experiments and comment on the possible sources of discrepancy. What is the maximum difference observed between the two?

5. Create a fourth figure with a total of 10 plots, 5 load displacement curves corresponding to the tries for each truss. Again, use color/line style for the aluminum results and another for the steel results.

6. Write up your results and submit to Stellar.

4 Deliverables

Please write up a report containing the following items:

1. Description of the material tensile test, all calculations, measurements taken, the results including plots of the stress-strain curves obtained and inferred mechanical properties for the materials, and, finally, the conclusions about the materials you think you tested based on a comparison to the candidate list.

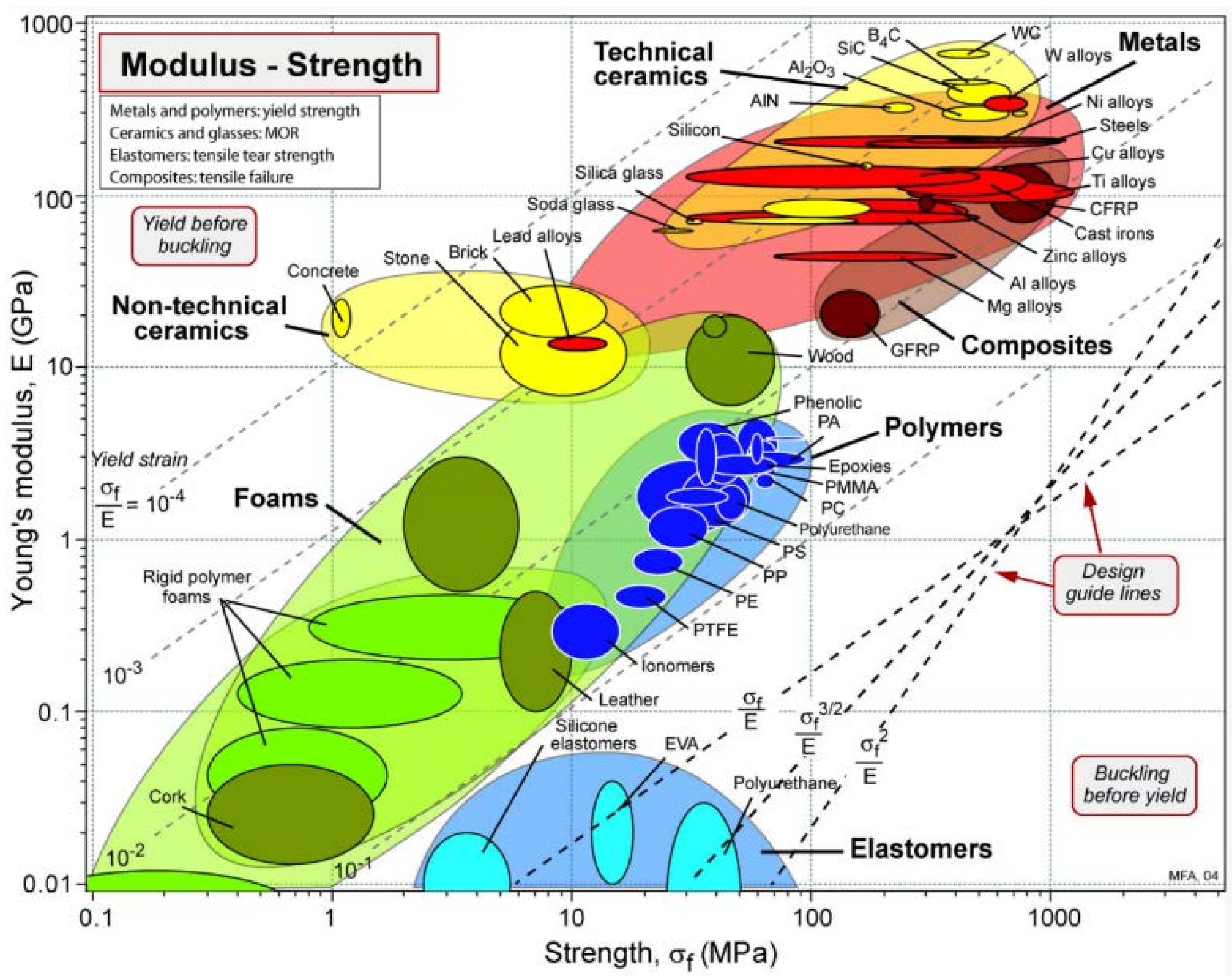
2. Description of the truss lab, all hand calculations, and answers/plots for the questions/deliverables in the Truss Lab section.

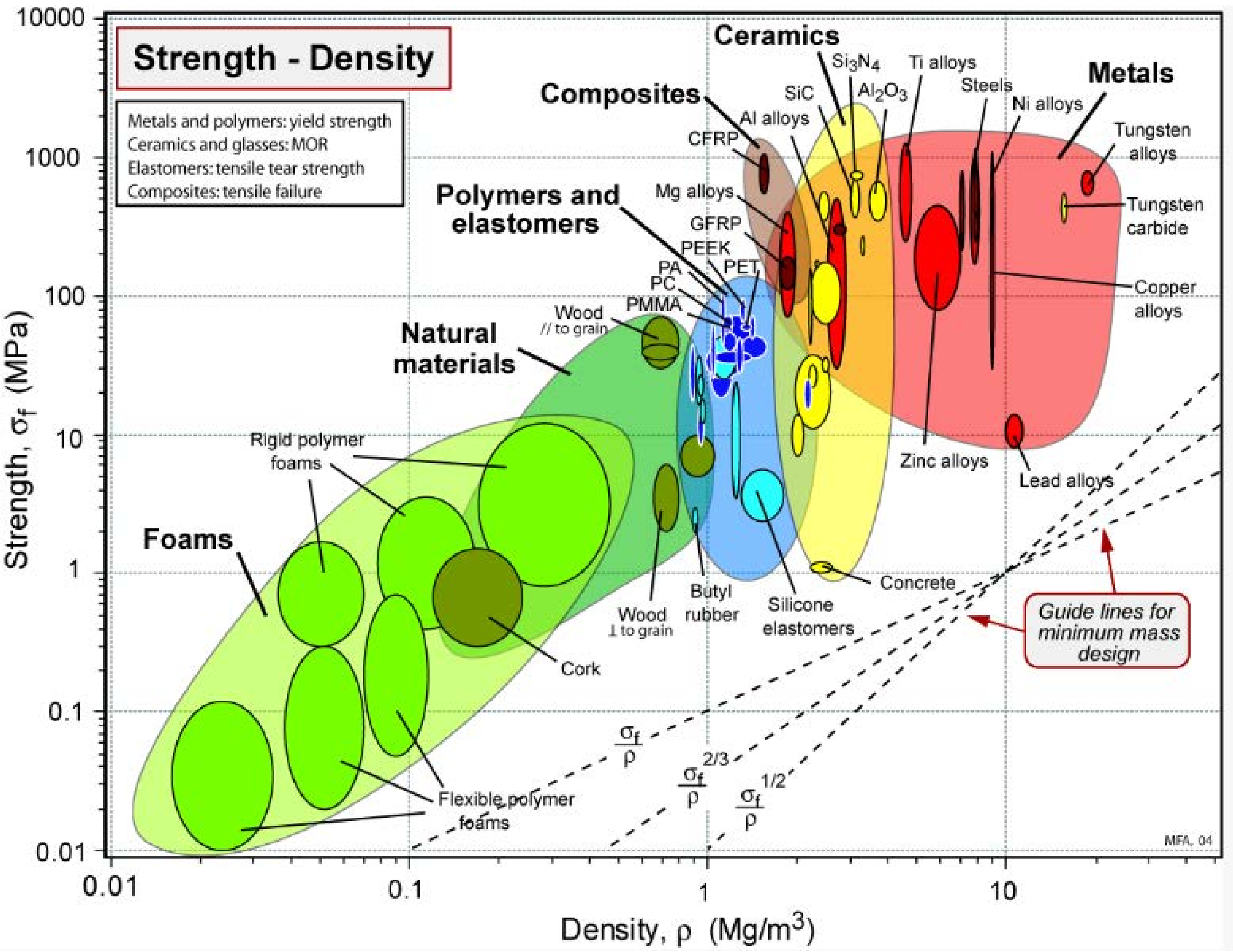
Appendices

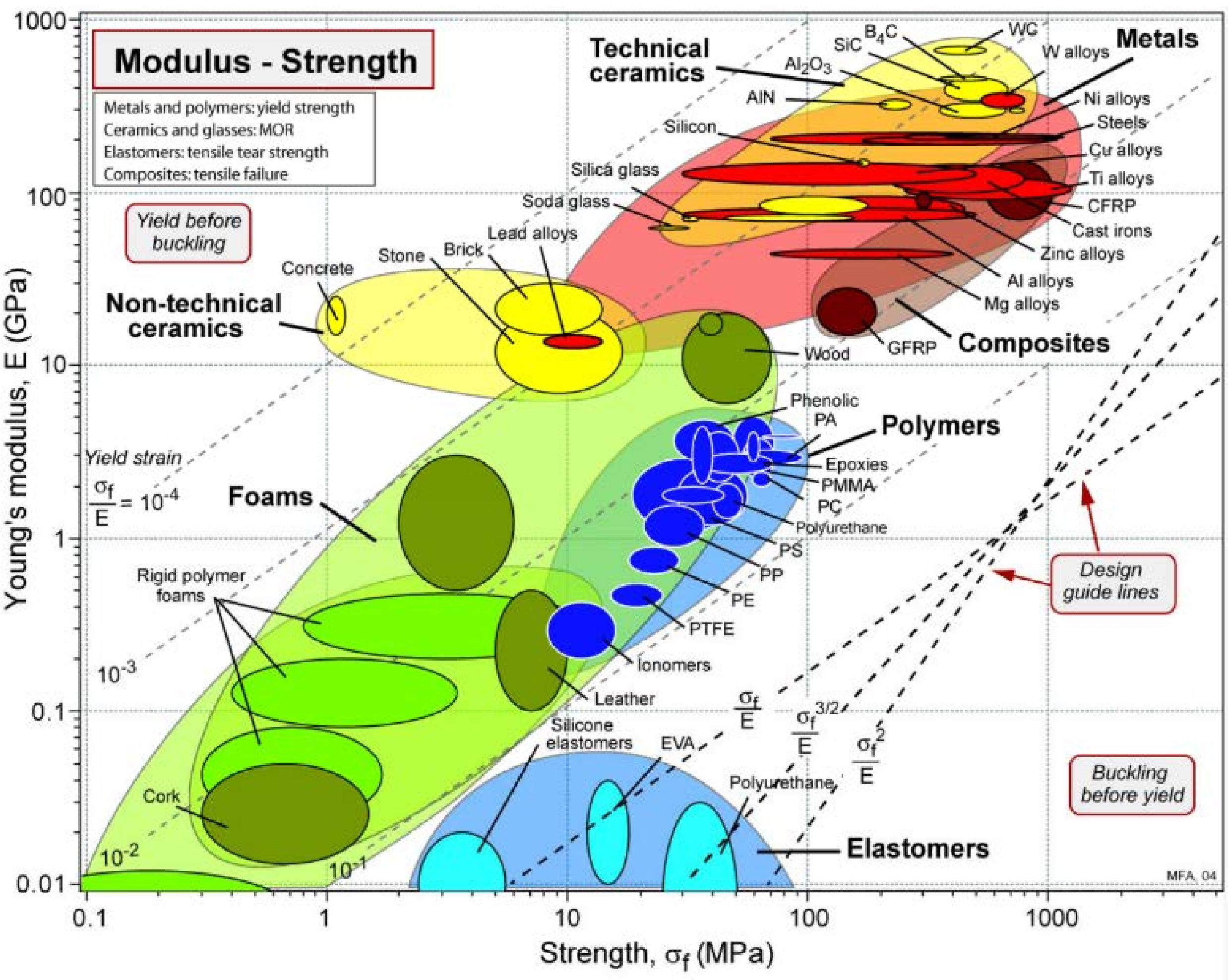
A Appendix A: Candidate List of Materials

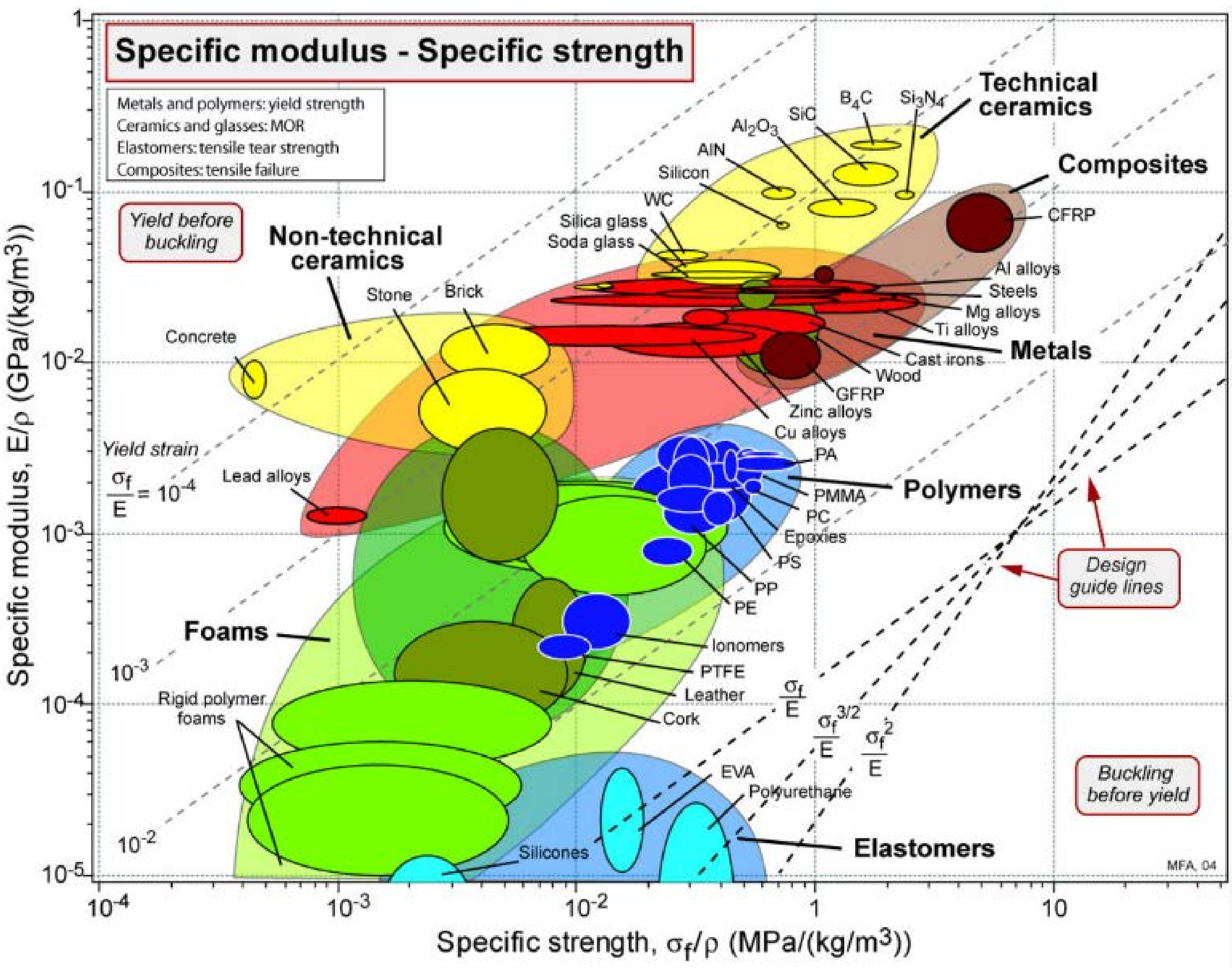
Each of the four mystery materials is represented in this master list of 25 materials; it is your job to find out which ones they are! Use either the Ashby diagrams on the following pages and/or the search tool at www.matweb.com (you may need to register for an account) to help you pinpoint the materials.

1. Acetal Copolymer, unreinforced
2. Borosilicate Glass
3. Steel 1018 (low carbon)
4. Titanium - Grade 2
5. Fe-Co-Ni Superalloy
6. Pure Aluminum - 100%
7. PMMA Acrylic - Cast Grade
8. Graphite Epoxy
9. AISI 1340 Steel, annealed at 800^o F
10. Aluminum Alloy 6061
11. Beryllium I-200H Grade 1
12. American Beech Wood
13. Kevlar Fiber Composite AS4C (3000 filaments/inch)
14. Lead-Tin Babbit Alloy
15. Titanium Ti-6Al-2Nb-1Ta-0.8Mo
16. Northern White Pine
17. Aluminum 5052-H32
18. General Purpose Nylon
19. 0-45-90 Carbon Fiber Composite Layup
20. Stainless Steel Type 304
21. Aluminum 2014-T4
22. American White Oak Wood
23. Lead-Tellerium-Cooper Alloy, UNS L51123
24. Ferro Zirmonite 200, ZTA
25. Tropical Balsa Wood


Modulus - Strength
Metals and polymers: yield strength
Ceramics and glasses: MOR
Elastomers: tensile tear strength
Composites: tensile failure
Yield before buckling
Buckling before yield
Design guide lines
Technical ceramics
Metals
Non-technical ceramics
Foams
Polymers
Composites
Elastomers
Young's modulus, E (GPa)
Strength, σ_f (MPa)
Yield strength
$\frac{\sigma_f}{E} = 10^{-4}$
$\frac{\sigma_f}{E}$
$\frac{\sigma_f^{3/2}}{E}$
$\frac{\sigma_f^2}{E}$
WC
B_4C
SiC
Al_2O_3
AlN
W alloys
Ni alloys
Steels
Cu alloys
Ti alloys
CFRP
Cast irons
Zinc alloys
Al alloys
Mg alloys
GFRP
Silicon
Silica glass
Soda glass
Lead alloys
Brick
Stone
Concrete
Wood
Phenolic
PA
Epoxies
PMMA
PC
Polyurethane
PS
PP
PE
PTFE
Ionomers
Leather
Rigid polymer foams
Cork
Silicone elastomers
EVA
Polyurethane
MFA, 04


Strength - Density
Metals and polymers: yield strength
Ceramics and glasses: MOR
Elastomers: tensile tear strength
Composites: tensile failure
Ceramics
Si3N4
SiC
Al2O3
Ti alloys
Steels
Ni alloys
Metals
Tungsten alloys
Tungsten carbide
Copper alloys
Composites
Al alloys
CFRP
Mg alloys
GFRP
Polymers and elastomers
PEEK
PA
PET
PC
PMMA
Wood // to grain
Natural materials
Rigid polymer foams
Foams
Zinc alloys
Lead alloys
Concrete
Butyl rubber
Wood ⊥ to grain
Silicone elastomers
Cork
Guide lines for minimum mass design
Flexible polymer foams
MFA, 04
Strength, σf (MPa)
Density, ρ (Mg/m3)
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10


Modulus - Strength
Metals and polymers: yield strength
Ceramics and glasses: MOR
Elastomers: tensile tear strength
Composites: tensile failure
Yield before buckling
Buckling before yield
Design guide lines
Technical ceramics
Metals
Non-technical ceramics
Composites
Polymers
Foams
Elastomers
WC
B4C
SiC
Al2O3
AlN
Silicon
Silica glass
Soda glass
Lead alloys
Brick
Stone
Concrete
W alloys
Ni alloys
Steels
Cu alloys
Ti alloys
CFRP
Cast irons
Zinc alloys
Al alloys
Mg alloys
GFRP
Wood
Phenolic
PA
Epoxies
PMMA
PC
Polyurethane
PS
PP
PE
PTFE
Ionomers
Leather
Rigid polymer foams
Cork
Silicone elastomers
EVA
Polyurethane
Yield strain
$\frac{\sigma_f}{E} = 10^{-4}$
10^{-3}
10^{-2}
10^{-1}
$\frac{\sigma_f}{E}$
$\frac{\sigma_f^{3/2}}{E}$
$\frac{\sigma_f^{2}}{E}$
Young's modulus, E (GPa)
Strength, σ_f (MPa)
MFA, 04



Specific modulus - Specific strength
Metals and polymers: yield strength
Ceramics and glasses: MOR
Elastomers: tensile tear strength
Composites: tensile failure
Yield before buckling
Non-technical ceramics
Technical ceramics
Composites
Metals
Polymers
Foams
Elastomers
Design guide lines
Buckling before yield
Yield strain
Concrete
Stone
Brick
Lead alloys
Rigid polymer foams
Silica glass
Soda glass
WC
Silicon
AlN
Al2O3
SiC
B4C
Si3N4
CFRP
Al alloys
Steels
Mg alloys
Ti alloys
Cast irons
Wood
GFRP
Zinc alloys
Cu alloys
PA
PMMA
PC
Epoxies
PS
PP
PE
Ionomers
PTFE
Leather
Cork
EVA
Polyurethane
Silicones
MFA, 04
Specific modulus, E/ρ (GPa/(kg/m3))
Specific strength, σf/ρ (MPa/(kg/m3))

B Appendix B: Analyzing Material Tensile Strength Testing Data

For each material, you will obtain the following tabulated data in a spreadsheet:

- Load experienced by the material sample in Newtons
- Elongation of the material sample in millimeters

Additionally, you will also be able to calculate the cross-sectional area of the material sample.

- **Correction of measured elongation data**

  In general, depending on the utilized measurement technique, the collected elongation data may not directly correspond to the actual elongation of the tested specimen. For instance, in the setup of our tensile testing machine, we actually measure the vertical displacement of the crosshead of the testing machine. This displacement is not exactly equal to the actual elongation of the tested specimen. Among other things, the elongation measured in this way also accounts for the elongation of (a part of) the testing rig. In order to avoid this issue, more sophisticated measurement techniques can be used, for instance extensometers or optical devices that are applied directly to the thin section of the tested specimen.

  Therefore, in case of our measurement technique, it can be helpful to correct the measured raw elongation data by removing the part pertaining to the elongation of the testing rig which will yield more accurate values for the actual elongation of the tested specimen. One relatively coarse approach to do this is to assume that the stretched part of the testing rig behaves like a linear spring of stiffness k^{rig} and that that spring is connected in series to the tested specimen. This scenario is depicted in Figure 5.

  Consider the following quantities:

  - Elongation of specimen: $\delta = L - L_0$
  - Elongation of testing rig: $\delta^{\mathrm{rig}} = L^{\mathrm{rig}} - L_0^{\mathrm{rig}}$
  - Stiffness of testing rig (Hooke's law): $k^{\mathrm{rig}} = F/\delta^{\mathrm{rig}}$
  - Total measured elongation: $\delta^{total} = \delta + \delta^{\mathrm{rig}}$

  Therefore, the elongation δ of the specimen can be determined from the measured total elongation δ^{total} as follows:

$$\delta = \delta^{\mathrm{total}} - \delta^{\mathrm{rig}} = \delta^{\mathrm{total}} - \frac{F}{k^{\mathrm{rig}}} \tag{1}$$

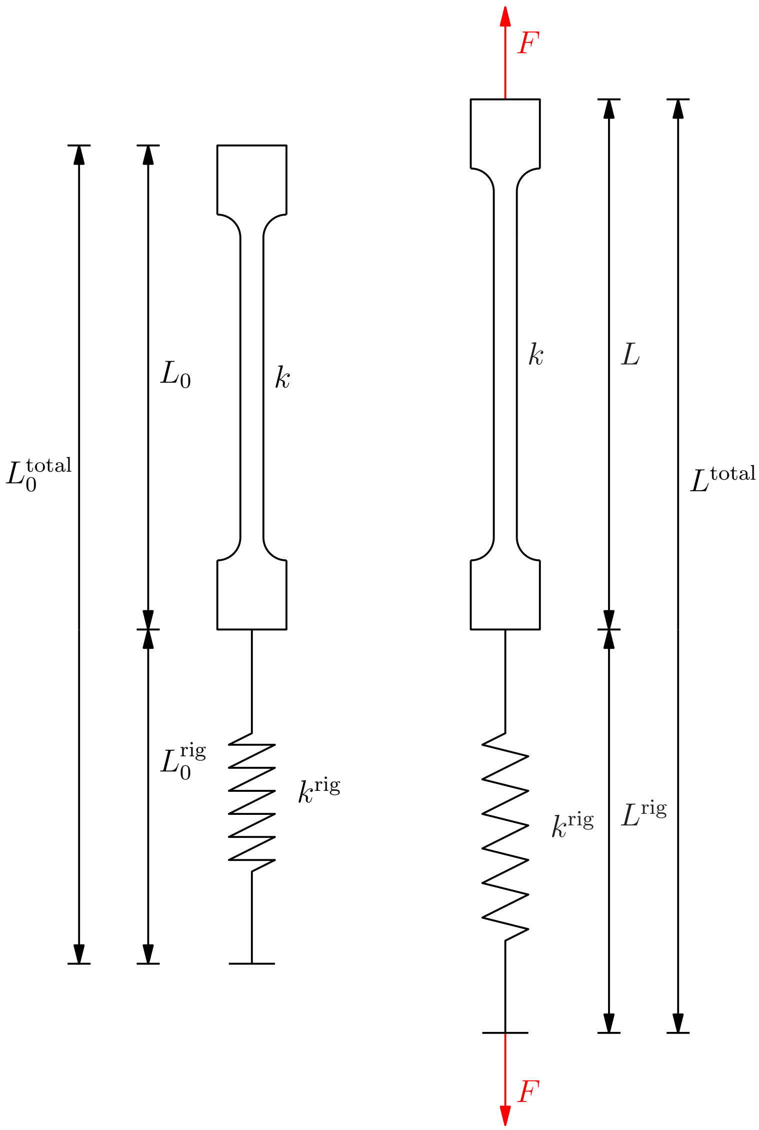


Figure 5: Left-hand side: serial connection of the unstretched specimen and the unstretched testing rig (depicted as a spring); right-hand side: serial connection of the stretched specimen and the stretched testing rig.

For our tensile testing machine, the following approximate value for the stiffness of the testing rig was found:

$$k^{\mathrm{rig}} \approx 4{,}000 \, \frac{\mathrm{N}}{\mathrm{mm}} \tag{2}$$

Using the outlined approach, more realistic values for the Young's moduli and the elongations at failure (which are described in the following) pertaining to the tested specimens can be obtained.

- **Stress-strain curve**

  In order to obtain the desired material properties, you will need to convert the Load vs Elongation data into a Stress vs Strain curve. The axial stress, since we are loading our material samples along a longitudinal axis, is given by

  $$\sigma = \frac{F}{A} \tag{3}$$

  where F is the applied load, and A is the cross sectional area of the material.

  Additionally, strain is the change in length, L, of a material under a given load, normalized by its original length L_0. In our tensile testing experiment, it may also be regarded as the elongation of the specimen, normalized by the original length L_0, so that

  $$\epsilon = \frac{L - L_0}{L_0} = \frac{\delta}{L_0} \tag{4}$$

  where δ is the elongation, L_0 is the original length of the specimen, and L is the current length of the specimen.

  Any property that is related purely to stress values (e.g. yield stress and ultimate strength) should be determined from a plot of Stress vs Strain as measured from the machine using Equation 3. Any property that that requires some measurement of strain (e.g. Young's Modulus and elongation at failure) should be determined from your best estimate of strain, from Equation 4, over time.

  Plotting the Stress vs Strain curve will allow you to see the elastic and plastic regions within the material more clearly, and should yield something that resembles the basic shape shown in Figure 6. This plot shows the strain as recorded by the tensile strength testing machine (you will only receive force-elongation data from the machine, which you will need to postprocess into stress vs strain). Some materials may not experience a plastic region and may experience a brittle failure, so that the stress-strain curve may look quite different from Figure 6.

Some notes on computing each of the desired material parameters:

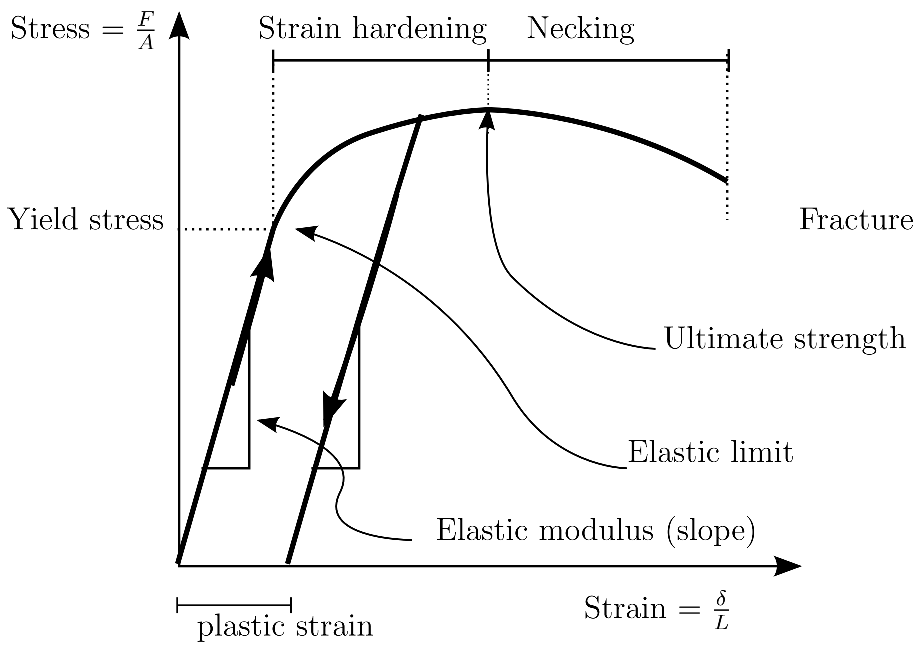


Figure 6: Stress-Strain curve

- **Calculating Young's Modulus**

  Recall that the Young's Modulus is the ratio of the stress to strain when a material is in its elastic regime - that is the linear region along the stress strain curve. In this region, the material can be thought of as a linear spring, because the material returns to its initial shape after being loaded and unloaded.
  Thus, the Young's Modulus can be determined by calculating the slope of the linear portion of the stress-strain curve shown in Figure 6.

- **Calculating Yield Stress (or Yield Strength)**

  The yield stress corresponds to the point where the transition from elastic to plastic deformation begins. If the material is stressed beyond this point, it will not return to its original shape, but will instead stay "stretched" (think of stretching a plastic bag - it stays stretched after you let go!). With respect to the stress-strain curve, this point corresponds roughly to the point where the curve stops behaving linearly.

- **Calculating Ultimate Stress (or Ultimate Strength)**

  The ultimate stress/strength is the maximum stress that the material can withstand. This corresponds to the maximum stress value achieved on the stress-strain curve. Beyond this point, the material's load bearing capabilities begins to rapidly deteriorate. After moving beyond this point, you will potentially observe a phenomenon called "necking", where the width of the material rapidly decreases as the sample stretches and approaches complete failure.

- **Calculating Elongation at Failure**

  "Failure" refers to the moment when the test sample breaks - that is, it is no longer a simple sample, but rather two or more pieces (typically two in an axial testing machine). On the stress-strain curve, this corresponds to the point where the curve abruptly ends. This is a result of the material no longer being able to carry any load at all.

A Final Note:
Finally, it should be noted that we are assuming that the cross section of the specimen is not changing during the extension. Hence, what we are plotting is not a true stress-strain curve, but rather an engineering stress-strain curve.