Material Properties of Balsa for FAC Modelers

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“There are two types of model airplanes: those that have crashed, and those that will crash,” but I have often wondered whether scientific principles can be used to design more damage resistant FAC ships. For instance, is it possible to calculate useful guidelines for leading edge dimensions and density?

A first step in the direction of answering that question is to obtain some of the material properties of balsa that can then be used in beam bending equations. The two most important properties for this endeavor are: the Young’s Modulus and the failure stress. Since balsa material properties vary with density, I set out to figure out some relationships we modelers can use to figure these out.

Young's Modulus is the proportion between the stress (force per unit area) and strain (deformation per unit length) within a part. It’s analogous to a spring constant. The failure stress is the force per unit area required to break a material.

The material scientists in the audience might point out that balsa’s material properties aren’t uniform in every direction because it has grain. For many situations, we can assume the balsa only experiences forces in the direction parallel to the grain (i.e. the axial direction), so all the material properties discussed from here on are axial.

These same material scientists might also point out that “failure” can be a subjective word and they would argue I need to specify whether failure is defined as yield, elastic limit, fracture, or a bunch of other things. Since balsa acts like a brittle material, it fractures shortly after yielding and many of these distinctions become less useful for practical purposes; therefore, I’ll use the terms “strength,” “failure stress,” and “fracture stress” interchangeably in this article to refer to when the stick is going to break.

On to the experiments: I tested six 1/16” square sticks of different densities. My testing method was to use the stick as a cantilever beam with a known weight hanging off the end. By measuring the length of the beam, the weight hanging off the end, and the vertical displacement of the end of the beam, I had enough information to work backwards to the Young’s modulus using the equation for deflection of a cantilever beam with a fixed end.

$$\delta = \frac{PL^3}{3EI}$$

Equation for deflection of a cantilever beam, where δ is the displacement of the end of the beam, P is the force, L is the length, E is the young's modulus, and I is the area moment of inertia

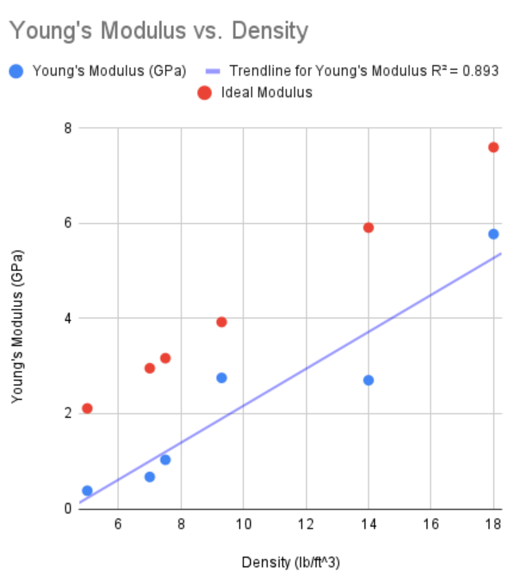
Instead of keeping the length constant and varying the weight, I determined it would be easier to vary the length. I started with the stick overhanging a little over an inch from the edge of the table, then slid the stick out in increments to increase the overhanging length. With a ruler taped to the end of a yardstick, I was able to measure both the length and vertical displacement. The test weight was an empty Solo cup hanging off a string cyanoed to the end of the stick.

To find the second material property, the failure stress, I recorded the length when the overhang was so much that the stick snapped, and using that information I was able to use the equation for maximum stress in a cantilever beam to work out the stress at failure. If I couldn't break the stick with an empty solo cup (which was the case for the denser wood) I added a few coins to the cup and repeated the test.

$$\sigma_{max} = \frac{PLy}{I}$$

Equation for maximum stress in the a cantilever beam, where σ_{max} is the max stress, P is the force, L is the length, y is half the thickness of the stick, and I is the area moment of inertia

Having run the experiments, we can now plot the results for Young's Modulus and the failure stress. First, here's the experimental results for Young's Modulus (blue dots and blue line):



I averaged the Young's modulus over as many data points as I recorded before failure for each stick to get the graph shown. Looking at the graph, we see that the modulus increases linearly with density, and varies between 0.38GPa (for a 5 lb/ft^3 density stick) and 5.77GPa (for an 18 lb/ft^3 density stick).

After conducting these experiments, I found out some folks from MIT did some more scientific experiments looking into the material properties of balsa[1], and they also found that the modulus increased linearly with density to a value “up to 6GPa” for high density balsa. So far so good!

The MIT folks also came up with a formula for the Young’s Modulus of balsa based on density using an idealized model (red dots on the graph). The short of it is that if you assume the balsa is an ideal honeycomb structure, the material properties are related to the material properties of the cell walls by the ratio of the densities of the balsa and cell wall. They also note that this formula overestimates the modulus compared to experimental data. My data also shows this formula (labeled on the graph as “ideal modulus”) to be an overestimate, so our analyses are in agreement.

$$E_{balsa}[GPa] = E_{cell\ wall} \times \frac{balsa\ density}{cell\ wall\ density} = 41 \times \frac{balsa\ density\ [lb/ft^3]}{97.2}$$

Where E is Young’s Modulus

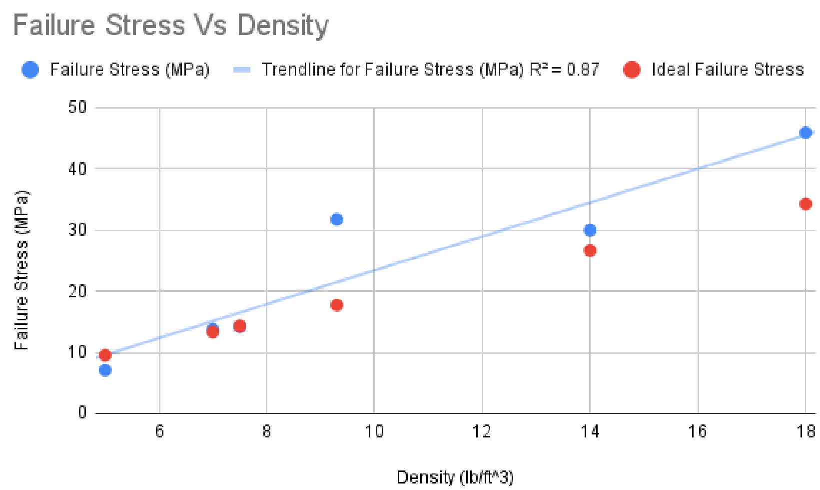
For a more accurate estimate of Young’s Modulus for us model builders, here’s the equation for the trend line Google Sheets fit through my experimental data:

$$modulus\ [GPa] = 0.388 \times density\ [lb/ft^3] - 1.71$$

Now, having seen the results for the Young’s Modulus, let’s take a look at the results for the failure stress:

Looking at the graph below, we can see that the fracture stress is also linearly related to density, and varies from 7.09 MPa (for a 5lb stick) to 45.92 MPa (for an 18lb stick). The MIT paper also found a linear relationship with dense balsa having a strength of 40 MPa. Yet another point of close agreement!

[1] Borrega, Marc, and Lorna J. Gibson. “Mechanics of Balsa (Ochroma Pyramidale) Wood.” Mechanics of Materials 84 (May 2015): 75–90



The idealized honeycomb model can also give a formula for the failure stress. The MIT paper says this formula is also an overestimate, but it seems to agree decently well with my data for low density, and then become a slight underestimate for high density.

$$\sigma_{balsa}[MPa] = \sigma_{cell\ wall} \times \frac{balsa\ density}{cell\ wall\ density} = 185 \times \frac{balsa\ density\ [lb/ft^3]}{97.2}$$

Where σ is the failure stress

For the pragmatic among us, here's the equation for my linear fit for fracture stress:

$$Fracture\ Stress\ [MPa] = 2.77 \times density\ [lb/ft^3] - 4.28$$

Stay tuned for part 2 where I'll use these properties (Young's Modulus and failure stress) to analyze one of the most common structural problems faced by the indoor FACer: the showdown between the leading edge and the basketball hoop.