Hook Design Process

The ultimate goal of this project is to design and 3D print a hook which will be able to lift a car. This article describes the design process for the first iteration of the hook.

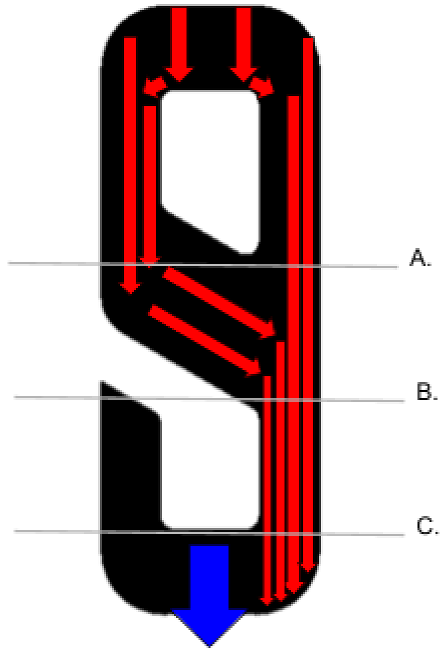
There are several requirements of the hook:

1. It has to be open on one side and closed on the other, like a typical crane hook.
2. It has to be printable on an Axiom or Axiom 20 printer with little to no support.
3. It has to be able to lift approximately one ton.
4. It has to have the AW3D logo on it.

Additionally, when designing any functional mechanical part, there are three main things to consider: geometry, material, and the manufacturing process.

For the first iteration of the hook, I looked to GrabCad for inspiration. Without thinking too much about the mechanical requirements of the hook, I chose to model a 'S style' hook because I liked the way that it looked and it would be easy to meet some of the requirements listed above. Below is the final model of the first iteration hook, modeled and rendered in Fusion 360. The overall dimensions of the part are 135x50x20mm.

One aspect which I knew would be important was symmetry. The reason that symmetry is important in mechanical loading is because a torque on a part can cause excess stress. The concept of torque can be illustrated in many ways, but one of the easiest to understand is with weights. If you hold a weight far away from your body with your arms fully stretched, it becomes significantly more difficult than if you were to hold it closer to yourself. The same logic applies here: if the load is applied off-center from where the hook is being held, there will be increased torque on the hook and the weight will have a mechanical advantage. Unfortunately, it would be impossible to create perfect symmetry because of the first requirement: having one side closed and another open means that the stress cannot be applied evenly throughout the part. Stress can be thought of as traveling in lines throughout a part. When a part has discontinuities, the stress concentrates. This is visualized below:

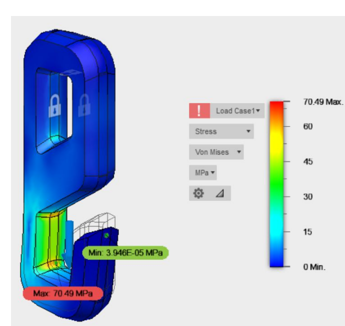


The red arrow represents the ‘path’ of stress flow throughout the part and the blue arrow represents the load. For this representation to be accurate, the lines drawn must go all the way from the top to the bottom of the part. The reason that this visualization is an accurate representation is because of the way that loads are defined - as a force over an area. As the area over which these lines can be drawn decreases, the lines must get closer together. Before line A, the stress is traveling symmetrically throughout the part. There are still concentrations along the sides because of the hole, but the load is symmetric and doesn’t cause any extreme loads. In between lines A and B, the main discontinuity, the hook opening, occurs. The stress lines must be continuous and therefore have to travel to the right side, essentially doubling the load at the corner just below line B. In between lines B and C, There are no discontinuities or stress concentrations because the stress can travel in a straight line - albeit there is a lot of stress that is traveling. However, at line C, the corner is sharp so the stress barely has any distance to disperse throughout the bottom half of the part and as a result, there is a large stress concentration here. Sharp corners have a tendency to create stress concentrations and are often avoided in industry - for example, airplane windows were square in the 1950’s but air pressure concentrations caused failures, and now, these windows are rounded.

So, this one design flaw would appear to cause this part to be subject to extreme forces at the corners. It is obvious why S-style hooks are not used for industrial cranes and are only used for relatively low-stress uses, like in bungee cables and carabiners, for example. And even in some carabiners, there are latches on both sides so that there is more continuity throughout the part.

The last aspect of the design was the logo, and for this, I arbitrarily decided to indent the logo 2mm and place it in the middle.

To confirm the faulted design of this iteration, I performed simulations in Fusion 360. Shown right is the result of a stress simulation with Nylon and a 200 lb. load.



With regards to materials, the Axiom series of printers allow for a lot of material options, and as such, a lot of materials will be tested, including PLA, ABS, PETG, Nylon, PC, Annealed PC, PETG Carbonite, and PBB. The manufacturing process will, of course, be 3D printing, and the orientation of the hook will be with the front facing side on the print bed. This choice is obvious for multiple reasons: it will be easier to print, and the layer orientation will be more mechanically favorable. In this orientation, the stress will be perpendicular to the direction of the layers, which means that layer to layer bonding won't be an issue.

As predicted, the stress is concentrated around the corners, and the part is expected to fail. Despite this, these parts will all still be tested to confirm the calculated errors. The next iteration of the hook will aim to solve problems with this first one. Although this hook won't be lifting a car, it's a good first step in understanding what's important in design for mechanical loads.

Before the tests, I had a general order for how well I thought the materials would perform, partly based on simulation results and partly based on my experience with all of these materials. Since the prints were going to be stressed in the Z-direction and the layers were stacked in the Y-direction (see figure below), layer bonding shouldn't have very much influence on the performance of the hooks. Obviously, a well-printed part should distribute stress more evenly and perform better over time, but for a one time test, it can be ignored.

My order, from worst to best, was this: PLA, ABS, PETG, PBB, Carbonite PETG, PC, Annealed PC, and 910 Nylon.
Below are the ultimate tensile strengths for most of these materials, all in Megapascals:

- PLA: 58 MPa
- PETG: 63 MPa
- ABS: 45 MPa
- PC: 70 MPa
- 910 Nylon: 56 MPa

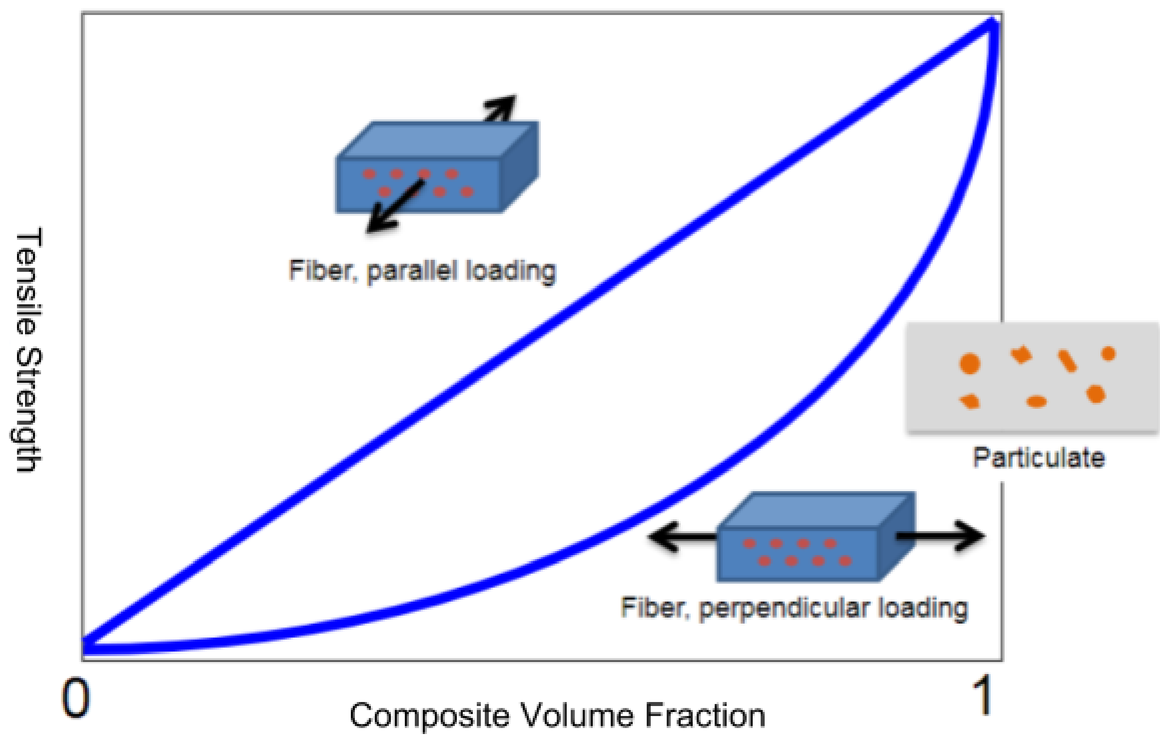
As for the Carbonite PETG, I would predict slightly better performance than out of regular PETG. The carbon fiber added to FDM filaments is added as particulate. Through several volume and stress assumptions, the UTS changes according to:

$$\sigma = \frac{\sigma_p \sigma_m}{\sigma_p V_m + \sigma_m V_p} \qquad (1)$$

Where σ is the UTS, V is the volume fraction, and the subscripts 'p' and 'm' represent the particulate and main materials, respectively. This is opposed to using continuous strands of a material, which results in the following:

$\sigma = \sigma_p V_m + \sigma_m V_p$ (2)

To visualize the difference between these, the following graph is provided:



This demonstrates that the correlation is not linear for particulate composites, so while adding carbon fiber should add some strength, the parts will still be more akin to their original selves unless they get to over 75 to 80 percent Carbon Fiber. Since most filament composites are around 20% particulate, the difference in mechanical properties should be noticeable, but not substantial.

The way that the test conducted was actually quite similar to a tensile test, so these numbers should be quite accurate. However, since the specimen weren't loaded symmetrically as in a tensile test, elongation should have some effect on the materials ability to distribute stress and withstand a torque. The hooks were connected by straps to both a crane and a tire. The tire would be filled with weights and the crane would slowly lift the tire off of the ground. If the hook survived, more weight was added.

Below are the results of the tensile test, in pounds:

1. Polycarbonate (Annealed) - 685

2. Polycarbonate - 685
3. Taulman Alloy 910 - 445
4. Carbonite PETG - 285*
5. PETG - 285
6. ABS -285
7. PBB - 285
8. PLA - 285

   *Crane had a sudden jerk to cause the break

So, my order wasn’t quite correct - I thought that Nylon’s flexibility would allow for better distribution of stress, but I assume that the corners were too sharp for this to make a difference. I also thought that there would be a bigger difference between the other filaments, but our increments must have been too large to notice them.