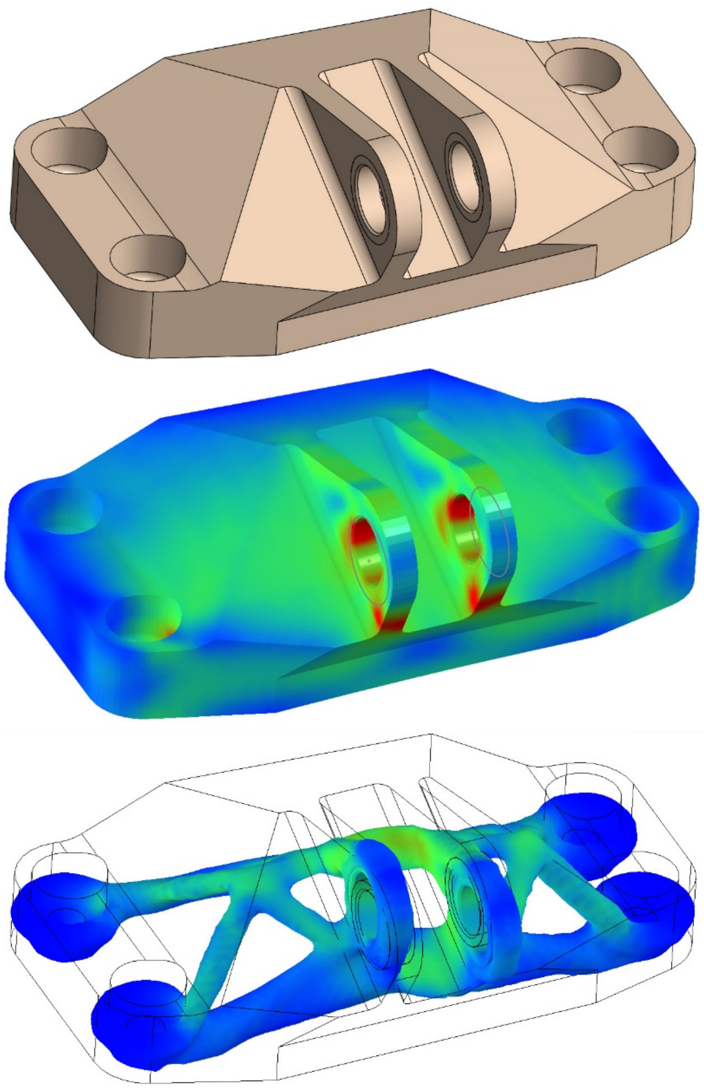
Topology Optimization

Translation Report



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Introduction

Mechanical engineers sometimes have to make tradeoffs between strong and light parts. But by intelligently designing the shape of the part, they can maximize the strength to weight ratio. This is difficult, however, and sometimes multiple attempts are required to get an acceptable part. Today, with the technologies of additive manufacturing (known less formally as 3D printing) and 3D computer controlled machining, parts can be more complex so the possible performance of these parts has been increased. Taking advantage of these technologies requires a skilled designer and more time to develop an optimal solution, though.

There is a new technology developing that may be able to save time and increase performance of parts, known as topology optimization. This technique uses a computer to calculate a shape for the part that gives it a high strength-to-weight ratio. The designer can use a software program to simulate the application of a load to a 3D model of the part. Then the program calculates what regions of material are the most important to the part's strength, and the less important material can be removed. Since these parts contain complex shapes, they can be impossible to manufacture by conventional methods, but additive manufacturing can make it possible to produce them.

I will describe structural topology optimization. While the solving techniques can be used to optimize for other characteristics, structural optimization is more relevant to mechanical engineering and more commonly researched.

Algorithm

Topology optimization reduces the amount of decisions a designer has to make beforehand when designing a part [1]. Examples of these decisions would be the number of lightening holes and reinforcement beams and how they connect to each other. In mathematics, this arrangement is known as topology, which gives the name topology optimization. The technology and mathematics to design these parts has been discussed and developed for more than 40 years, but has been held back by manufacturing capabilities until more recently [1]. With additive manufacturing, the limits on the shapes of parts that can be made are almost none, so the complex, organic shapes that topology optimization produces are now feasible to make in the real world [1].

Usually in structural topology optimization, the goal is to minimize the bending that occurs under a given load, with a limit to the volume of material used for the part, or to minimize the weight of the part with a limit on the stress placed on the material [2]. The most common method for this used currently is known as the density-based method [3], introduced in 1989 by M. P. Bendsøe [4]. I will explain it in the following paragraphs.

The goal behind this method is to determine where to place material, within a volume defined by the user, to minimize weight while maximizing strength under the given loads [4]. A way to think about this is to cut the volume into many small pieces, called elements [4]. Then the question is what elements should be included in the final part, and which should not [4]. Information to determine this comes from a mathematical analysis, where each element is described by a simple equation [1]. The combination of all these simple equations yields a number that represents the amount of bending (known as displacement) or the weight of the part, depending on what approach is used [1]. This number is known as the objective function [1]. “Objective” refers to the goal of minimizing either bending or weight, and “function” means that it converts the densities of the elements to the objective. The algorithm then tries different variations of elements included or excluded to try to minimize this number, while constrained by maximum values of displacement or volume [3]. After each iteration it improves its results a little until the part changes very little between iterations [4]. Getting to where the part changes little is known as converging, and it means the part is completed [1]. But having the decision between whether to include or exclude an element as a binary choice with only those two possibilities can make this method very difficult mathematically [4]. Usually it means that there may be no solution that can be calculated [4].

The math works out much easier if the choice for including or excluding the element is treated not as a binary choice, but as a continuous value between 0 and 1 [4]. This is known as the element’s density, where a value of 0 means that the element should definitely not be included in the final part, known as void, and 1 means it definitely should, known as solid [4]. Intermediate values represent a less sure choice [1]. This simplifies the math but introduces some other problems, which are described in the following paragraphs.

One of the main problems is that with the density based approach is that the algorithm is encouraged to make a smooth transition between solid and void [1]. Instead of a sharp line where the material ends, there is a wide band of elements with densities somewhere between 0 and 1 [1]. Of course, when the part is made in real life, the only options are solid and void, so a cutoff value must be chosen [1]. Any elements that have a density less than the cutoff value are excluded. But if the transition is smooth, then no matter what cutoff value is chosen, the geometry of the part will not be defined very well [1]. By this I mean that instead of having clear lines of solid material connecting the part, they can become wide blobs that may even be floating in space, disconnected from the rest of the part [1].

Results can be improved using a model called SIMP, which stands for Solid Isotropic Material with Penalization [1]. This algorithm is the most common one used today [3]. I will describe each of these terms to make the meaning of this clear. “Solid” simply means that the material is continuous throughout, unlike a material that already has holes in it, like a sponge. “Isotropic” means that the material has the same properties in all directions. Metals and plastics are isotropic materials, for example. Materials that are not isotropic are known as anisotropic and include wood and other materials with a “grain.” These materials can respond differently to forces depending on the direction of the force, like how it is much easier to split a piece of wood with its grain than against it. Assuming the material is isotropic makes the math much simpler and this assumption is true for the materials that are used for topology-optimized parts. “Penalization” is how the problems described in the above paragraph are mitigated [1]. While the specific mathematics are outside the scope of this report, what is important is that a penalization factor which is adjustable can be applied [1]. This factor discourages the algorithm from making a smooth transition and encourages it to make a well-defined boundary between solid and void [1]. How large the number is determines how aggressive this action is [1].

When the penalization factor is applied, the next issue to arise is in the density based approach is called "checkerboarding." [1] Since making regions of density between solid and void is penalized, sometimes regions are created that have a pattern of alternating solid and void elements. This increases the calculated strength of the part. However, the element size is so small compared to the part that these patterns are usually impossible to manufacture. To eliminate them, a filter is applied to the elements [1]. This makes it so that each solid element is blurred to its neighboring elements. Effectively, this makes the minimum size of the geometric details larger than the elements, which eliminates the checkerboard [1].

With these fixes applied, SIMP is an efficient way to implement the density based method [1]. The density method has the advantage that the same elements can be used for each iteration of the design, since each element is always in the part and only their density changes between iterations [1].

A Test of Topology Optimization Software

I tried the topology optimization software integrated into SOLIDWORKS, a computer-aided-design program commonly used by mechanical engineers, for myself. I did this to see how intuitive it was and gather some data to use for visualizations. These are the steps I took:

1. I modeled a space for a cantilevered beam as a simple box. I set its material to be aluminum.
2. I used the tools in the software to fix one end and apply a load to the opposite bottom edge (See Figure 1). As a control, I ran an analysis on the box to show the stress that developed in the material (See Figure 2).
3. I set a goal to remove 85% of the mass of the box. I chose the mesh size, which determines how big the elements are. Then I ran the topology optimization, which took about 40 minutes to compute on my laptop. The output gave me a graph of what material was essential to the part's strength (Figure 3), and what would be okay to remove.
4. I adjusted the cutoff for how much material to remove. When that was satisfactory, I exported this shape out of the simulation (Figure 4).
5. Since the shape was very rough, I used it as a guide and traced around it to make the shape of the part (Figure 5).
6. I ran the stress analysis again to see how this part performed. It held up very well, evenly distributing the load throughout the material. The plot of this stress analysis is Figure 6.

Figures

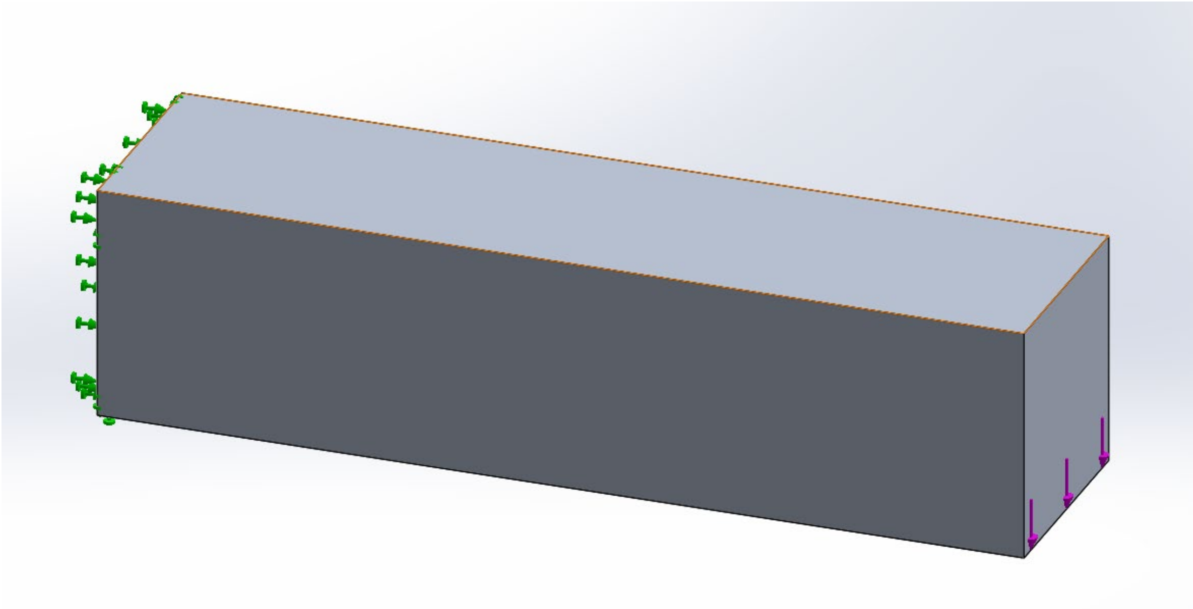

Figure 1. The setup used for topology optimization and both stress analyses
The green arrows represent the left side being fixed, and the purple arrows show the load applied on the right bottom edge of the part.

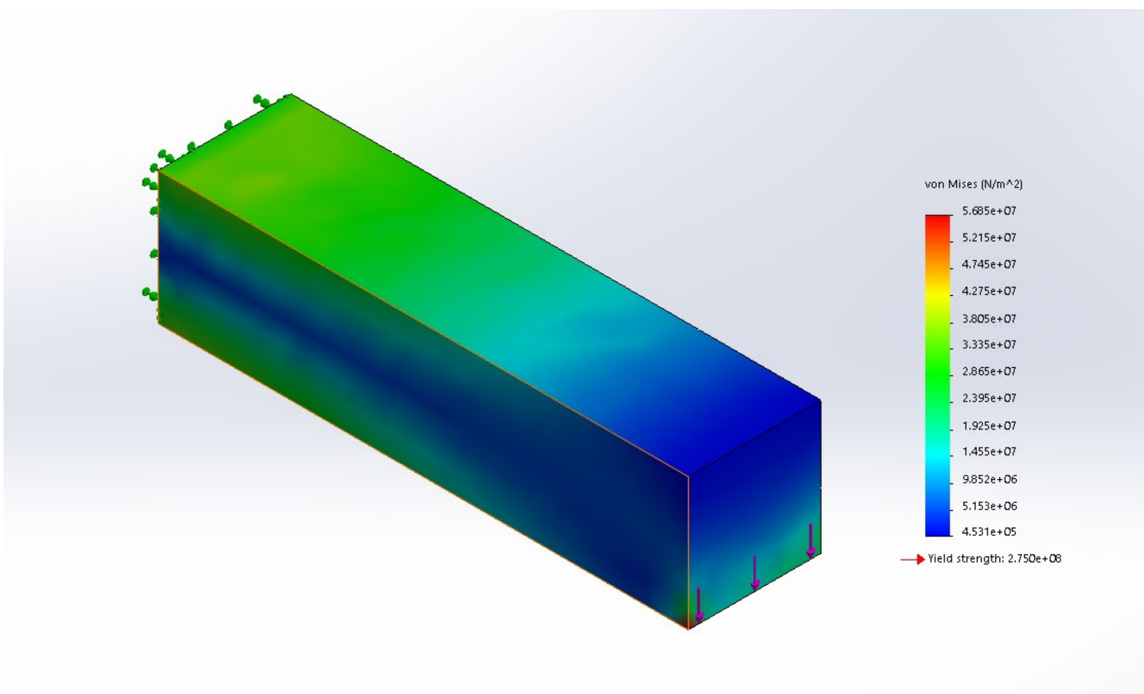

Figure 2. Stress analysis of non-optimized cantilever
Note how the most stress is developed near the fixed side, on the top and bottom. In the optimization, these areas will be important and have more material there.

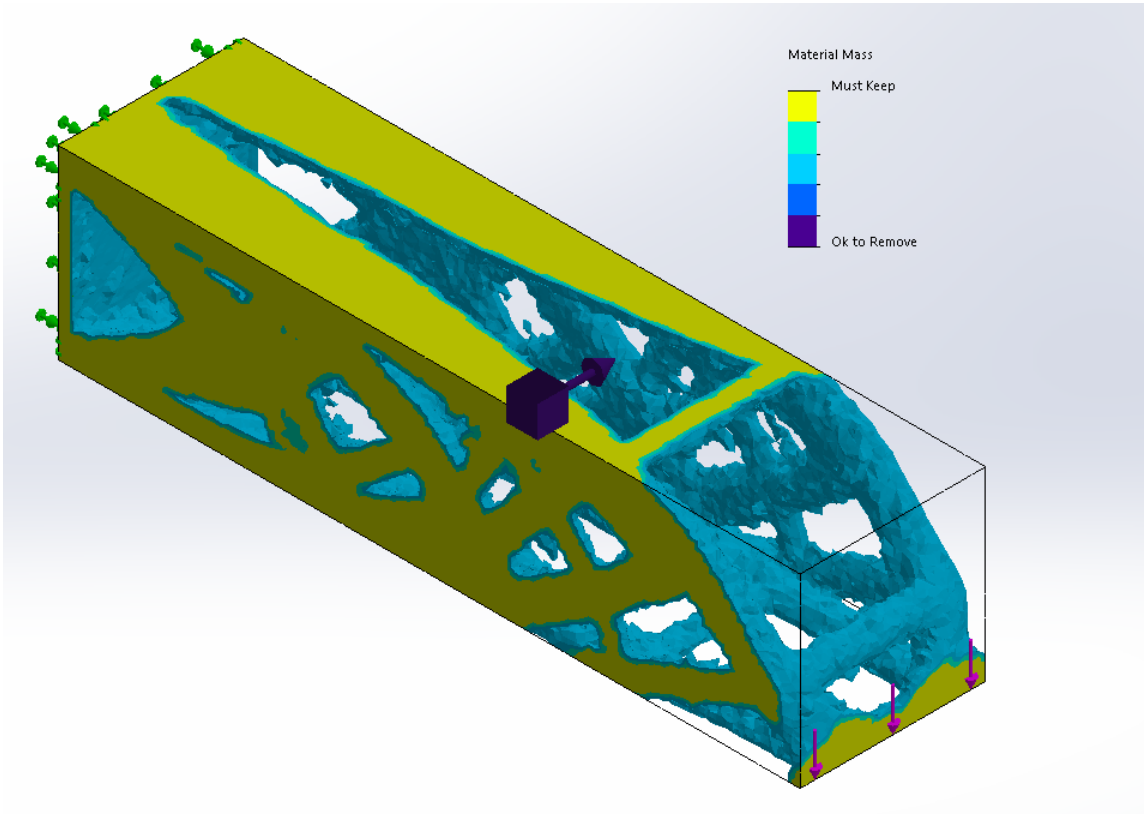

Figure 3. Results of topology optimization.
This shows what elements are the most important.

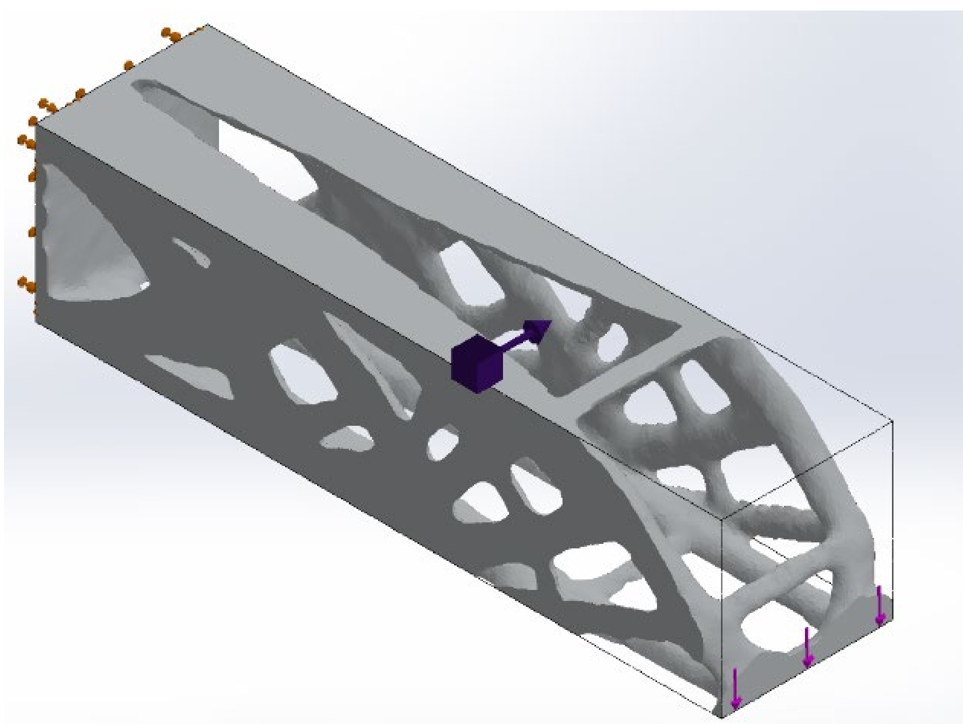

Figure 4. Smoothed results of topology optimization

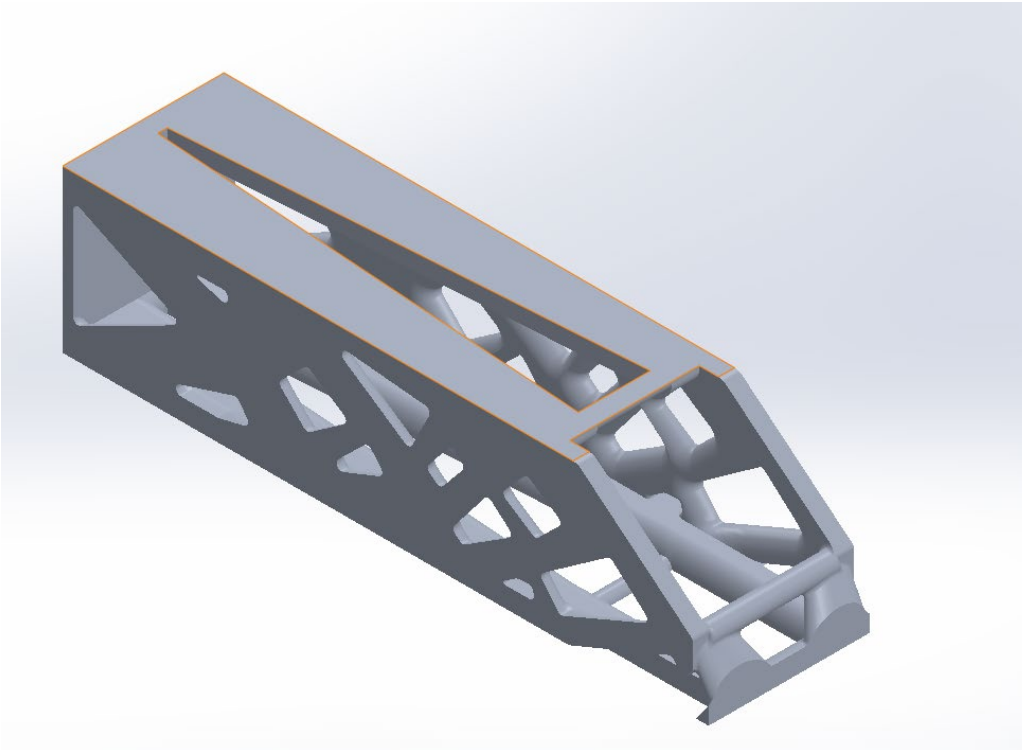

Figure 5. Part traced to eliminate rough edges

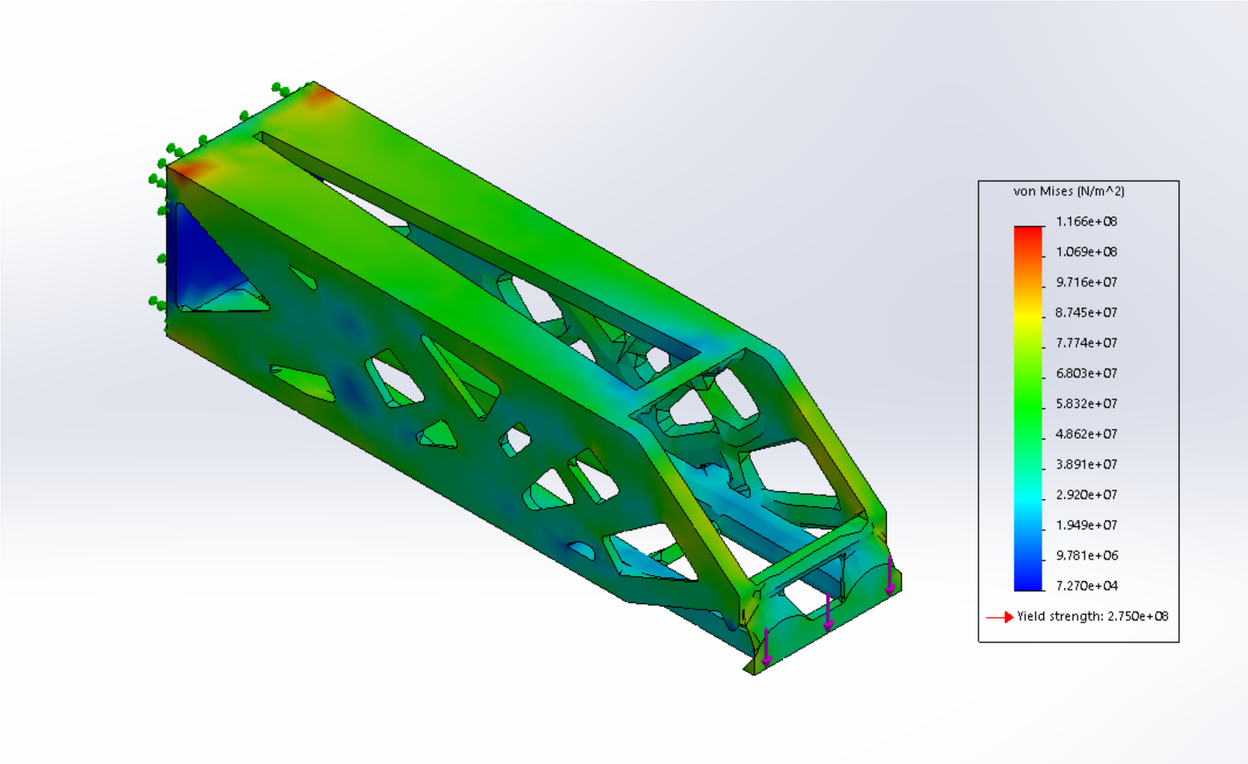

Figure 6. Stress analysis of traced part

Applications

As part of my research into applications, I looked at a case study of using topology optimization to design an industrial robotic arm which was presented at the IEEE/IFToMM International Conference on Reconfigurable Mechanisms and Robots [5]. The team set out to reduce the weight of the arm as much as possible, while having the end of the arm be displaced no more than the original, under the same load [5]. They also required that the arm would not be more prone to vibration, as this is often caused by drilling and other actions the arm would be expected to perform [5]. They checked both of these goals with a computer simulation [5]. The arm's weight was reduced to 44% of its original value while meeting both of their other goals [5]. This shows how factories may be one important application for topology optimization. This reduced weight could help automated factories reduce energy usage and cost.

Another field that is beginning to use topology optimization is the automotive industry. I found a report from the Society of Automotive Engineers that listed some examples of how topology optimization may change the design process of automobiles. The weight reduction of these optimized parts will be beneficial both for improving the performance of race cars, and the energy efficiency of cars for transportation. Some things that need to improve to use topology optimization for large scale production is a reduction in cost of additive manufacturing, faster production time, and means of joining the optimized parts together. Some examples of parts that would benefit from topology optimization were listed. One of them was a bracket used to mount an air conditioner pump to the engine block. Subject to loads from two belts, and constrained by a limit on the displacement of the bracket under these loads, the weight of the bracket was minimized. This gave a final part with a mass of only 380 grams. [6]

Since the applications of strong and light parts reach far and wide, it's hard to predict specifically what technologies and industries will benefit the most from topology optimization. For large-scale production, it is rapidly becoming more feasible as additive manufacturing improves. I believe topology optimization will be an important part in the future improvement of almost all machinery.

Future

To see how topology optimization might be used by the next generation of designers, I interviewed one of the current students on my high school robotics team, Magnus. Recently, Magnus has been experimenting with topology optimization software to see if it might be useful for designing the team's robots. I asked him if the software was easy to learn, whether he thought it might be used on the team's next robot, and how easily the topology optimized parts could be manufactured. He responded that the version within SOLIDWORKS was easy to use, but the part was exported as a shape composed of many small triangles, which was sometimes hard to integrate with the rest of the software. He said that the team is considering using it for the next robot since one of the main limitations of the competition is weight. This means the weight savings from topology optimization could help them be more competitive. However, one of the difficulties he had was getting the parts ready for manufacturing. All the simple plastic 3D printers that the team has access to build the parts layer by layer, and the parts have a weakness where the layers attach to each other. This means that the material is not isotropic as the algorithm assumes, so parts are not as strong as the computer predicts. This puts very complex 3D parts out of the team's reach for now. Still, for more flat parts that are manufactured out of sheet metal, the topology optimization results are useful. They can be used as a reference to design a part that can be made by machining. Since these parts are the type most commonly made by the team, topology optimization may be a useful tool to the team now.

With our experience using SOLIDWORKS but not any topology optimization or other simulation software, the student and I were able to figure out how to use it quickly to get a result. Because of this, I think that topology optimization software will be easily adopted as the cost of additive manufacturing reduces and more of these high-performance parts are used.

Conclusions

In the near future, I believe that topology optimization will become much more common in mechanical design. It will come with the improvement of additive manufacturing, and as additive manufacturing comes down in cost. The basics of the software is easily picked up if the user has experience with computer-aided-design. It will allow for improvements to the weight and/or strength of parts across all machinery. It will allow designers to go from concept to finished design more quickly than before, especially for parts where very high performance is required. It will never replace traditional tools of design, but is another useful tool for a designer to have. I expect to use it in my future career as a mechanical engineer. Topology optimization is part of the future of design.

Works cited

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