A DESIGN METHODOLOGY FOR CONTINUOUS FIBER ADDITIVE MANUFACTURING USING ADVANCED COMPUTER AIDED ENGINEERING TECHNIQUES

by

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Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON
December 2017

Acknowledgements

I first want to thank Dr. Taylor for mentoring and guiding me through my coursework for the past few years. Additional thanks go to Dr. Adnan and Dr. Dancila for their support and feedback.

My thanks also go to my friends and family, who have been so supportive of me in my academic pursuits. I want to extend my gratitude to my grandparents, my father, Bernard, and my brother, Joshua. I especially want to thank my mother, Cheryl, and dedicate this work to her. I'm a better person because of her.

December 20, 2017

Abstract

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A design methodology for Continuous Carbon Fiber Additive Manufacturing (CCFAM) developed using Computer Aided Engineering (CAE) techniques takes advantage of both the mechanical strength of composite materials and the Fused Filament Fabrication (FFF) method. By performing topology optimization and Finite Element Analysis (FEA) on a load-bearing part, engineers can design much lighter optimized parts that are just as strong as those produced using FFF. This weight reduction is achieved by relying on the mechanical strength of continuous carbon fibers printed alongside a traditional thermoplastic matrix. The FFF additive manufacturing method enables the production of complex shapes, which can match the load-driven, organic geometries derived from topology optimization and other advanced CAE techniques. The efficacy of this design methodology has been demonstrated in a design case study of a motor mount for a vertical take-off and landing drone.

Table of Contents

Acknowledgements ... iii

Abstract ... iv

List of Illustrations ... vi

List of Tables ... vii

Chapter 1 Introduction ... 1

Chapter 2 Background ... 2

- 2.1 Additive Manufacturing ... 2
- 2.2 Composites ... 11
- 2.3 Composites in Additive Manufacturing ... 17
- 2.4 Continuous Fiber Reinforced Polymer 3D Printing ... 22

Chapter 3 Methodology ... 29

- 3.1 Process Requirements ... 29
- 3.2 Process Limitations ... 38
- 3.3 Design Case Study Introduction ... 41

Chapter 4 Design Specifics ... 42

- 4.1 Problem Setup and Modeling Guidelines ... 42
- 4.2 Analysis ... 45
- 4.3 Optimization ... 49
- 4.4 Results ... 50

Chapter 5 Conclusion ... 54

- Appendix A: Altair and Eiger Software Screenshots ... 57
- Appendix B: Printer and materials ... 61

List of Illustrations

Figure 2-1 FFF Process Diagram [4] 5
Figure 2-2 FFF Discretization [34] 7
Figure 2-3 Heat sink Designs Created using a metal 3D printer [10] 10
Figure 2-4 Biocompatible titanium hip replacement [10] 11
Figure 2-1 Hand Layup Example: Applying a ply to tooling [13] 13
Figure 2-2 Wet Layup Composite Part Manufacturing [14] 14
Figure 2-1 Continuous Carbon Fiber 3D printed part 23
Figure 2-2 Wet nylon (top) vs dry nylon (bottom) 24
Figure 2-3 Onyx Parts [20] [21] 27
Figure 3-1 Printing a carbon fiber layer 35
Figure 3-2 Eiger Support Settings 39
Figure 4-1 Motor mount loading condition 43
Figure 4-2 Optimization and analysis setup 45
Figure 4-3 Deflection Results from Analysis 49

List of Tables

Table 3-1 FFF and CFRP Material Comparison [25] [26] [27] 36

Table 4-1 Design Comparison 51

Chapter 1 Introduction

Manufacturing methods continue to change as innovative technologies are developed and old methods are supplanted by them. The basic guidelines and principles of good manufacturing, however, remain constant as engineers seek to optimize designs based on customer desires and their derived engineering requirements. A design that accomplishes a perfect balance between manufacturability, design requirements, and cost is rare, though every engineer and designer strives to achieve it with each new project. With the constant advancements in global knowledge, specifically with manufacturing technology and design techniques, design methodologies are constantly improving.

As new manufacturing technologies enter the industry, they bring with them their own set of design constraints, advantages and disadvantages. The full potential of these technologies cannot be realized until best-practice guidelines have been established. Additive manufacturing is still recognized as a fairly new technology. Fused Filament Fabrication (FFF) in particular is used mainly for rapid prototyping. This means that the parts are built according to designs made with another manufacturing method in mind; the printed parts are being tested for ease-of-assembly, handling, fit and form. In order to fully utilize additive manufacturing methods, a design methodology must be established for producing consistent end-use parts. Developing these design methods requires a deep understanding of the technology and includes studies that cover the materials used as well as the effect that process parameters have on material properties [1].

Design methodologies are still being developed for many 3D printing methods, though several of them have generally accepted rules for producing good quality parts. The advent of Continuous Fiber Reinforced Polymer (CFRP) 3D printing has brought much-needed strong mechanical properties to the world of FFF. As such, it is more important than ever to develop a design methodology for producing parts that can fully take advantage of the manufacturing upside presented by FFF [2], instead of under-utilizing the technology by only producing prototypes.

This document outlines one such design methodology. It follows part design from conceptualization, including required loads and boundary conditions, to analysis and optimization for those loads and finally to final manufacture of the part. This methodology takes advantage of the manufacturing capabilities of FFF, namely the ability to produce complex load-driven geometries. These geometries have the advantage of being stiffened by continuous fibers in specified layers throughout the part. This allows for additional weight and cost savings in the final design without compromising part strength.

Chapter 2 Background

2.1 Additive Manufacturing

Additive manufacturing methods (commonly referred to as 3D printing) offer a new way to manufacture parts. Instead of traditional subtractive manufacturing methods in which raw materials are machined into the desired geometries then assembled using various joining techniques, additive manufacturing techniques add material only as it is required to build the part. The result is less wasted material and the engineering freedom to produce far more elaborate geometries. Using additive manufacturing, internal features and complex, previously non-viable geometries can easily be manufactured [3]. Using traditional machining methods limits the operator to working on only what they can see and reach with the tools they have available. They are limited to exactly what size hole they can drill, bore or ream, the exact size of their cuts, and how much material is removed based on a given operation. If they want more or less to be removed, for example, a different tool size is required. If certain internal geometries are to be produced with a specific shape and specific internal open volume, then traditional subtractive manufacturing may be inadequate to achieving the manufacturing goals because of the limitations of subtractive manufacturing. There are of course, ways to circumvent these issues with traditional manufacturing techniques. For specific internal geometries, the part may be built in stages from multiple joined sections instead of from a solid piece. This then requires joiners, adhesive or some other mechanism to ensure the part stays together in its intended shape. These additional joining mechanisms may be undesirable as they increase the required number of steps, which leads to increased costs and proclivity for error [5].

Part production can be easier and more time-effective using additive manufacturing for rapid prototyping and even sometimes for end-use parts. By avoiding the need for assembly, the time spent in post-processing can be dramatically reduced. Rapid prototyping is often used for fit-and-form testing in production which speeds up the design process and cuts down on error by having a physical part that one can test in an assembly. The more exciting part of additive manufacturing, however, is the possibility of designing and manufacturing end-use parts. For the Fused Filament Fabrication (FFF) method, one of the challenges faced in producing end-use load-bearing parts is that the materials used are relatively weak. Thermoplastic materials ABS and PLA are commonly used but they lack the required strength and stiffness for many applications. This naturally limits the usefulness of the process. Some additive manufacturing processes take advantage of other materials with stronger properties and the Continuous Carbon Fiber Reinforced Polymer (CFRP) additive manufacturing method is one such process [6.

The most important manufacturing method to understand when discussing CFRP 3D printing is Fused Filament Fabrication (FFF). There are dozens of different manufacturing techniques all lumped under the terms “3D printing”, “additive manufacturing”, and “rapid prototyping”. Broadly, they refer to the manufacturing techniques that add material to shape a part, typically in layers, until the final geometry is realized. Usually what comes to mind when one thinks of 3D printing are the material extrusion processes Fused Deposition Modeling (FDM) which is also called Fused Filament Fabrication (FFF). These processes utilize thermoplastic, amorphous polymer as a filament (typically Acrylonitrile Butadiene Styrene, ABS, or Polylactic Acid, PLA). This filament is kept in a spool near the printer which is mechanically fed, usually through a Bowden tube, to the carriage (gantry) which contains a stepper motor, heating element, and extruder. The filament passes through the heating element, which brings it into its glass transition temperature in a range reaching up to its melting temperature, and is extruded through the nozzle by the rest of the material pushing the melted filament from behind as it’s fed by the stepper motor. The material is extruded out of the nozzle as the gantry moves in the xy-plane of the printer to trace the outer profile of the part and then a raster pattern is used to produce the infill. Once the profile for a given layer has successfully printed, the printer will either move the carriage up in the z-axis or the print bed down in the z-axis, effectively moving the printing layer up by one. In this way, the part can be built layer-by-layer until the final form is complete. This process can be seen detailed in Figure 1.

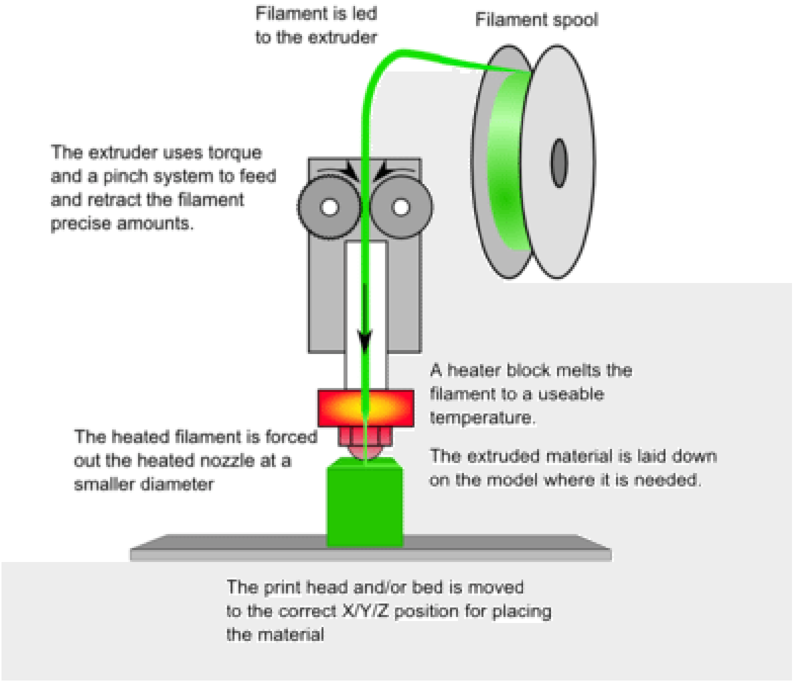


Figure 2-1 FFF Process Diagram [4]

This method comes with a number of advantages. The most obvious advantage is the design freedom that this process allows [5]. Although almost any geometry can be created with this process, many require support material. With supporting material produced alongside build material to prevent drooping and part failure, complex geometries including internal features can be created. This design freedom allows the user to take full advantage of Computer Aided Engineering (CAE) tools. The Finite Element Method (FEM) has long been used as a tool in design for structural analysis problems, accurately producing stress and deflection solutions. Other CAE tools, namely topology, shape and size optimizations, use finite element analysis solutions and optimization algorithms to propose organic, design-driven, and lightweight design solutions [6].

For simple geometries, FFF uses only as much material as is required to produce the part. Compared to other machining techniques, which cut away unneeded material, additive manufacturing has relatively little waste. For more complex geometry, support structures may be required. The G-code instructions can be altered based on a set of restrictions and parameters, however, to reduce the required amount of support material. This requires an amount of user experience, else the operator runs the risk of a failed print, or over-using support. The raster pattern and infill density are both user-set parameters that can be changed by the designer depending on the application. Parts that require a certain amount of structural strength and stiffness may require high infill density, while others can benefit from the reduced weight that a low infill density setting will provide, for example.

Many of the process constraints come from the hardware used. For example, the accuracy of the print is limited by the stepper motors used and the operator's calibration settings. Print time increases linearly as part tolerances decrease. The industry average FFF print tolerance averages at 0.2 mm, but can range anywhere from 0.05 mm to 0.5 mm. The resolution of the print is limited by the nozzle size and process parameters (i.e. printing speed) [3].

Despite the numerous advantages both in manufacturing and in the design freedom this process allows, there are several drawbacks as well. For one, the part is built in layers. This means the strength of the part is fundamentally weaker in the z-axis (in out-of-plane loading) because it is then reliant on the bond between layers of material [7]. Another drawback is that for any curved or sloped surfaces in the part, if they occur in the z-direction (meaning that the slope must be expressed in the part over the course of several layers), then the part will inherently include a discretization or "stair stepping" effect. This will result in a lower quality surface finish for the sloped layers, which can have negative effects on the end-use part. Fortunately the primary benefit of additive manufacturing, the design freedom and ability to create complex geometries, can be used to overcome many of its shortcomings. For example, part orientation, generating supports, and other parameter changes including infill density, print speed, bead width and layer height can all be adjusted to minimize or entirely eliminate the negative effects of the process on a given part. See Figure 2-2 for a model of discretization in FFF.

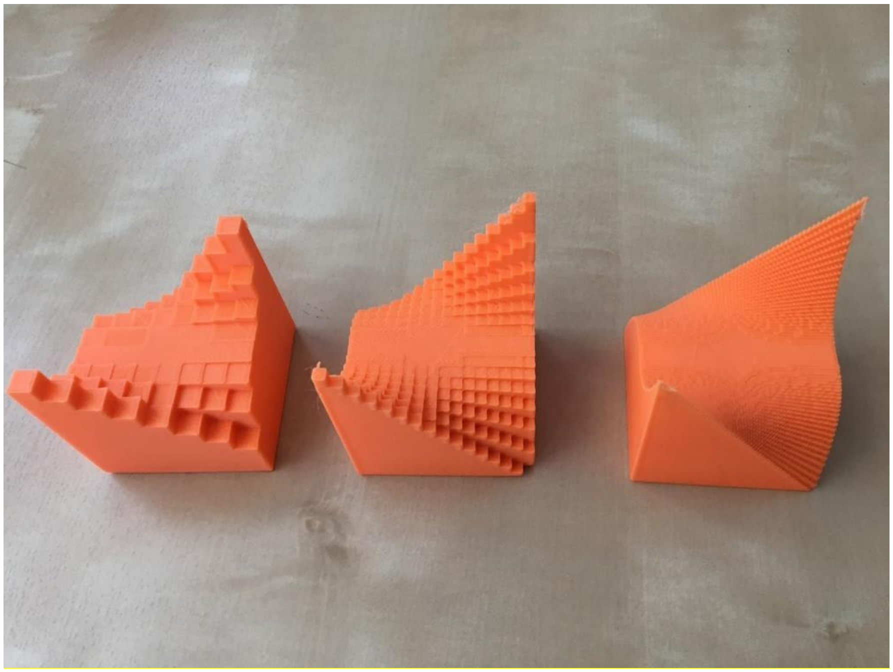


Figure 2-2 FFF Discretization [34]

.STL files are generated by discretizing a solid model with triangular elements. These triangular elements cannot fully match a curving or circular geometry, so the .STL file places the triangles inside the curve to approximate it. When this .STL attempts to recreate the model in slicing or printing software, if the wall thickness is correctly the same size as the minimum wall thickness based on bead width, the print will include thin walls, or may not print material in that area at all because of the discretization effect from the triangular elements removing material from the model. To fix this, a finer .STL configuration with more triangular elements can be used. Otherwise, slightly increasing the wall thickness in the solid model and generating a new .STL file can also solve this problem.

In the printing software (Eiger, KISSlicer, polyprinter, etc.) The part is sliced according to the user settings previously discussed. These slices are the layer-by-layer hot-end and gantry movement instructions. These instructions are saved as a .gcode or .x3g file and relayed to the printer. The printer reads these files and sends the resulting commands to the appropriate stepper motors and heating elements which will then carry out the instructions for printing the part.

The FFF method can also be used to print metal parts, which yields a great increase in strength and stiffness. However, more expensive hardware is required than that used for thermoplastic filament. The nozzle must be heated up to the appropriate extruding temperature for whatever material is being used and metals naturally have a higher melting temperature than thermoplastics. They behave differently from thermoplastics when extruded at this temperature as well. Instead of a continuous stream of molten filament, many metal printers will extrude a discontinuous stream of very small droplets of molten metal [8]. This style of metal 3D printing doesn't have the same geometry constraints as Powder Bed Fusion (PBF) techniques.

Powder Bed Fusion techniques use a laser or electron beam to melt, or sinter, small metal particles. When printing, the part is self-supported by the metal powder. However, that means that any internal geometries require an opening to allow any superfluous powder to escape. FFF metal 3D printing doesn't have this limitation. In fact, it can produce similarly complex part geometries to FFF thermoplastic printers by making use of supports in a similar fashion.

For PBF, the most common design issue to overcome is part porosity. When sintering tiny powdered particles of metal, there will inevitably be part porosity where the particles didn't perfectly fuse together. Any porosity in a part reduces the part's strength, not only because there are small pockets that don't have material when they should, but also because those small pockets introduce stress concentrations. These stress concentrations exacerbate the problem, by driving stresses to the sections of the part that weren't properly fused during the sintering process.

Another method is Direct Energy Deposition (DED), which sends a spray of particles out of a nozzle which are then struck by a laser to build the part layer-by-layer. This doesn't have the advantage of being self-supported by a powder bed that PBF techniques do. This method is good for producing very quick low-quality parts. It is also useful for using as a kind of spot-repair for any failed parts [9], but isn't as useful for producing end-use parts.

Metal 3D printers are good at producing strong, lightweight metal parts quickly. They are better for small production runs; for larger runs, other methods are more desirable. It should be noted that, though they are similar, metal 3D printing and thermoplastic 3D printing are not interchangeable processes. Metal 3D printing requires more foresight and is generally considered the more complex of the two. Also, the fact that metal 3D printing techniques exist does not mean that they are always the best option for a strong part. Often, traditional CNC techniques are just as good or better when producing a part of sufficiently simple geometry. This can be used to work-around the unique requirements for metal 3D printers, namely cooling and excess heat considerations as well as support generation. Supports generated during metal FFF are often made of metal as well. This makes post-processing extremely labor intensive, and often requires additional machining after the print to remove supports and obtain a reasonable surface finish.

Another consideration is that longer metal 3DP prints are more likely to fail. During the process, the metal is repeatedly heated and cooled, which creates a lot of internal stresses in the part. These stresses cannot be relieved during the printing process. The main draw of additive manufacturing is the ability to produce complex part geometries, but this can be detrimental when the part is subjected to these internal stresses, which continue to increase as the build continues. These stresses cause warping , which can surpass a minimum acceptable threshold in deviation from the intended geometry and be considered a failed part. One way to avoid this is to design cooling channels into the part, but this places another set of design constraints on the engineer. At the moment, CNC techniques are considered more cost effective and quicker than metal 3D printing [10].

Figure 2-3 Heat sink Designs Created using a metal 3D printer [10]

Figure 2-4 Biocompatible titanium hip replacement [10]

2.2 Composites

Designing composite parts has the advantage of many different potential manufacturing methods to choose from. These parts are characterized by very high stiffness and decreased weight when compared to metal parts. However, the material properties of composite parts are anisotropic, meaning that although they can be strong in a given direction, they are often much, much weaker in the transverse direction or out-of-plane directions [11]. This is a function of the fiber orientation and layering method used to build the part. There are design techniques that can be used to compensate for this directionality in composite parts, namely alternating fiber direction in successive plies, or making use of short or chopped fiber mats instead.

The hand layup method for manufacturing composite parts makes use of prepreg tape, which is rolled out from a spool and cut it to size for each layer required. The layers are shaped and applied to tooling that to produce the desired geometry. This is then cured in an autoclave. This method produces strong, lightweight, stiff parts that are useful in any number of practical applications. However, the process from beginning to end is time consuming and the materials used are expensive for both the designers and the manufacturers [12].

Composite parts are similar to 3D printed parts in that they are often built up in layers. Instead of extruding the material through a nozzle, however, the common layup method uses pre-impregnated (prepreg) tape which has parallel fibers encased in resin. This tape is cut to size and placed on tooling in the appropriate layup sequence in layers. While the methods and materials are different, the principle of building a part up in layers to achieve the desired geometry is very similar between layup and FFF. The layup process includes no only building the part on tooling layer-by-layer, but also ensuring that other components are correctly installed including a properly sealed vacuum bag. Once the lay-up process is complete, the entire assembly is placed in an autoclave. The autoclave controls both the temperature and pressure applied to the part. This cures the part and results in a completed composite part ready to use [12].

Prepreg carbon fiber part production is very common. This process involves utilizing a layup process with pre-impregnated tape. This prepreg consists of thousands of fibers which are pre-impregnated with resin and bundles into tows. These tows are then arranged in a single unidirectional ply (tape), or woven into a mat. The tape (or mat) is cut to size and oriented in such a way that the desired plies are attained. These plies are placed in the appropriate layup sequence, which is a product of the design requirements, then placed on tooling to obtain the desired geometry of the part. This is achieved by manipulating each ply into the correct shape by hand and firmly attaching them to the previous layer or mold surface. Figure 2-1 shows one such example of the manufacturer attempting to lay a carbon fiber ply onto tooling that matches the desired shape of the final part.

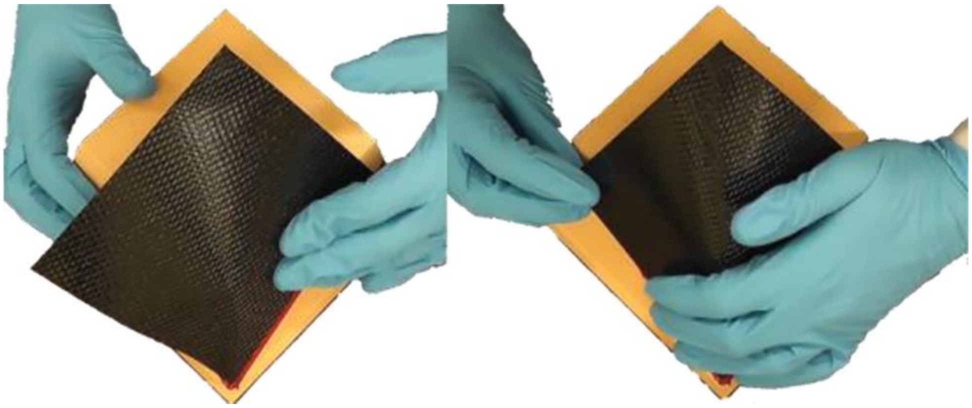


Figure 2-1 Hand Layup Example: Applying a ply to tooling [13]

This method produces high-quality parts that can have relatively complex features. It also boasts lower start-up costs than other composite manufacturing processes. However, production volume is low by necessity and the cost of materials and labour is high. The adaptability of the design makes up for this, limited only by the skill of the manufacturer and the complexity of the tooling required, which must itself be manufactured. Improvements to this process are fairly difficult to come by. In order to improve production rates and reduce part variability and cost, it is up to the engineer to design the part such that it is easier to manufacture using this process.

After the layup process is complete, the resulting part is placed in an autoclave, which heats the part to the appropriate temperature and applies the appropriate pressure to cure it. The final part is then removed from the autoclave and separated from the tooling. Barring any additional post-processing, the part is ready to use. This process yields extremely strong and stiff parts that are far lighter than many equivalent metal part designs.. They end up being very expensive, however, due to the material and manufacturing cost. In return, engineers can make use of their high specific strength and specific stiffness, while understanding the limitations of anisotropic load-bearing parts.

Wet layup doesn't use the same prepreg tape as traditional layup. Instead, dry fibers are placed on tooling as required and then covered in wet resin. The resin is used to produce an impregnated composite material. This is done by using rollers, brushes or other tools to force resin into the fibers (which are often in the form of a fabric for this manufacturing method). Room-temperature curing resins can be used to simplify the process even further. This method yields parts with similarly high values for material properties when compared to prepreg hand layup. Figure 2-2 shows the basic layup pattern and manufacturing techniques used for this process.

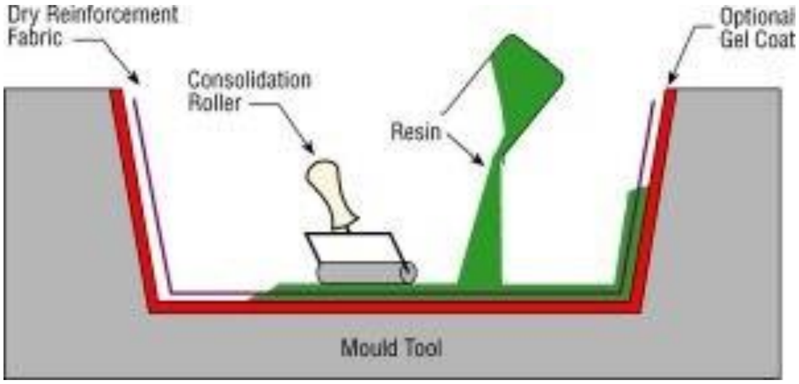


Figure 2-2 Wet Layup Composite Part Manufacturing [14]

One of the main advantages of wet layup is that it has been in use for many years, so the process is fairly well documented. It has fairly simple manufacturing principles that can be easily taught. The tooling required is often low cost and room temperature curing resins eliminate the need for an expensive autoclave. There is a wide variety of materials that can be used for this method and the parts it produces can obtain very high fiber contents.

However, the success of this process is entirely dependent on the skills of the manufacturer. The laminator must check each part for proper resin mixing. If the end part has a low resin content, the laminate may have dry fibers, which affects the end-product quality of the part. The material properties may also suffer from voids in the part, which may be critically detrimental for load-bearing parts. Additionally, the available resins are limited if there is a requirement of being workable by hand. The viscosity will need to be below a certain value to achieve the desired shapes working by hand. This is often achieved by diluting the resin, which may compromise the mechanical and thermal properties of the end part.

Chopped fibers are commonly found in mats that use the same hand layup process as the one used for prepreg hand layup. Chopped fiber parts take advantage of short fibers to build composite parts in a way that is less anisotropic than parts built using long strands of continuous fiber. They are generally easier to manufacture and design with, while maintaining high weight-to-stiffness ratios. This material exhibits a wide range of uses. The properties, however, can be affected by the nature of the material itself. The short fibers are randomly oriented, so they are treated as quasi-isotropic, with averaged material properties being used [16].

The nature of the randomly oriented fibers makes it much easier during manufacture to achieve near-perfect coverage of the fibers in resin. This eliminates the possibility of dry fibers found using other methods, which can be detrimental to the structural capabilities of the part. Short fiber composites are the easiest to manufacture, especially when compared to its long-fiber counterparts. However, since the fibers are so short, this composite type offers the smallest increase in mechanical properties for the material. They are often manufactured by forming the short fiber composite material into the final parts with a mold or during extrusion.

One composite manufacturing method, Automated Fiber Placement (AFP), appears very similar to CFRP 3D printing. However, this process has its own set of limitations and advantages. The process involves parallel fiber tow lines being placed next to each other on a tool that matches the final shape of the part. These fibers can be placed in specific orientations on the tooling such that the load paths traveling through the part follow the stiffer sections, which offers an opportunity for an extra layer of optimization in design for this process. The fibers are placed on the part in layers until it reaches the desired thickness. The part is then placed in an autoclave to cure, much like traditional layup composite manufacturing techniques. This technique has some obvious advantages over traditional hand layup, namely that the possible part size is much larger. Also, since the process is automated, the part can be built automatically after setup, which reduces required man-hours spent actually building the part; after setup, the machine takes care of the rest.

There are some limitations, however. For example, the geometry of the part is limited by the tooling. The tooling itself must be manufactured at some point, which means it is fundamentally constrained by those manufacturing methods. Additionally, complex geometries, including internal features made all at once in a single process are difficult to achieve and require an extra level of design (joining). The fact that the part must be cured in an autoclave may also limit actual applications as the cost of an autoclave large enough to fit massive parts can greatly increase expected costs. If an autoclave large enough to accommodate the part can be acquired, however, this process has the ability to manufacture parts that are much larger than the CFRP 3D printer, which is limited by the size of the build platform and z-axis height [16].

Automated fiber placement uses a machine that acts similarly to the continuous carbon fiber 3D printer. It places a prepreg tape in layers on tooling which is heated then consolidated using a roller or shoe as it’s placed down. In this way, you can build up layer by layer until the final part geometry of an end-use part is achieved. This method has the advantage of laying down multiple fibers at a time in any order. However, it doesn’t have the option to place layers without fiber, which decreases design freedom. It also can produce parts that are very large, which reduces the need for joining operations in the final assembly (depending on the application). The size and shape is constrained by the tooling and also by the fact that the end-part must be able to fit into an autoclave for curing.

2.3 Composites in Additive Manufacturing

The continuous carbon fiber 3D printing method uses the basics of FFF (FDM) additive manufacturing (rapid prototyping) technologies to build parts layer by layer using CFRP material. The CFRP material can make use of a number of different materials for the matrix and fibers, but one common combination uses a nylon filament matrix impregnated by placing carbon fiber strands in the layers and locations where they are required. This method takes advantage of the properties of composite parts and of additive manufacturing by allowing the user to control the location and orientation of the carbon fiber which, in conjunction with FEM analysis and optimization methods can allow for reduced costs and material usage. By using two vastly different materials, composites are made stronger, stiffer, and tougher than either of the two materials would be separately. The nylon provides toughness and a path for loads to travel along to reach the stiffer and stronger carbon fiber layers. The carbon fibers provide the part’s strength and stiffness that composites are known for. Additionally, this combination yields much lighter parts than those produced using metals that have similar properties.

One massive difference between traditional, subtractive manufactured parts and composite parts is that traditionally manufactured metal parts can be treated as isotropic (meaning that they have the same mechanical and thermal properties in every direction), while composites must be considered anisotropic. This means that the strength, stiffness and other properties are dependent on the direction the load is applied which places a number of design restrictions on the engineer. This anisotropic nature is true not only for composites, but also for parts built using FFF [17]. Understanding how a part will react to various loading and boundary conditions is crucial to designing a successful composite part. For certain load paths, the part can be extremely stronger by relying on the fiber to carry the loads. Conversely, for other loading conditions it can be extremely weak as it may rely on the matrix as well. Because the material properties of the material is dependent on the loading direction, the designer must realize that relying on the matrix material to carry a load can lead to part failure by way of delamination or fiber breakage. Even if the fiber is discounted, FFF produces anisotropic parts as a function of the build process [17].

The anisotropic nature of composite materials present engineers with the opportunity to realize tremendous upside, namely in their ability to produce stiff, strong parts that are lighter than similar parts produced from metal. By 3D printing composite parts, the user can realize additional upside inherent to additive manufacturing methods. Additive manufacturing produces parts that can take advantage of complex geometries and grant a large amount of design freedom to engineers. Being able to print stronger materials greatly increases the capability of the process. 3D printing structural, load-bearing parts has always been difficult due to the limited capabilities of available materials. Because of this, ABS or PLA 3D printed load-bearing parts have all the capability of printing complex geometries, but are required to increase the volume of material in the design to achieve reasonable strength for the part. The advent of composite 3D printers means that stronger materials can be used to alter geometry by removing now-unnecessary material, while maintaining requisite stiffness [18]. The main disadvantage of composite parts is that the materials are far more expensive than more conventional FFF materials (ABS and PLA).

Prepreg hand layup is a common composite manufacturing method. CFRP 3D printers can be used to produce parts that would be difficult or impossible to manufacture using well-established hand layup techniques [2]. While hand layup (dry and wet) are both limited by the skill of the manufacturer, CFRP 3D printers will consistently produce high quality parts according to user-defined settings. The skill of the user for CFRP 3D printing has more to do with designing for additive manufacturing and understanding the limitations of the hardware than it does having the physical capabilities and long-term experience required for hand layup. The geometry of parts made by laying plies up against tooling are also limited. Tooling places a greater limit on part geometry than it might appear to at first glance. The tooling itself must be machined, or otherwise produced. Also, there is no way to get good-quality internal or flowing geometries using this method. In this way, the CFRP 3D printing method can produce much more customizable parts with the ability to place individual layers of fibers in a mostly-nylon part as well as produce more elaborate geometric patterns.

The same advantages hold true for wet layup methods. One important note to make is that dry fibers are not a common problem with the CFRP 3D printing method. Instead of the operator using their hands or simple tools to attempt to get an even, complete coating of resin, the FFF 3D printer simply moves the tool to place matrix material on every uncovered fiber; it would take a failure of the machine (i.e. a breakdown or clogged nozzle) to mistakenly place thermoplastic. The reliability of FFF printing cannot be underestimated when discussing its applications in industry. Other manufacturing methods may have a relatively high rate of failed parts and require years of process optimization and refinement using a statistical approach before obtaining reasonable failure rates. FFF, however, will consistently produce identical parts after the correct process parameters and printer settings have been decided on. In short, once a print has been successfully manufactured, it is a simple matter to produce an identical copy of that print. When the print does fail, it is usually the cause of user error. For example, if the incorrect material is loaded into the machine, but the temperature for the heating element isn't updated, it is common for the material to either overheat, burn, and clog the nozzle or for the underheated un-melted material to become stuck. Since the thermoplastics used in FFF are hydrophilic, use of old material that has taken in moisture may also result in a poor print. If the wrong support structure is selected, it is possible for the part to shift during printing, which can result in misprints or warped parts. Finally, incorrect orientation of the part or inappropriate use of support material can lead to over-supported parts (which wastes material and is especially relevant in higher volume print runs), or under-supported parts which are likely to fail. Each of these causes of failure can be attributed to an incorrect set up by the operator and are ultimately avoidable. Once the correct settings are decided upon, applied to the software, and proven to work, successive prints will rarely fail.

The Fused Filament Fabrication (FFF) method provides the opportunity for designers to achieve part designs that are designed specifically to accommodate the load-paths that are generated for a part under a given load [19]. Producing these optimized, organic and naturally flowing geometries is extremely challenging for traditional machining methods. In the past, engineers have been required to make compromises in their part design to accommodate the fact that the design would actually have to be manufactured. However, with the ability to manufacture just about any geometry using the FFF method, engineering design freedom has expanded to unprecedented levels. The search for stronger materials than the common thermoplastics, ABS and nylon, has been spurred by this design freedom. At the moment, instead of being constrained by manufacturability, engineers are constrained in this method by the rather poor mechanical properties of parts made out of thermoplastics. Load-bearing materials like 3D printed metals as well as CFRP and even microfiber filaments are important for the long-term development of this manufacturing technology. It allows for parts that have the requisite mechanical and thermal properties to be manufactured in such a way that the shape of the part takes advantage of the optimized solution that follows natural load-paths through the part.

The advantages of FFF metal 3D printers are namely that the metals produced are fully dense and that the process can effectively produce precise internal features [10]. While the process is generally considered to be complicated to design for, once the appropriate geometry and process parameters are achieved, FFF metal 3DP is extremely consistent. In any manufacturing application, there are an expected number of failed parts. This process, however, very rarely fails for a proven print if it is set up correctly. This predictability is a massive asset in manufacturing. Main disadvantages of this method include high cost and long processing times. Parts will often take several iterations before the right process parameters and part geometry are attained. The fine-tuning period greatly increases the time-to-market for mass-production using this technology. Two markets that are interested in this type of technology are the automotive and aerospace industries, where speed and cost aren’t usually prohibiting factors.

Metal 3D printers are also constrained by their lack of available materials. This is because each printer requires a very specific set of process parameters depending on the material used. These parameters are different for every material; there is no one-to-one correlation between two materials. As such, finding the correct settings for a printer requires a great deal of trial-and-error research. Available materials that are the most consistent in industry right now are stainless steel, aluminum, titanium, cobalt chrome and Inconel alloy. The material chosen depends entirely on the application and availability. The surface finish on these parts is quite poor due to the layer-by-layer approach, similar to thermoplastic parts. The supports generated using this process must also be removed; CNC machining is a common next-step for metal printed parts both to remove supports and to machine in any fine features.. The parts usually require additional operations on the surface. After the build, then, metal 3DP parts will require additional post-processing and finishing to obtain a reasonably surface finish.

2.4 Continuous Fiber Reinforced Polymer 3D Printing

Continuous Carbon Fiber Reinforced Polymer (CFRP) 3D printing takes advantage of the speed and flexibility of additive manufacturing with the added benefit of having the freedom to choose which layers to place fibers and which to leave as matrix material only. This can be used to attain requisite stiffness in a part while designing to minimize carbon fiber use to reduce cost. Other benefits include being able to print complex geometries with internal features thanks to the FFF method [18]. The carbon fiber itself has a length limitation because, unlike with nylon, ABS and PLA, the fiber must be cut to length at the end of each printed layer. The minimum length limitation is constrained by the location of the cutting mechanism (which is located on the gantry for the Mark Two). The overall process has the same limitations as many additive manufacturing methods as well as the anisotropic nature shared by other composite manufacturing processes. One such limitation is that composite parts are notoriously weak in out-of-plane loading because the stiffness from the fibers only exists in a 2D plane (they cannot be placed in the z-direction). This same through-the-thickness weakness is shared by the Mark Two as a function of the additive manufacturing method, which also places the fibers and resin in layers. The out-of-plane stiffness for the Mark Two is also fairly low as the part is only held together in that loading condition by the bonds between layers. These layer bonds are much weaker than the material properties of either the fiber or the matrix. The carbon fiber can be placed in alternating fiber orientations as with conventional composite parts, so in that way transverse loads can be treated in a comparable manner to traditional prepreg layup parts.

The Mark Two Continuous Carbon Fiber 3D Printer presents a novel manufacturing technology that allows designers to take advantage of composite parts by using the fused filament fabrication additive manufacturing process, namely the complex, organic and load-driven geometries generated using finite element method optimization techniques.

Figure 2-1 Continuous Carbon Fiber 3D printed part

The Mark Two Continuous Carbon Fiber 3D Printer utilizes the material extrusion process (FFF) to take advantage of being able to place continuous lengths of carbon fiber in the part for added stiffness and create Carbon Fiber Reinforced Plastic (CFRP) parts. Any composite, by definition, requires two materials: a matrix and a fiber. To accommodate this requirement, this printer makes use of a two nozzle design. One nozzle prints nylon while the other is used to place the carbon fiber filament. For each layer, in order to cease printing the nylon, a command is simply sent to the stepper motor to stop printing. There is a blade that is used to cut the carbon fiber to length for each layer, which naturally limits the minimum allowable length of fiber to the distance from the tip of the nozzle to the blade. The fiber is naturally easy to break as a thin filament, but must be placed side-by-side, doubling back on its length for some fiber configuration settings. The nylon used for the matrix material is hydrophilic, so it must be kept in a dry-box. The nylon travels from the dry-box to the printer encased in a Bowden tube. The nylon is, however, exposed to air at the stepper motor and on the carriage near the nozzle, meaning that it can still take in moisture at those locations. Before printing with the nylon, it is important to perform a purge if the printer has not recently been used. This purge will expel any wet nylon filament from the Bowden tube and only the dry nylon will be used to print.

Figure 2-2 Wet nylon (top) vs dry nylon (bottom)

One important note to make for the CFRP method is that the strength of the parts is reliant on the length of the parts. As the size of the part increases, its strength will naturally decrease [23]. The rule of mixing for this particular method has also been found to be lacking; it doesn't properly describe the behavior of CFRP parts. Fiber discontinuity is also a common issue that must be dealt with using this method. The printing pattern is to blame, as when the fiber layers are set in "contour" mode, the concentric rings begin on the outer contour first, and print moving inward [23]. There is no way to print so that the position where the fiber begins will perfectly meet and become continuous with the point where the fiber ends. By necessity, the process causes the print head to shift inwards after each contour to continue printing on the same layer. When printing in the "isotropic" mode, the print head must go out and around in a small loop, meaning at the ends the fibers aren't perfectly straight and parallel to one another, but enter return raster at a slight angle before correcting and becoming parallel again. This loop on the head is a product of this hairpin turn.

This method is not limited to only carbon fiber and nylon materials. Markforged's machine can also print Kevlar, fiberglass, and their own propriety short-chopped fiber blend called Onyx. The Kevlar and fiberglass materials are similar to the carbon fiber in that they can be printed as the fiber with nylon as the composite [18]. This plug-and-play interchangeability is a positive mark towards the efficacy of this process as it allows great flexibility in material selection and design. Onyx, their proprietary short-chopped fiber impregnated polymer, seems to be printable just as it is without the need of a cutting blade. Printing chopped fiber parts is fundamentally different from printing with a continuous carbon fiber as it is not limited by the orientation of the fiber in each layer, so the transverse stiffness in a layer will be just as strong as the stiffness in the primary loading direction. The material is still anisotropic, however, as the material properties of the part in the through-the-thickness direction will still be weaker than the in-plane material properties. Other continuous fiber printers may also use the more common FFF materials PLA and ABS, but these are not currently available with the Mark Two. This is a restriction of the software (Eiger), not the process itself.

Short fiber composites present a different side to composite manufacturing that is less anisotropic than traditional continuous fiber composites. They can be manufactured in a few ways, namely by using chopped fiber strand mats or by extrusion. Short fiber composites must be built in layers similar to how other composite parts are manufactured. This means that they aren't perfectly anisotropic, which would give this composite type a massive advantage over others. Additionally, the randomly oriented short fibers give the part random mechanical properties, within a reasonable range. This means that short fiber composites require extensive testing and process refinement to consistently produce parts that can carry the desired loads. This material type works perfectly with the FFF 3D printing method because short fiber material can be extruded out of a nozzle. One advancement in this area uses microfibers instead of short chopped fibers, and can print a part layer-by-layer to completion using FFF. The parts produced are discretized in layers, meaning that, as with other 3D printed materials, the resulting parts are weak in certain loading conditions. The material does increase the strength of the base matrix material that is impregnated with the microfibers, which increases the number of possible applications for this manufacturing method. In short, microfiber impregnated matrix material that can be extruded in the FFF method provides tremendous opportunity for designing parts that are stiffer and more lightweight than was previously possible with thermoplastic polymer 3D printers.

Similar to short fiber composites, microfiber composites can produce parts after being extruded into a given shape. This material works perfectly for additive manufacturing processes, specifically for FFF. This material is made of nylon that contains carbon fiber produced as very small microfibers. The resulting material is stronger, tougher, stiffer, and more heat resistant than regular nylon. The fact that it can be manufactured using the FFF method is great for the additive manufacturing sphere; stronger materials with little engineering drawback are very desirable. The drawback to this material, however, is the cost. It is much more expensive that nylon filament, as one can imagine.

This material is also useful for the continuous carbon fiber 3D printer. Not only can it print parts with better thermal and mechanical properties than nylon on its own, it can also be combined with fiberglass, carbon fiber, or Kevlar fibers that the continuous carbon fiber 3D printer can. This will only further improve the quality of the mechanical properties in the part. The drawback, of course, is the material cost. This material may very well be used to strengthen parts, but, unlike with the design methodology for carbon fiber reinforced nylon, the user cannot tell the machine not to place carbon fiber in certain sections to minimize cost when the fiber is simultaneously placed in the matrix material but the matrix material itself is impregnated by additional microfibers. Also, the support material will also be comprised of the microfiber impregnated nylon, making design for additive manufacturing to reduce required support material critical to keeping costs low. The parts printed using this method, then, will always have a relatively high material cost when compared to CFRP.

Figure 2-3 Onyx Parts [20] [21]

Optimization refers to an iterative process that perform multiple analyses on a part under a given loading condition and with specified material properties to determine how to best remove material (to lighten the part) or meet some other design objective. With the advent of CAE tools like finite element analysis, designers can make use of a numerical iterative optimization process. The results of optimization, then, typically show the best geometry for the load paths in a structure. For topology optimization, a geometry is generated based on a set of design variables. Two important methods of numerical topology optimization in use are the SIMP and ESO (SERA) methods. The SIMP optimization method optimization generally occurs by labelling each element with a black-and-white score, or p-factor, of 0 or 1, 0 meaning there shouldn't be material there and 1 meaning that there should be material there. This p-factor can also generate solutions in which the density is found to be between 0 and 1. These "grey" areas can be penalized to obtain nearly pure black and white topologies [6]. Another structural topology optimization method is the ESO method, which can be generally referred to as a heuristic method. It makes use of a criterion function which is calculated for each element as part of an iterative processes that is used to eliminate elements that have the lowest criterion function (i.e. the 1 is forced to become a 0). This method calculates a large number of possible solutions with a value assigned to each solution, which is called the performance index. The global optimum is the solution with the highest performing index out of all of these solutions (or the lowest depending on what criterion was selected). By making use of these methods, an optimized design is generated [6].

Non-uniform rational B-spline (NURBS) is a modeling tool used to take the noisy, organic geometry generated by a topology optimization and create a smooth, useable surface geometry that can be treated as a solid model [22]. This method is used to more closely match complex, optimized shapes. It is a more accurate alternative to taking measurements of part cutouts from the optimization results and manually applying them in a separate solid modeler. While the NURBS tool wasn't used in this design methodology, it is worth mentioning as a possible alternative geometric design tool.

Chapter 3 Methodology

3.1 Process Requirements

The Carbon Fiber Reinforced Plastic (CFRP) 3D printing method enables the user to print composite parts using the FFF additive manufacturing process. As with any composite manufacturing, two distinct materials are required: a matrix and a fiber. The fiber is the stiffer of the two and generally has a much higher tensile strength. This lends the part very high strength in the appropriate fiber direction. These stronger, stiffer fibers are, however, much more brittle than the matrix material. The relatively ductile matrix material encases the fibers, lending them some measure of protection from transverse and compressive loads, while transferring loading conditions between layers. The matrix helps to discourage delamination and connects the fibers together in such a way that they are less likely to individually snap or break when subjected to an overwhelming load and instead share the given part load across many fibers which greatly increases the part's overall strength and stiffness. This symbiotic relationship between matrix and fiber is what makes composite parts desirable. They can be much lighter than isotropic metal parts ,depending on the application, while display similar material properties in their strong directions. In transverse or out-of-plane loading, they are often much weaker due to their anisotropic nature, however.

While the two basic materials, fiber and matrix, are required for the process, the specific materials used can be anything that meets the criteria for each component. Common materials used in CFRP 3D printing are PLA and nylon . Thermoplastics are often used in FFF because of their workable nature when heated about the glass transition temperature. The possible fibers extend to carbon fiber, fiberglass, and Kevlar. The printer used in this investigation is the Markforged Mark Two continuous carbon fiber 3D printer and the materials chosen for the Vayu motor mount case study are nylon and carbon fiber.

It is worth mentioning that a 3rd material type has recently entered into the CFRP scene that uses short or microfibers imbedded in the thermoplastic matrix material. One such material is Onyx. Developed by Markforged, Onyx is a polymer reinforced by short micro- carbon fibers. It is similar in nature to the material used in short chopped fiber mats, and shares a number of characteristics with that material. Traditional continuous fibers are highly anisotropic, but the short chopped fibers offer a slightly more isotropic material. Since the layering process used in FFF is by necessity used to create Onyx parts, however, this isotropic nature is limited to the xy-plane as the through-the-thickness properties still suffer from delamination and reliance on layer bond strength.

This layer-by-layer approach follows the same steps as the FFF process. The FFF process uses a filament of the printing polymer (usually PLA or ABS, but other materials like nylon can be used as well). The thermoplastic is stored around a spool. The filament is fed through the machine to the stepper motor, then from the stepper motor to the top of the carriage. The carriage is the part of the machine that contains the heating element and nozzle. Some printers will also contain the stepper motor on the carriage. This filament is pushed through the heating element, which melts the plastic. The melted plastic is pushed through the nozzle at the end of the heating element by the un-melted filament being pushed into the heating element behind it. In this way, the appropriate amount of material is extruded through the nozzle at a specified bead width and layer height, dependent on the capabilities of the hardware (the nozzle diameter) and the setting which are usually specified in the slicing/printing software.

CFRP 3D printers follow production steps that are similar to those used in FFF. The material is extruded out of the nozzle at a given rate. The carriage is moved in the xy-plane by two belt and pulley systems (one in “x” and one in “y”). Some printers will allow the carriage to only move in one plane, or perhaps online “x” and “z”. Whichever of the three directions, x, y and z, is neglected will be picked up by a third pulley or lead screw in the bed. Generally speaking, a lead screw controls the z movement and pulleys are used to control the x-y movement. Using these controls, the nozzle is moved on the carriage to trace the outer contour of the part. The number of “walls” (outer contours) can be specified in the slicing/printing software. After the contour(s) are printed, the nozzle comes back to the inside of the part and prints the raster pattern, or infill. This shape used in the pattern and infill density are two key settings that can be adjusted in the slicing/printing software. In this way, each layer is traced in contour and then filled in by the nozzle as it moves along the xy-plane on the carriage. The bed/carriage is then moved in z by the lead screw up by a distance of one layer height (for the Mark Two, this distance is 0.125 mm), and the process begins again for the next layer.

This process necessarily produces discretized steps when printing a curve in the through-the-thickness direction (z-direction) as each subsequent layer must be laid on the previous layer at an offset distance to create the curve. This stair-stepping effect leads to a poorer overall surface finish and, depending on the application, can affect fit and form testing of the part. Another consequence of this effect is that the layers may separate (delaminate) when subjected to bending or compression loads. In these loading conditions, the stair-steps act as small stress concentrations that place the highest stress at the same location as the section between layers that are held together by nothing but the bond between layers, which is much weaker than the material. Additionally, the raster angle settings may affect the part properties, further complicating the material properties in the xy-plane [24].

There are several methods to avoid producing discretization in end-use parts, but sometimes the effect is unavoidable and remains a key limitation of the FFF 3D printing process. One such method involves simply rotating the part to accommodate the curve in the xy-plane instead of through several layers in the z-direction. Part orientation is a key design decision for load-bearing parts. Another possible solution is to print the part in two pieces, each in a different orientation to eliminate the stair-stepping and then combining them in a joining process (with adhesive or mechanical fasteners). This involves an extra few steps of post-processing and joining, however, which eliminates some of the key advantages of additive manufacturing.

Another key consideration in this process is how to print supports. Many parts will include complex inner geometries or overhangs. As the printer lays down material to create an overhang, it will have nothing to print on as it was previously using the earlier layers as a foundation to apply the material to the new layer. So, for overhangs, support material is required. Support in FFF is a method by which material is placed such that overhangs and other complex, unsupported geometries will have something to print on. The supports have their own generally accepted patterns that are designed to be easy to remove. Some prints even have a second nozzle on the carriage that prints a totally different material from the build material (called the support material). The support material is dependent on the build material. Ease-of-removal is a crucial deciding factor for support material; some of them can be removed by soaking in a solution or bath which will dissolve the support material and leave only the build material behind.

For printers with only one nozzle, there is only one appropriate support material (like the Mark Two); the build material must also be used as support material. This necessitate the use of specific support structures that allow for easy removal of the support. Because the build and support materials are the same, it is more difficult to remove. This leads to longer post-processing times to remove the support material and makes removal of support material from internal geometries anywhere from difficult to impossible. The Mark Two has default settings for support material that cannot be changed in Eiger (the slicing and printing software used for the printer). It uses an accordion-type of support that is meant to be easy to remove by lifting up one end and pulling all subsequent support off as one piece. However, some geometries, like the mounting cylinder in the Vayu motor mount case study, make this difficult. This specific support generation also tends to move or buckle during printing, which leads to burned parts as the hot nozzle prints the next layer and brushes up against the deformed support.

For the FFF additive manufacturing method, slicing/printing software is used to set parameters and develop a tool path for the nozzle to follow during printing. Popular slicing software includes KISSlicer, Slic3r, MakerBot desktop and FlashPrint. Some of software, such as MakerBot desktop and FlashPrint will both slice and print internally. Other printing software require the part to be sliced beforehand. In slicing software, an STL of the part is imported. The STL file format is does not specify units, so it is important to visually confirm that the part imported is correct. In the slicing software, various parameters can be changed including, print speed, extrusion rate, infill density, the raster pattern, number of walls, number of floor layers, part orientation and others. Another notable feature is the ability to generate support based on parameters like minimum offset angle (the angle at each an overhang occurs) and support type (accordion vs tree-like, or other shapes). When the part is sliced, a layer-by-layer toolpath is generated according to the inputs available in the software. This layer-by-layer toolpath is communicated to the printer in the form of G-code, which tells the nozzle exactly where to move, when to extrude material, and which material to extrude as well as communicating any other parameters specified in the slicing software like extrusion rate and nozzle travel speed. The printer then follows the G-code line-by-line for each layer according to the specified user settings to print a completed part.

These basic FFF production steps are followed by the Mark Two to print the nylon matrix, which is treated as both the build and support materials. The carbon fiber is printed continuously from a spool that is fed by a stepper motor into a heating element and through a nozzle much the same as any other thermoplastic filament. The carbon fiber doesn’t follow the same pattern of contour then raster pattern that the build materials for FFF generally follow. Instead, the walls are created using nylon so that the fiber is full enclosed and then the fiber is placed in the infill using a raster pattern that is determined in the slicing software, Eiger. There is a minimum length of fiber that can be printed which is determined by the length from the nozzle tip to the cutting knife on the carriage of the printer. This knife will neatly cut the fiber to length when this minimum length is equal to the remaining fiber length required to complete the layer. The printing pattern that the fiber follows is defined by the software as either “concentric” or “isotropic” fiber modes. The concentric mode causes the printer to print the fiber in concentric rings around the part that follow its contour. The rings are printed until the minimum length of the fiber for a contour is reached. Contours that would have been generated that have a total length-to-print of less than the minimum printable length will not be printed. Isotropic mode causes the fibers to print some number of walls in concentric mode, while the rest are printed in a side-by-side continuous raster at a given angle like traditional prepreg tape used for layup. At the end of each fiber line, the nozzle follows a looping curve at the end of each line in order to place subsequent fibers side-by-side and parallel to the previous fiber line.

There is a setting for the number of fiber walls, which allows the user to decide how many concentric rings of fiber will be printed to follow the contour for the isotropic mode, which in turn determines how the length and number of parallel fiber lines that will be printed in isotropic mode. Figure 3-1 shows a layer of isotropic fibers being printed after a single contour.

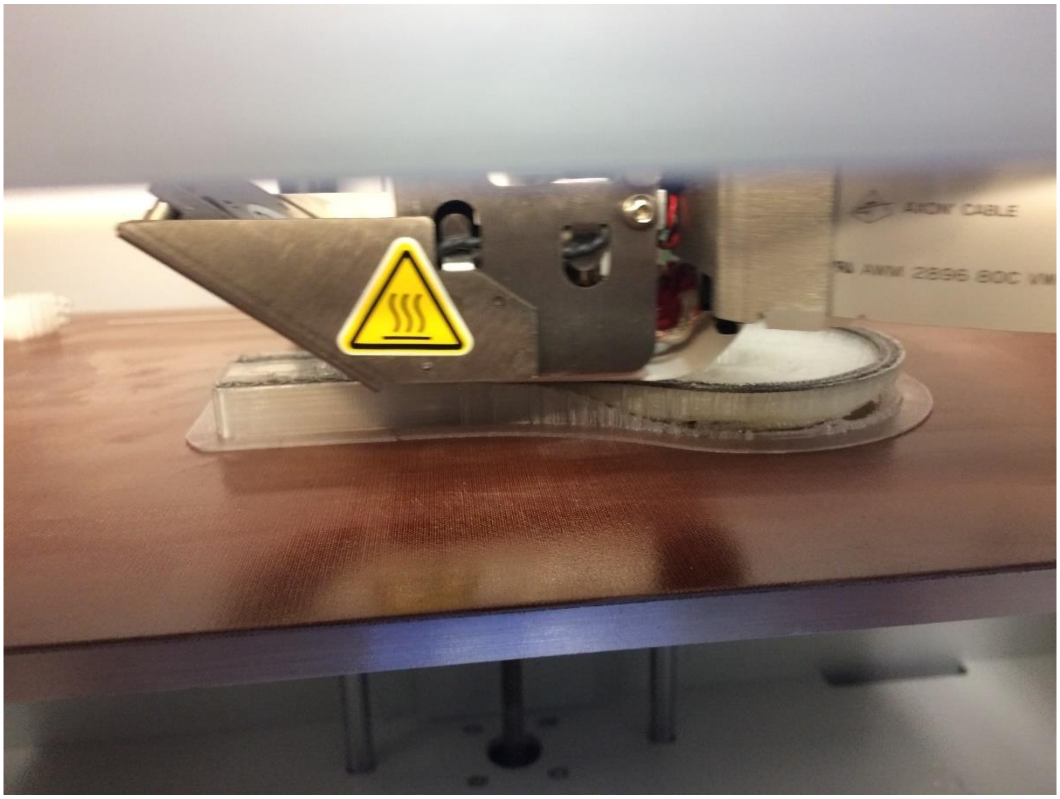


Figure 3-1 Printing a carbon fiber layer

It is important to understand both how the process works and the purpose of different materials used in the process so that the advantages and limitations of this manufacturing method can be understood in full. The limitations of printing in layers are evident in delamination, anisotropic material properties, and limited capabilities with curved edges in the z-direction. Delamination is an important factor to consider in any layer-based manufacturing method. One notable comparison can be made with traditional prepreg layup techniques, which use a number of plies with fibers at different angles to build up the part layer-by-layer. The FFF method has similar problems with delamination and those issues are compounded when using CFRP. In certain loading conditions, there is a lot of stress applied at the boundaries between layers. The strength at these boundaries consists only of the bond strength, instead of the standard material strength of the matrix or fiber. For the purposes of the Vayu motor mount case study, in which all of the fibers were printed in the 0°, the strength of the part in the transverse direction (perpendicular to the fiber direction, or 90°) is essentially the same as the strength of the nylon.

Table 3-1 FFF and CFRP Material Comparison [25] [26] [27]

	PLA	ABS	Nylon	Carbon Fiber
Tensile Strength, Ultimate (MPa)	48	32	54	700
Elastic Modulus (GPa)	3.039	2.230	0.94	54
Density (g/cm^3)	1.25	1.07	1.10	1.4

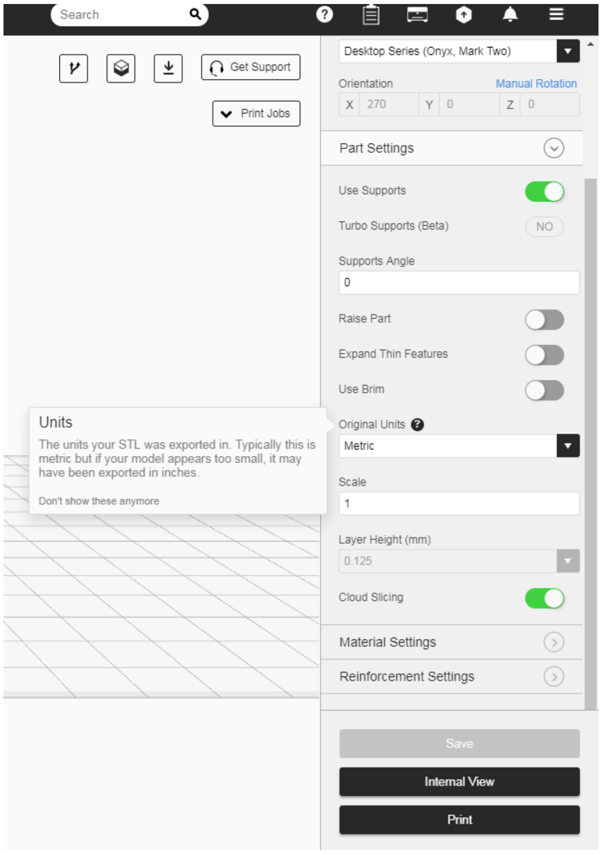
From Table 1, nylon has a higher than normal ultimate tensile strength, but a very low elastic modulus when compared to the other two common thermoplastic printing materials. This makes the nylon much tougher than either the PLA or ABS materials. Carbon fiber has the highest stiffness and ultimate tensile strength, of course, which complements the nylon's toughness. The resulting composite material makes use of this combination of tough and durable nylon and the extremely strong and light, but brittle, carbon fiber. The resulting part is very strong and can make use of the nylon to transfer transverse and through-the-thickness loads to the carbon fibers. Nylon on its own is less desirable for structural parts and relies on the strength of the carbon fiber when used in structural parts. Additionally, though many thermoplastics are hydrophilic, nylon is especially so. For the purpose of 3D printing, nylon must be kept in a dry-box with regularly replaced desiccant pouches to avoid it absorbing any moisture. If the nylon (or any other 3D printing thermoplastic) takes on too much water, it becomes impossible to print with it. The end parts will have a bubbly effect, or fail to bond between layers. It can lead to excessive warping of the part as well as a massive decrease in its material properties. The loss of quality in the end-product part is immense. Additionally, the nylon must be purged before each print as there is some amount of it that is open to absorbing moisture in the air as it passes from the enclosed Bowden tube through the stepper motor and as it passes through the enclosed Bowden tube to the nozzle. After each purge, these two sections of wet nylon are expelled. This action must be performed each day before the machine can be used to print parts, otherwise the operator runs the risk of poor quality sections occurring in the part.

The Carbon fiber gives the user the advantage of extremely high stiffness at an order of magnitude higher than other FFF materials, but comes with its own set of limitations. For one, the fiber itself is small and difficult to work with. The entire spool of carbon fiber must remain under tension, else it will come undone. Re-winding the expelled filament is extremely difficult and time consuming, making initial handling of the fiber important to timely part delivery. This filament must be simultaneously fed into its own Bowden tube and kept under tension until it reaches the carbon fiber stepper motor. It is very easy to accidentally break the fiber as it is being fed into the moving motor during loading, which can lead to broken pieces of fiber in the tube. The fiber itself must also be cut to size during printing, meaning that there is a minimum acceptable printable length of fiber, which places additional design constraints on the user. Each layer will be one continuous fiber in the isotropic mode (barring the contour walls). In the contour mode, each contour will have its own separate fiber, which is cut to size by the printer's knife. This means that in contour mode there is a minimum acceptable contour length, which can severely limit fiber placement. This can be an issue depending on the loading conditions of the part.

3.2 Process Limitations

There are also limitations for the process itself. One important limitation to note is the requirement of proper bonding, both between the first layer and the print bed, and between subsequent layers. Whenever two different materials are used in printing, it is important to consider how the two materials will bond with each other between layers. The purpose of using carbon fiber in the FFF process is to produce CFRP parts that will guide the load to the stiff, strong fibers. The layering process creates a discretization effect which can naturally produce stress concentrations in the part, which is undesirable. The nylon is meant to act as a mechanism for transferring load to the fibers; it is not meant to carry the brunt of the load itself. This effect exacerbates the FFF process discretization issue in parts that are built with overhangs or changes in curvature in the through-the-thickness (z-) direction.

In order to print with the Markforged Mark Two continuous carbon fiber 3D printer, their proprietary software, Eiger, is required. It runs in browser and utilizes the cloud to slice the STL. All of the parts and a complete print history are kept in the software. When a part is uploaded it can be saved in a project folder. The software comes with complete estimates of total material cost, volume of material used, and an estimated print time. It includes many of the same settings that other additive manufacturing software has including an option for controlling infill density, raster patterns, number of wall layers, number of roof and floor layers, orientation, material selection, etc. This software automatically places and generates support according to your settings if it is required, but there aren’t any options for different support types (for example, tree-like supports are not an option). Typically, when deciding on a support type, there are a number of considerations for the FFF additive manufacturing method. Without having the choice to generate the appropriate supports for a given geometry, post-processing can be made much more difficult. If the support removal is made more difficult, it can greatly increase the time required to generate a complete part and will also have a negative effect on the surface finish of a completed part. Figure 3-2 shows Eiger's available part and support settings.



Desktop Series (Onyx, Mark Two)

Orientation

X 270 Y 0 Z 0

Use Supports ●

Turbo Supports (Beta) NO

Supports Angle

0

Raise Part ○

Expand Thin Features ○

Use Brim ○

Original Units

Metric

Scale

1

Layer Height (mm)

0.125

Cloud Slicing ●

Units

The units your STL was exported in. Typically this is metric but if your model appears too small, it may have been exported in inches.

Don't show these anymore

Figure 3-2 Eiger Support Settings

The Eiger software also decides how to place the stiffening fibers in the part automatically, based on some basic user settings (the contour or isotropic modes being one of the decisions the user can make). Unlike other software, Eiger doesn't allow the user to manually place material. This means that when setting up the print the designer must consider that they may choose the layer for the fibers to be printed and their basic orientation, but cannot pick and choose the specific fiber placement (for example, the user cannot have irregular lengths of fiber on part of a layer, but leave the rest of that layer without fiber). This is a major design consideration for the user when designing for the Mark Two. It limits the ability of the user to place filament where it required only. The results of this limitation are over-designed parts which will be more expensive than is necessarily required by the design constraints. The carbon fiber filament purchased from Eiger costs \$150.00 for 50 cm^3. This comes out to \$3.00/cm^3, which is of course extremely expensive. Having the ability to design such that the operator can choose to use less fiber where it is not needed without the limitations of conventional composite manufacturing techniques is one of the original draws of the CFRP 3D printing technology. While the user can take advantage of this design freedom by picking and choosing individual layers to place the fiber, they are unable to limit or otherwise directly edit fiber placement in a given layer. Since the carbon fiber, unlike the thermoplastics, must be cut to length at the end of each layer print, it is further constrained by a minimum fiber length. For layers below a certain print length dictated by the tool path for the fiber, fibers cannot be printed. Additionally, all of the settings for material and basic print settings are decided by the software and cannot be altered by the user. This means that if the material is not supported directly by Eiger, it cannot be used in the machine. This rules out the most common FFF printing materials, PLA and ABS, which further limits design freedom when manufacturing parts with the Mark Two.

Another limitation of the software is the ability to change the infill density. By having stiff fiber layers in a design, it should allow the designer to limit the amount of nylon to only what is required to transfer the applied loads to the load-bearing, stiff fiber layers. By reducing the amount of material, both cost and weight can be reduced, while maintaining stiffness with the fiber layers. However, the infill density on Eiger starts to give nonsensical weight estimation if the user sets the infill density anywhere lower than about 5%. When the infill density is decreased the weight of the part should also decrease, but the estimation in Eiger will show an increase in the amount of material used. This inaccuracy may affect the quality of the final print, so to ensure quality, the minimum infill density allowed on the machine should be placed at 5%.

3.3 Design Case Study Introduction

General applications for this manufacturing method can be found in the aerospace and automotive industries such as with the Vayu motor mount drone case study. The main advantages of this method are an increase in stiffness when compared with other additive manufacturing methods and an ability to decrease material use and weight. The major downside to these improvements is the cost, which is considerably higher than parts designed and produced with traditional FFF in mind. Industries which are willing to pay for the increase in performance are most likely to take advantage of this manufacturing technology. In aerospace applications, weight reduction is often a critical component of the design decision-making structure. Decreases in weight can lead to increases in range and payload for the craft, which can pay for the increase in initial cost over the long term.

The Vayu motor mount design case study clearly illustrates the application of this design methodology. The part has clear loading conditions that are advantageous for CFRP. Since the motor mount experiences a bending load, continuous fibers running at a uniform angle up the length of the part should be used to provide the requisite stiffness. The motor mount is part of a larger assembly: a drone. This vertical takeoff and landing drone has four distinct motors mounted to it. The motors each provide lift; the applied load for analysis was considered to be a 17 lbf point load applied to the end of the mount. Other forces will occur in flight, but they were considered to be negligible. For other part designs, if these forces cannot be ignored, the design can be modified to include cross members and reinforced sections to increase part stiffness in those loading conditions.

The drone required a redesign for the motor mounts as the original parts were made using FFF and, while they were able to meet some of the design requirements, the more weight that can be saved in this application, the better the overall design. The purpose, then, was to use the CFRP design methodology guidelines to develop a redesign for the motor mount that was light and just as stiff as the original part. Additional consideration had to be made for budget, as the addition of carbon fiber to the part design greatly increased material costs for the project. By properly sizing the number of fiber layers required, the cost can be minimized while achieve the original redesign goals.

Chapter 4 Design Specifics

4.1 Problem Setup and Modeling Guidelines

The Vayu motor mount case study perfectly illustrates the potential usefulness of the CFRP 3D printing process. The motor mount consists of two main non-design sections: 1. a mounting cylinder that connects the mount to the drone and 2. A circular head that is used to attach the motor to the motor mount. These two sections are constrained by the assembly requirements for the part. The cylinder must be used to connect the mount to the drone and the motor must be able to fit and properly mount in the circular head. These two sections then, are classified as “non-design space”. The dimensions and features required for appropriate fit and form for final assembly (i.e. mounting holes in this case) cannot be changed; the engineer is required to design the final geometry around these conditions. The rest of the geometry, however, can be changed and as such is labeled “design space”. The mechanism for determining how material should flow from one non-design section to the other is determined by FEM or other engineering techniques. The precise location and loading conditions of the mount can be seen in Figure 4-1.

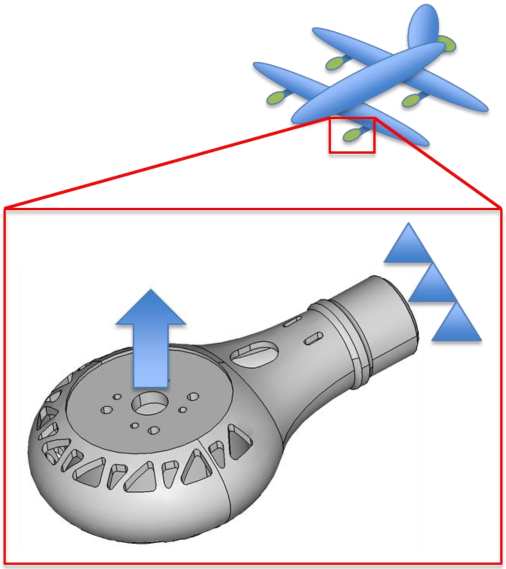


Figure 4-1 Motor mount loading condition

In order to properly model the motor mount, one must decide how to apply the correct loads and boundary conditions. Based on the function of the part, it is reasonable to assume that an applied load must be modeled at the location of the motor. According to Vayu's calculations, this end of the mount is acted upon by a load of 17 lbf. Since the part is attached to the drone at the mounting cylinder on the opposite end, the part must be constrained to reflect this. The inner nodes on the front portion of the mounting cylinder are constrained such that they cannot move. This is the boundary condition for this analysis. This combination of loading and boundary conditions puts the mount in a bending load case, much like a cantilever beam. The point load on the end of the beam causes a reacting load and moment at the constrained end. The beam, then, experiences bending. When considering the placement of the fibers, it is important to consider the locations where they will do the most good. In bending, there are two main loads being applied to the top and bottom of the part. One will experience tension and the other will experience compression, though which end experiences which load depends on the direction of the applied point load. The fibers, then, should be placed at the top and bottom where these loads are being applied such that the fibers carry most of the load rather than the nylon in order for the part to have the greatest strength and stiffness. The fibers will be most sorely needed along the length of the mounting cylinder, continuing up into the cup which holds the rotor. As for where the fibers should be placed, it makes the most sense to place two sets of fibers since the part is in bending: one near the top end of the cylinder and one near the bottom end. Though this can be inferred with an understanding of applied bending, it must still be determined exactly how much fiber will be required and exactly which layers the fiber will be placed. In order to determine which layers to place the fibers, one must understand that the fiber placement is also constrained by the geometry (namely the thickness) of the part, particularly in the circular end where the motor is placed. Because of this, if the fiber is placed too high or too low on the cylinder, the software will automatically reduce the amount of useful fiber to match the layer contour. For it to be most effective, the fiber should travel the entire length of the part from one tip to the other, without showing any large discontinuities. This lends consistency to the material properties throughout the length of the part, which will reduce the chances of part failure or unwanted large deflections under load. This configuration can be seen in Figure 4-2, which shows the design space in yellow, non-design nylon and carbon fiber in purple and blue, boundary condition in white and the applied point load in orange.

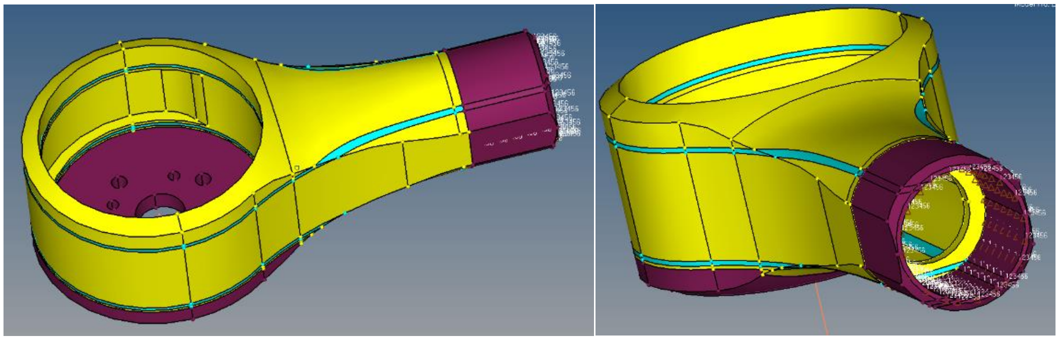


Figure 4-2 Optimization and analysis setup

The original motor mount was designed by Vayu using ABS plastic, with a traditional FFF method. It was designed with extra struts and increased thickness to accommodate the material properties of the ABS. The mount was printed in one piece, with all mounting holes incorporated into the design of the part. The purpose of the Vayu motor mount case study was to design a part that was lighter, while maintaining the requisite stiffness as defined by the original part. Analysis was performed on the part using Altair Hyperworks and Optistruct. The original part was imported into the software and meshed. The appropriate material properties were defined in the software as well as the boundary conditions and applied load. Analysis was then performed on the part to determine its deflection. This deflection result was used as the baseline stiffness comparison for the re-designed part. The rest of the design methodology follows from the following basic requirements: 1.The new part should be lighter than the original part 2. The new part should have the same stiffness (deflection) as the original part.

4.2 Analysis

Once the loads have been correctly evaluated and modeled analysis and optimization can begin. The purpose of this analysis will be to determine how many layers of carbon are required and where they should be placed as well as attaining and optimized geometry for the nylon matrix “design space” material. Analysis for this case study was performed in Altair’s Hyperworks using Hypermesh to develop a mesh and

Optistruct to perform analysis and optimizations. The part is first modeled in solid modeling software (in this case, SolidWorks). Then, the geometry is imported into Hypermesh. Once there, the part is divided into design and non-design space. The non-design space is specified as previously stated to allow for proper assembly in the final build. However, the carbon fiber layers are also specified as non-design in this analysis to ensure that the final geometry has enough material in the layers which require carbon fiber for the additive manufacturing software, Eiger, to place it. This is done by performing a Boolean cut on the part to divide it into design and non-design sections. The planes used to place the cuts define the thickness of the carbon fiber layers as well as the size of the non-design components. The layer height multiplied by the number of layers will give the value for the carbon fiber section thickness. Once the cuts have been applied to the parts, the separated sections of the part should be given their design/non-design specification by assigning appropriately named components to them.

In order to determine the correct number of layers of carbon fiber to apply to the part, a size optimization can be utilized. This will yield the optimized thickness for a given set of conditions. The maximum allowable deflection is set by the analysis results for the original motor mount design. This sizing operation will result in a desirable thickness; the appropriate number of layers can be determined from this value by dividing it by the layer height. This will rarely result in a whole number, so the appropriate number of layers would be this value rounded up for a safe design. In this case study, the results for deflection for the first set of analysis was close enough to the original Vayu part’s that a few iterative analysis studies were enough to define the required number of layers for the carbon fiber. This was done by first estimating the correct number of layers, performing analysis and then adjusting that layer thickness based on the deflection results. After a few iterations, an appropriate layer thickness was attained such that it there is enough carbon fiber to achieve the same deflection results as the analysis from the original part, but no more than that. The final deflection results show a slightly greater stiffness calculation than the original part because the layer height is a pre-set condition set in Eiger for the CFRP 3D printer.

Once the thickness of the carbon fiber layers has been determined, it can be applied to the part using Boolean cuts. The non-design nylon areas should also be defined in this way. Cuts should be made at the base of the cylinder where the part is constrained and the geometry cannot vary due to the mating requirements of that end and at the mounting holes for the rotor, which also have basic dimensional requirements for proper mating with the motor. The newly created sections must then be defined by assigning each new section as its own component (i.e. the two carbon fiber sections will be a component named “Carbon Fiber – Non-Design” and the nylon sections will be divided into “Design” and “Non-Design” as shown in Figure 4-1.

Now that the part is properly defined, it can be meshed. Meshing describes the process of defining the element size and shape and applying it to a solid model. Choosing the correct settings for a mesh is critical to the success of any FEA. In this case, a rough mesh was first used. The reasoning for this is two-fold: 1. It reduces analysis time required to solve the model and 2. The results form a coarse mesh will give a good indication of approximate fiber layer thickness as well as stress and deflection results. Once these had been determined, the mesh was refined and made finer in stages until a stress convergence was reached. The deformation results were also used as a guideline for mesh resolution. Tetrahedron elements were used to create the mesh, which formed 3D triangular elements deflection over the geometry. By sizing the elements after ensuring stress convergence and appropriate mesh resolution based on deflection, accurate results are ensured.

Once the part is meshed, the elements must also be assigned to the appropriate components. At this point, the components should have properties assigned to them. Two properties must be created: 1. Carbon Fiber 2. Nylon. They should have the PSolid designation. These properties in turn require materials to be assigned to them, so two correlating materials must be created to define the mechanical properties of each property. Since carbon fiber is anisotropic, it requires a different format than standard isotropic materials. This format in Hyperworks is called Mat9Ort. This material designation allows the user to define the material properties (modulus of elasticity, tensile strength etc.) in each direction compared to each other direction. The stiffness of the composite must be determined in each direction: E_1 based on the strength of the linearly elastic carbon fiber, as well as E_2 and E_3 based on the composite stiffness in those direction, which is reliant on the stiffness of the carbon fibers as well as the nylon matrix. The Poisson ratio values (v_{12}, etc.) can be calculated using the stiffness, as well as the values for the shear modulus (G_{12}, etc.) . This results in a well-defined anisotropic material.

This analysis has a number of purposes, including checking the model for stress convergence and accuracy. The main comparison between the original part and the redesigned part, however, was to obtain the deflection value which is intended to give some indication of stiffness for each part. This deflection value was taken at a common point on the part for both the original and re-design: the top center edge of the cup's inner wall, shown in Figure 4-3. This location showed the max deflection for the original part and the geometry linking the placement of this point to the constrained end is consistent in subsequent designs.

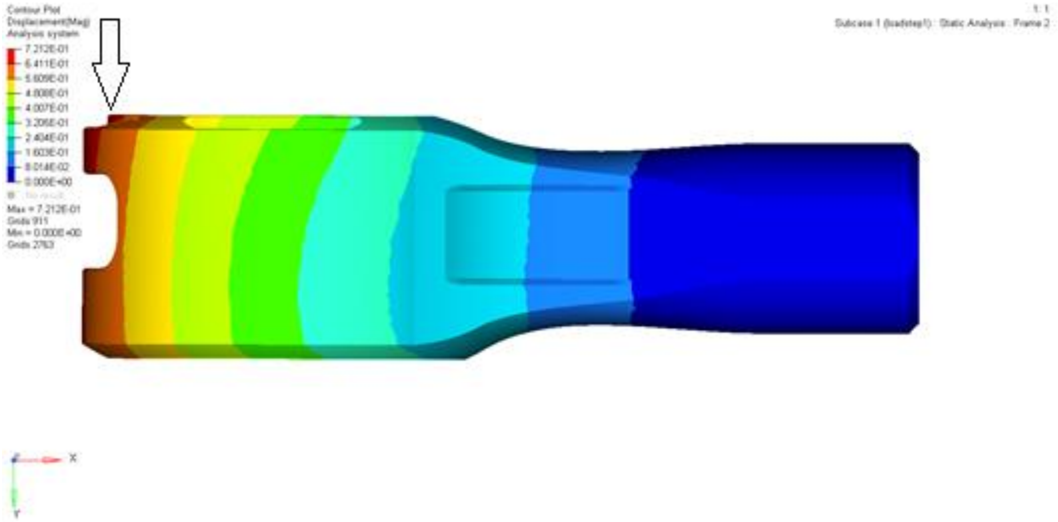


Figure 4-3 Deflection Results from Analysis

With the components, elements, material properties, and loading conditions appropriately defined, the part is ready for analysis. When the analysis is run, the software performs the FEM based on the user-defined element settings (size, shape, and order). The resulting solutions show both the deflection of the part at each node and the elemental stress throughout the part. These should be used to compare to the original part for consistency and accuracy. If the results make sense, then an optimization can be performed. At this point, a .fem file has been created as part of the analysis. The following topology optimization will take the same FEA as was used to run the static analysis and will iterate upon it to determine the correct element densities. These densities will be used to define which elements must be present in order to ensure the part doesn’t fail and which can be removed without harming its structural integrity.

4.3 Optimization

The topology optimization requires some amount of set up. First, the design variable must be defined (in this case, the “top-op desvar”). The design variable tells the software what type of optimization is to be performed. Additional constraining variables must also be selected. For this optimization, stiffness is being maximized (which is the same as minimizing compliance), with a volume fraction constraint. This will remove material from the design space iteratively while maintaining stiffness. Results for incremental increases in volume fraction can be seen in Appendix A.

The SIMP method makes use of FEA by assigning individual elements in the mesh a density value from 0 to 1 based on the design criterion and optimization algorithms used. It doesn't make sense to have elements with partial densities, so a method must be used to decide if elements with these intermediate density values are assigned a 0 or 1. This range is assigned a penalty factor by the user to determine the part's final geometry based on the optimization results. These elements can be penalized based on any number of design objectives, including weight minimization, cost minimization or compliance minimization.

4.4 Results

A design methodology for Continuous Carbon Fiber Additive Manufacturing (CCFAM) developed using Computer Aided Engineering (CAE) techniques takes advantage of both the mechanical strength of composite materials and the Fused Filament Fabrication (FFF) method. The proposed design methodology for CFRP 3D printing has shown positive results for the Vayu motor mount case study. The resulting design achieved its design goals of reducing part weight while maintaining similar stiffness. In order to keep costs down, iterative analysis was performed on the design to determine the required number of fiber layers as well. The part designed for CFRP meets its design goals, but is substantially more expensive than the original part built using FFF. The 36% weight reduction is perhaps substantial enough to warrant further investigation into uses for this manufacturing technology. Additional refinement of this design methodology may be used in the future to optimize the part for carbon fiber layer reduction in an effort to reduce costs even further.

Table 4-1 Design Comparison

	Original	Redesign
Weight (g)	49 (Calculated) 57 (Measured)	39 (Calculated) 36 (Measured)
Cost	$1.72	$14.95
Deflection (mm)	0.77	0.72

One general guideline to follow for this printer are to keep in mind the importance of orientation for the method as well as for fiber placement. For traditional FFF additive manufacturing, the orientation of the part is critical to print success. As previously discussed, the orientation of the part can have a major impact on the amount of support material required, elimination of discretization, and overall surface quality improvements. When printing with the CFRP 3D printing method, there is a further consideration for the orientation and layer-location for the carbon fiber filament. Layer-location here means not only where the fibers are located, but also how they are printed, because their orientation will change with the orientation of the part, which may limit your design space depending on the loading condition. The most important consideration is to make sure that the fibers are adequately placed such that they carry the load in an advantageous manner. If the part is oriented in such a way that the fiber placement is compromised for a given load in favour of a slightly better surface finish, then the part is likely to fail. As such, it appears to be commonplace for this method to sacrifice surface finish and required post-processing in order to achieve part stiffness in the appropriate locations. The compromise for increased stiffness in return for a worse surface finish is one that must be taken to properly utilize CFRP parts made with this method. One easy way to increase the surface finish quality would be to include the option to use different types of supports. The auto-generated supports in Eiger follow an accordion-type pattern that tends to shift during printing which can lead to misprints and burned material. The addition of alternate support types that can be controlled by the user would greatly improve the quality of life when working with the Eiger software. Removing nylon support material from nylon build material also decreases part surface quality. Nylon has a very low elastic modulus and tends to elongate a lot before breaking. Methods other than hand-tearing the material and filing down the remaining support should be investigated for best surface finish using the Mark Two.

Another guideline in part design for the method is to continue to consider the infill density required of the nylon. So much of the design is focused on the carbon fibers and increasing the stiffness, but the nylon (or whichever matrix material is being used) can be equally important to achieving the engineering design goals for a project. The infill density must be considered for weight reduction while maintaining a connection to transfer loads between carbon fiber layers. As a product of the design for this process, the end part may contain carbon fiber in every single layer of the print. Even if it is, the nylon infill still constitutes a significant portion of the part. Most of the weight reduction in part design for this process will come from removing nylon in the form of cutouts or a vast reduction in infill density. The quality of the nylon is also crucial to a complete print. The finish on a part printed with wet nylon is horrendous and the degraded nature of the material properties will greatly affect part strength. The best way to counteract these effects is to keep a consistent, watchful eye on the infill density for every print and to respect the nylon build material by keeping it locked inside its dry-box and regularly replacing the desiccant pouches inside. Dry nylon is crucial to a good build and must not be neglected.

A final consideration for this design process is to respect the limitations of the Eiger software and take them into consideration when designing the solid model of the part. For any 3D printing process, it is important to keep in mind the layer height, bead width, printing speed, and other parameters. It is just as important with this printer to keep in mind for both materials. Since the software doesn't allow for manual fiber placement, it will only place the software in areas where the geometry allows for it. If a wall is too thin to accommodate the full process for a layer (1. X number of wall layers in nylon 2. A full contour of the outer geometry in carbon fiber and 3. Isotropic fibers laid down parallel to each other at a specified angle 4. A raster-pattern infill of nylon to fill in any gaps according to a specified infill density), then the software simply will not place the fiber there. It is important to go through the print preview for each part, thoroughly inspecting each layer (especially the carbon fiber layers) for consistency and correctness. In short, the user may specify that a layer should contain carbon fiber at certain settings, but the software can and will ignore that command and place the fiber only where it will physically fit. The solution to this problem is to use the "measure" tool in SolidWorks (or the equivalent in whichever solid modeling software is being used) to ensure that the wall thickness meets at least the minimum thickness required for the printer to follow the given instructions. If a part will require 2 walls, design with the appropriate bead width in mind. The same goes for the width of the carbon fiber filament. For the carbon fiber to print successfully with the "isotropic" setting and the least number of contours (one), the layer will require three times the printed diameter of the fiber). Alternatively, the settings can be changed so that each process can be fit into a single layer for the print. For example, reduce the number of walls printed in nylon, or the number of contours specified for the carbon fiber.

It is especially important to keep these design guidelines in mind when manually applying cutouts to a part. For a topology optimization, it may be tempting to remove exactly as much material as is specified by the software. However, the physical limitations of the manufacturing process must be considered. A smart designer will keep these limiting factors in mind from the very beginning of the design and when any changes are made according to optimization or iterative analysis results. In this way, the number of failed prints can be minimized and the successful prints will perform better.

Chapter 5 Conclusion

Based on the results from the presented case study, this design methodology appears effective. It achieves the design goals for reducing part weight while maintaining stiffness while at the same time optimizing part dimensions for minimizing material use. Comparing this manufacturing technology's design constraints to those of similar technology's shows that the CFRP method provides a larger amount of design freedom, which enables the use of advanced CAE techniques to develop optimized geometry for a given loading condition. CFRP 3D printing gives designers a reasonable manufacturing method for physically producing this complex geometry, without compromising the part's mechanical strength requirements. While a similar part with a simpler geometry could have achieved the same stiffness using more traditional composite manufacturing, the cost of the redesigned part has been reduced due to the design capabilities afforded by CFRP 3D printing. Similarly, this method produces a lighter part than one that could be made using traditional machining techniques on aluminum or steel, and a much stiffer one than could have been produced using FFF or other additive manufacturing methods.

There are several potential recommendations for future research on this topic. For example, due to the difference in stiffness between the fiber and matrix layers, there is necessarily a difference in strain between them. At the point where the two materials meet, the nylon or matrix material is attempting to deflect in accordance with the applied loads, the same as the carbon fiber. However, the fiber is much stiffer so will deflect far less than the matrix. This causes an Interlaminar shear strain to exist between the matrix and fiber layers, though for the purposes of this analysis, because of the low deflection results, this interlaminar shear was considered to be negligible for this analysis. Future work may include incorporating a model of the behavior between these two layers under a load.

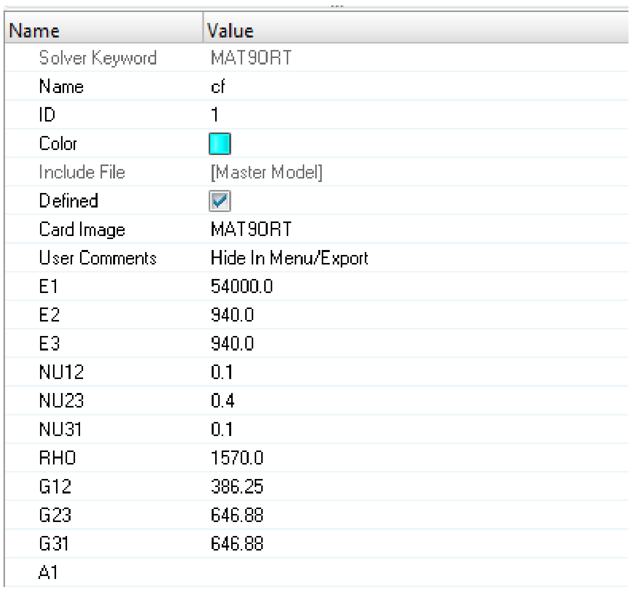
Additionally, the FFF method itself will cause internal stresses to appear in the part as hot material is extruded out of the nozzle and laid against cool material, where it contracts as it cools down. These internal stresses due to the temperature differential also were not considered in the analysis for this part.

One final consideration for future work involves the nature of thermoplastic materials. The fibers used in this analysis exhibit linear elastic behavior. However, thermoplastic materials are viscoelastic, meaning that they do not deform linearly with respect to time in the same way that the fibers do. The time-dependent nature of these materials was not captured in this model and is an area of great interest for a more complete analysis of loaded CFRP parts.

In addition to model improvements, shape optimizations can also be used to further refine final part geometry by thinning out walls and increasing part height where necessary (to accommodate the bending load). Improvements to Eiger’s capabilities may also affect future design work, allowing for the design to be more specifically tailored to the application. This may include a functionality for lower infill density settings, or manual placement of carbon fiber filament, or any other software improvement.

Each of these areas of interest may improve the CFRP additive manufacturing design methodology. The motor mount case study for a vertical takeoff and landing drone provides a good example of its efficacy; the final design is significantly lighter than the original while remaining slightly stiffer and the end, while minimizing carbon fiber use to keep costs low. Room for further improvement to this methodology bodes well for the long-term development of CFRP additive manufacturing technology.

Appendix A: Altair and Eiger Software Screenshots



Name	Value
Solver Keyword	MAT9ORT
Name	cf
ID	1
Color	🟦
Include File	[Master Model]
Defined	☑
Card Image	MAT9ORT
User Comments	Hide In Menu/Export
E1	54000.0
E2	940.0
E3	940.0
NU12	0.1
NU23	0.4
NU31	0.1
RHO	1570.0
G12	386.25
G23	646.88
G31	646.88
A1	

Figure A1: Sample MAT9ORT material properties card (units are in N/mm^2)

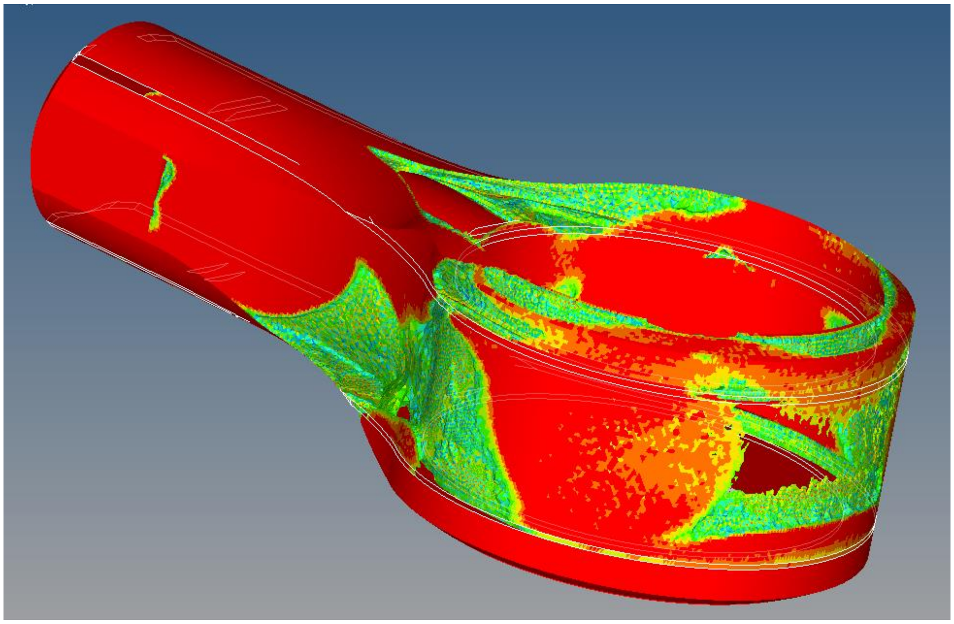


Figure A2: 60% Volume fraction topology optimization result

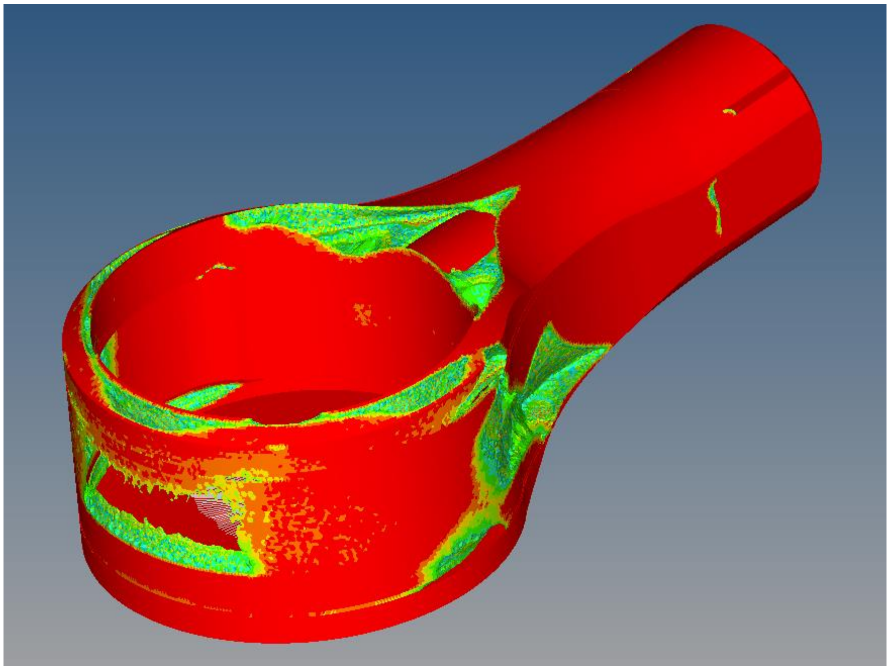


Figure A3: 70% Volume fraction topology optimization result

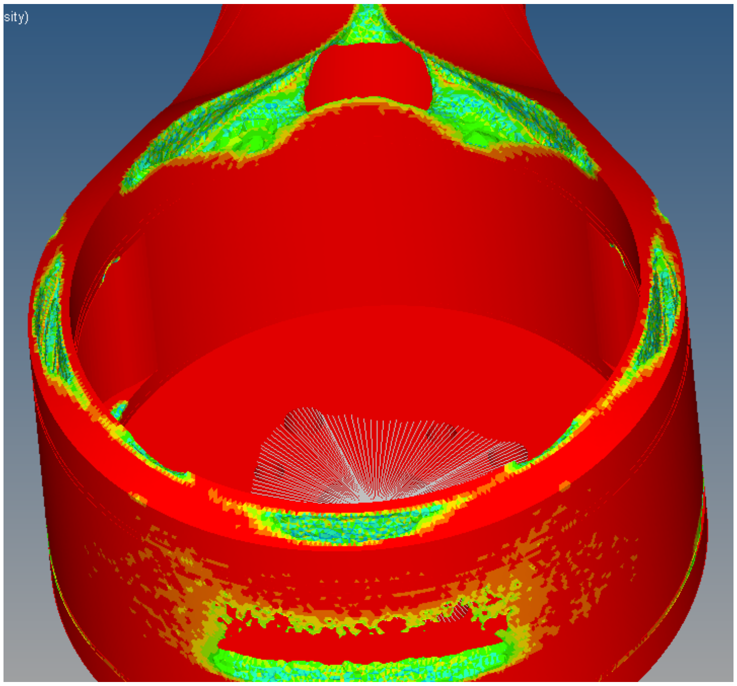


Figure A4: 80% Volume fraction topology optimization result

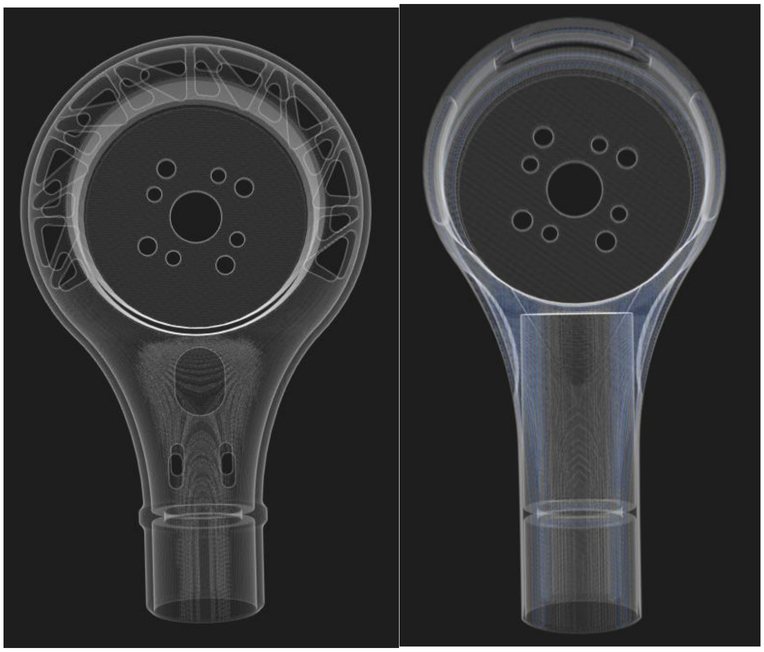


Figure A5: Original motor mount (Left) and redesigned Motor Mount (Right) (Eiger)

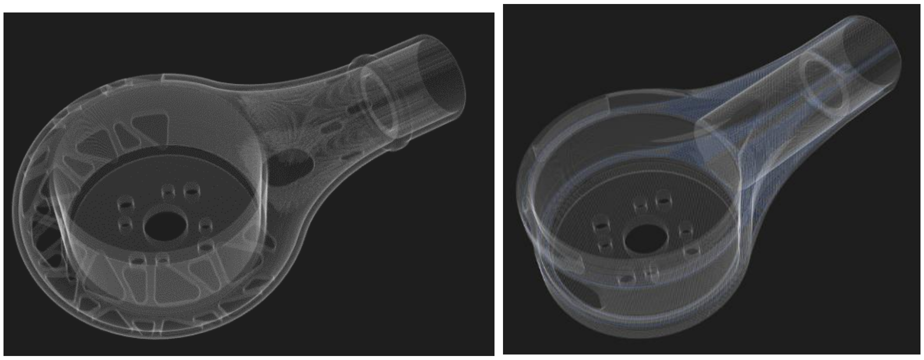


Figure A6: Original Motor Mount (Left) and redesigned Motor Mount (Right) (Eiger)

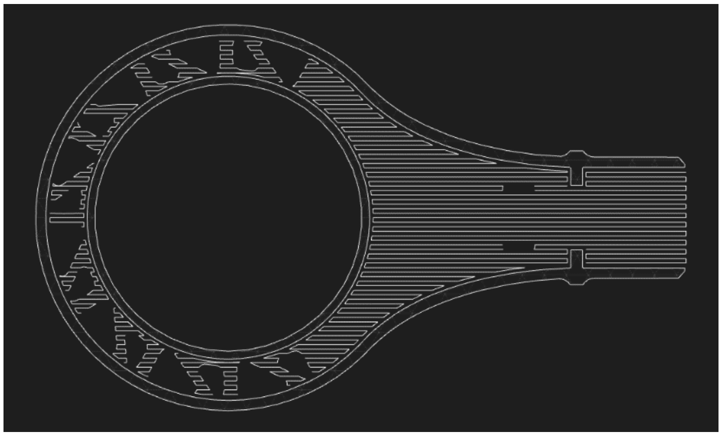


Figure A7: Layer view of the original motor mount

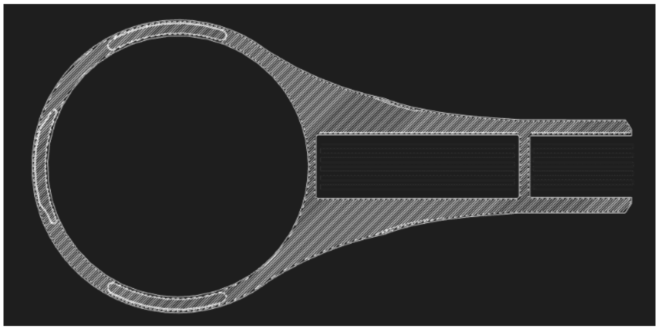


Figure A8: Layer view of redesigned part

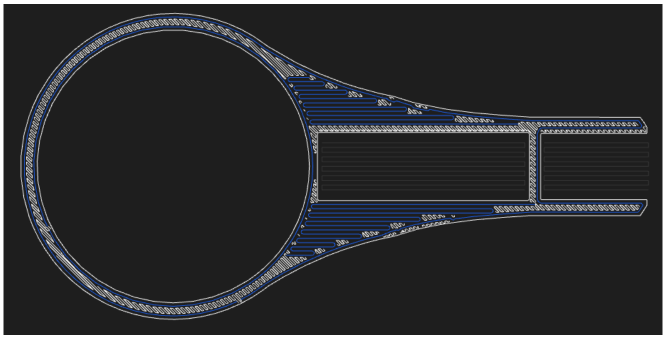


Figure A9: Layer view of redesigned part with carbon fiber

Appendix B: Printer and materials

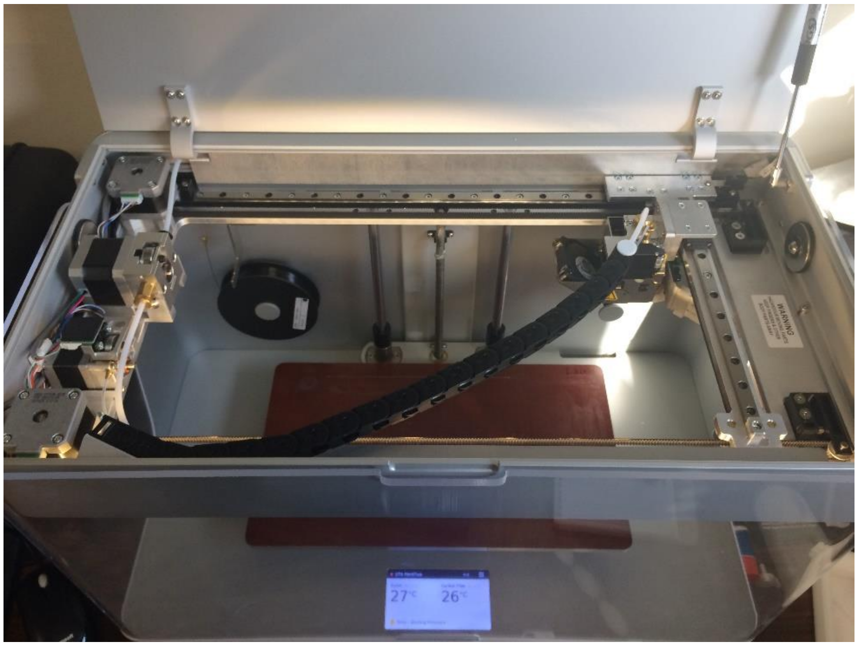


Figure B1: CFRP 3D Printer (Mark Two)

Figure B2: Nylon traveling through a Bowden tube from dry box to printer

Figure B3: Carbon Fiber spool

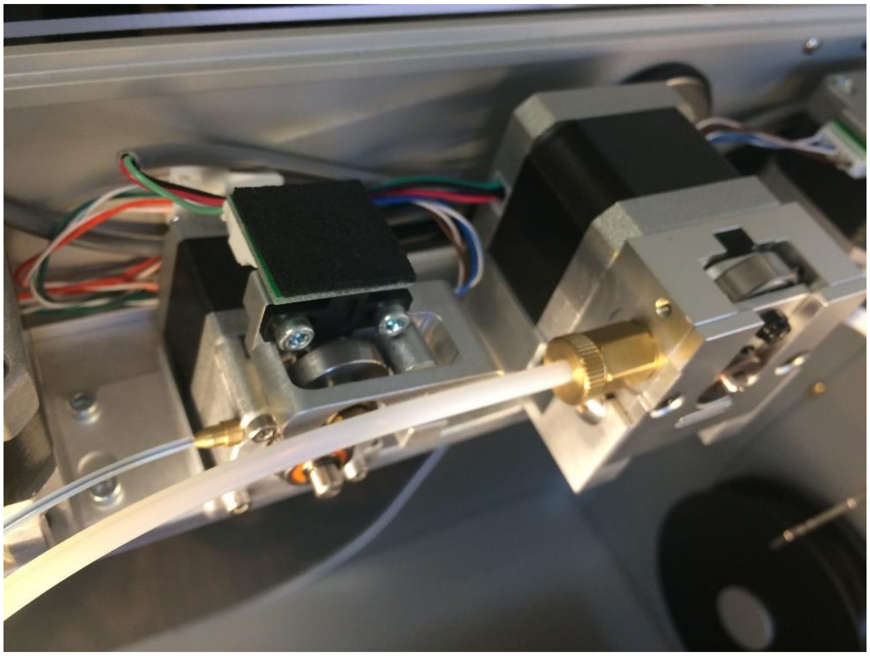


Figure B4: Stepper motors for the nylon and carbon fiber filaments

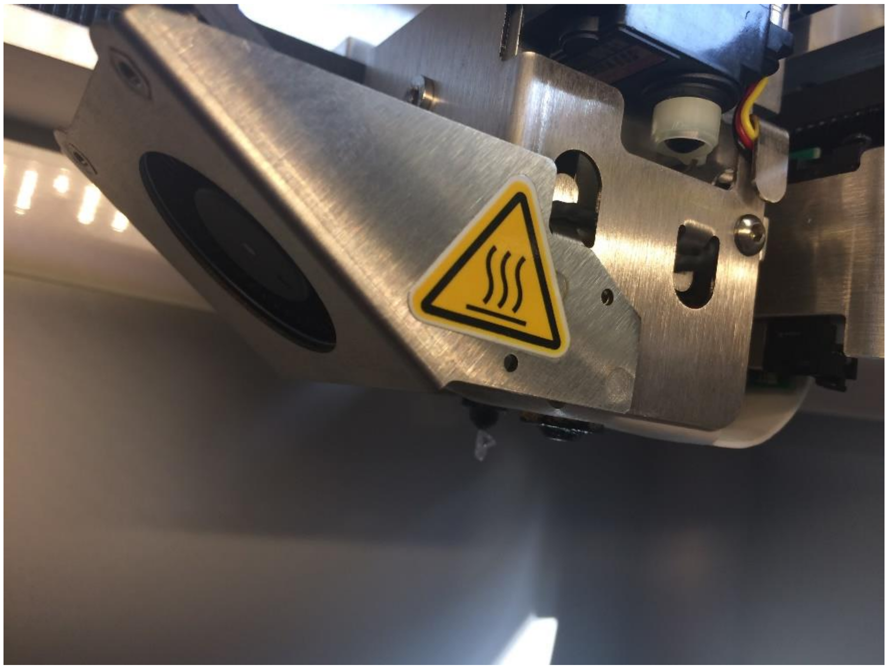


Figure B5: Gantry, heated nozzles and carbon fiber cutting mechanism

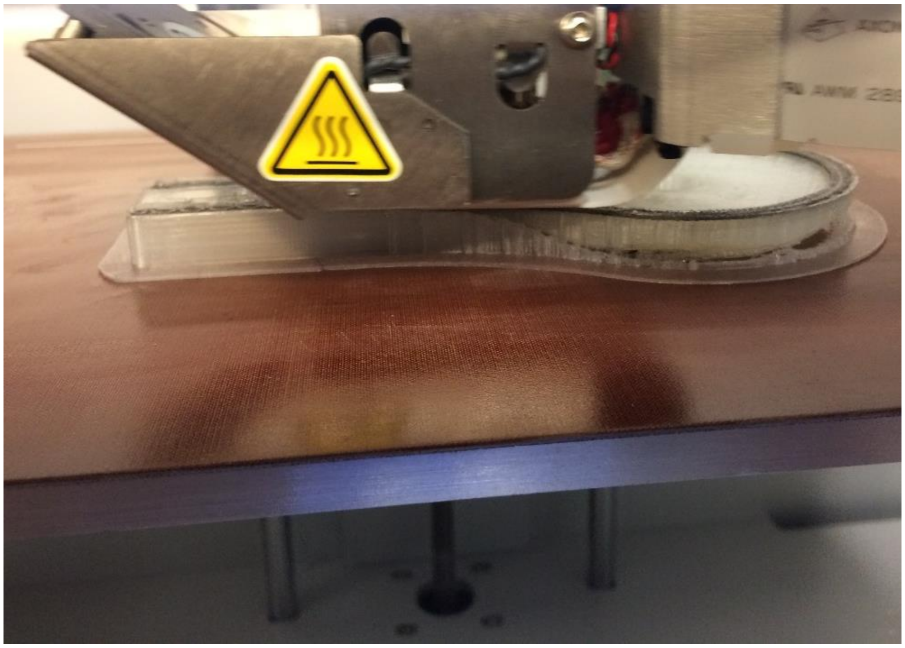


Figure B6: Printing carbon fiber layers

Figure B7: Completed part with support material

Figure B8: Completed part with support material

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