Solid Freeform Fabrication 2023: Proceedings of the 34th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

ADAPTING A DESIGN FOR ADDITIVE MANUFACTURING WORKFLOW TO ACCOUNT FOR CONTINUOUS CARBON FIBER REINFORCED PARTS

Gavin Adams
Additive Manufacturing and Design
The Pennsylvania State University
University Park, PA

Nicholas Meisel
Engineering Design and Innovation
The Pennsylvania State University
University Park, PA

Abstract

The use of continuous carbon fiber (CCF) reinforcement in material extrusion 3D printing has the potential to revolutionize the material extrusion field of additive manufacturing. Notably, the Markforged X7 system utilizes this CCF reinforcement with the aim to produce parts with mechanical results rivaling or surpassing those of aluminum. However, due to certain constraints with the deposition of CCF in material extrusion parts, such as an inability for CCF to be deposited throughout layers in the Z-direction, traditional design for additive manufacturing (DfAM) techniques need to be reevaluated. This paper will explore (1) how existing DfAM considerations (e.g., topology optimization, functional integration, minimum feature size, etc.) can be tailored to CCF and (2) how an existing DfAM workflow can be adapted to account for manufacturing limitations specific to the deposition of CCF. The research is demonstrated through a hoist sling case study, which highlights the importance of considering fiber orientation and routing in the design stage to ensure accurate CCF reinforcement and achieve ideal mechanical results relative to the loads associated with the part. The result is an initial, potentially valuable workflow for designing CCF parts to be created using AM.

1. Introduction

For years, industries such as aerospace, automotive, and medical have sought to leverage the various advantages additive manufacturing (AM) has to offer while also searching for strong, lightweight structures. One of AM's main advantages is its ability to create functional components with complex geometries that are difficult to manufacture by conventional and subtractive methods, thus shortening the design-manufacturing cycle and reducing production cost [1]. Material extrusion is the most widely used AM technique due to its low cost, minimal waste, and consistent accuracy [2]. Material extrusion also requires no chemical post processing, less capital investment, and is generally considered to be a cost-effective process [3]. The material extrusion printing process has primarily served as a prototyping tool for designers; designers have, for the most part, stayed away from creating functional production parts. One of the main reasons for this is that the resultant parts tend to exhibit poor tensile and thermal performance [4]. However, recent advancements in multi-material extrusion have led to the development of processes capable of producing robust fiber-reinforced parts. Fiber reinforcements have shown to significantly increase the strength and stiffness of a part and produce components with mechanical properties similar to and sometimes exceeding aluminum [5]. This technology is offered commercially in the Markforged X7 printer, where one nozzle expels a chopped carbon fiber and nylon matrix, called Onyx, while a second nozzle deposits reinforcing continuous fibers [6–8]. The two nozzles do not extrude material simultaneously; one stops while the other is extruding. Fabricating a fiber layer starts when the bare end of the fiber is laid down and ironed in with the flat tip end of the print head. This ironing action of the print head changes the fiber filament from a circular to an elliptical cross section geometry after being deposited onto the print bed [9]. When the routing of continuous fiber for the layer is almost complete, there is a blade system built into the extruder that cuts the strand before depositing that remaining length onto the build surface. The adhesion force of the continuous strands of fiber on the part pulls the remaining fibers through the nozzle until it is fully passed through. It is also worth noting that the start point of the fiber layer is moved for each layer so there is no corner which would serve as a weak point in the structure [9].

To achieve favorable mechanical results in CCF material extrusion, the internal fibers must be laid in an orientation suitable for the applied loading conditions. A more definitive design for additive manufacturing (DfAM) workflow needs to be developed describing how to produce an optimal design alongside case studies showing how to follow this process. To develop this, a material extrusion workflow should be established and tailored towards the new design challenges faced by CCF. S. Yang notes a series of design methodologies tailored towards AM and proposes a workflow through which successful products can be manufactured [10]. This framework is broken up into four sections: Design Specifications, Design Process, Process Constraints, and Redesigned Structure. This general design framework is especially interesting and relevant towards CCF as it initializes design from the perspective of functionality. Many DfAM workflows, by contrast, focus on optimizing an existing model. Design optimization is usually not entirely effective for CCF applications due to process limitations such as the ability to route fibers in specific orientations, limitations in available fiber lengths and material properties, and the need to align the fiber reinforcements with the loading direction to achieve ideal mechanical performance.

In conjunction with design methodologies, it is important to consider the materials used in CCF printing. This knowledge can aid in achieving ideal performance from a design. By understanding the properties of these CCF-relevant materials and how they interact with the continuous fiber reinforcement process, designers can make informed decisions when creating functional end-use components. As an example, the Onyx matrix material in the Markforged X7 system exhibits a tensile strength twice as strong as ABS due to its micro-carbon reinforcement [11]. When used with continuous fiber, Onyx functions more like a matrix as its primary purpose is to bind, protect, and transfer the load to the stands of continuous fibers [1]. The reinforcing fiber options offered by the Markforged X7 include fiberglass, Kevlar, high-strength high-temperature (HSHT) fiberglass, and carbon fiber. Each fiber option has specific applications and can drastically change the characteristics of a part. Fiberglass can provide increased strength; the manufacturer claims that it exhibits 2.5x increased flexural strength and 8x stiffer properties compared to onyx in dog bone specimens. Kevlar provides abrasion resistance and is utilized in parts that experience repeated and sudden loading. This material is as stiff as fiberglass yet is more ductile. HSHT Fiberglass produces parts with the strength properties of aluminum and has an increased heat tolerance [12]. The manufacturer claims that it is 5x stronger and 7x stiffer than Onyx. The final reinforcing fiber is carbon fiber, which offers the highest strength-to-weight ratio. The manufacturer claims that it is 6x stronger and 18x stiffer than Onyx [12]. Two different types of reinforcing fiber infills can be used with each reinforcing fiber type; the two fiber infills available within Markforged's slicing software, Eiger, are isotropic and concentric fill. Figure 1 is a cross-sectional visualization of the two different fill patterns.

Conventional material extrusion printers offer a similar fill pattern to isotropic fiber fill. The fibers are routed back and forth in a zig-zag pattern to simulate the unidirectional layers of a laminated composite. The fiber layers are rotated by 45 degrees to achieve unidirectional strength within a fiber group, though this 45-degree angle can be changed if needed. This option also traces concentric rings around all walls to improve wall strength. By contrast, concentric fiber fill lays the fibers only around the perimeter of a wall and has an Onyx matrix. This helps to resist bending about the Z-axis and strengthens the walls against deformation. The number of fiber shells can be specified by changing the number of concentric fiber rings within the software [13,14]. Continuous carbon fibers are composed of brittle strands that can endure loads when subjected to tension, bending, and compression. However, they demonstrate ideal performance when utilized under tension. To withstand tension, fibers should be running along the length of the part and considered "stretched" when under force. To withstand a bending force, a sandwich panel should be utilized to overcome the outside face being in tension while the inside face is under compression. Compression loads need to have their force distribution considered. Fibers should serve as a scaffold under the load, thus distributing the load along the fiber's path [13,14]. When defining the tensile properties of CCF, the fiber volume fraction plays a critical role in determining the part's mechanical properties. The fiber volume fraction is the ratio between the volume of continuous fiber strands and the volume of the entire part. While there are other considerations to determining a part's true mechanical performance, such as fiber fill pattern, these values provide an estimate as to how a part will perform in tension. K. Saeed attempted to characterize the material properties of continuous carbon fiber. In his studies, he performed a series of tensile tests on dog bone specimens with CCF strands and altered the part's fiber fraction volume [15,16]. This study's findings found a linear relationship between the fiber volume fraction and tensile strength of the part. The findings were also similar for elastic modulus. At a fiber volume fraction of 20%, CCF parts exhibit tensile properties like aluminum [15].

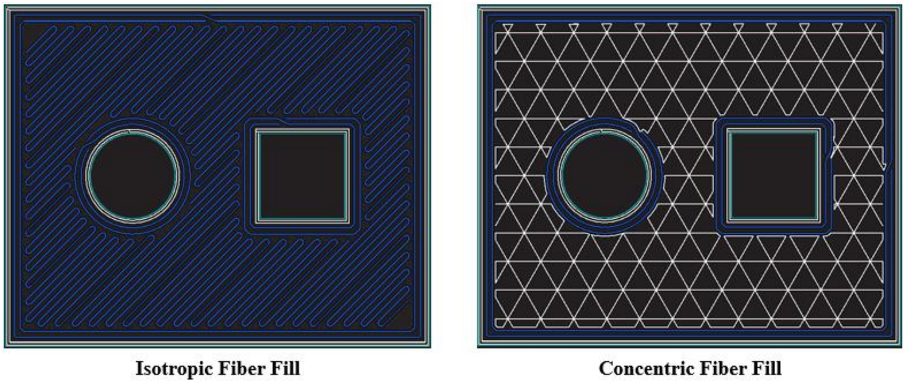
Isotropic Fiber Fill **Concentric Fiber Fill**

Figure 1. Fiber Fill Patterns

Considering this body of existing research, there is still a need for a DfAM workflow which integrates the use of CCF. To address this need, this paper adapts existing best practices in DfAM to better support the creation of CCF products. Each step of this methodology will be discussed and the key considerations for each stage will be defined. The methodology will be demonstrated through a relevant case study, specifically the redesign of a load-bearing component on a hoist sling. Finally, limitations within the case study application, future research areas, and their potential impact on the workflow will also be discussed within the conclusion.

2. Adapting a DfAM Workflow for CCF

The design workflow, shown in Figure 2**,** has been developed by adapting the methodology proposed by S. Yang for AM-enabled design. This workflow is specifically tailored towards CCF and aims to provide a structured process for designing a successful solution for CCF reinforcement. This adapted workflow offers a systematic approach for creating CCF products by considering the unique characteristics and challenges of CCF materials and the associated manufacturing process.

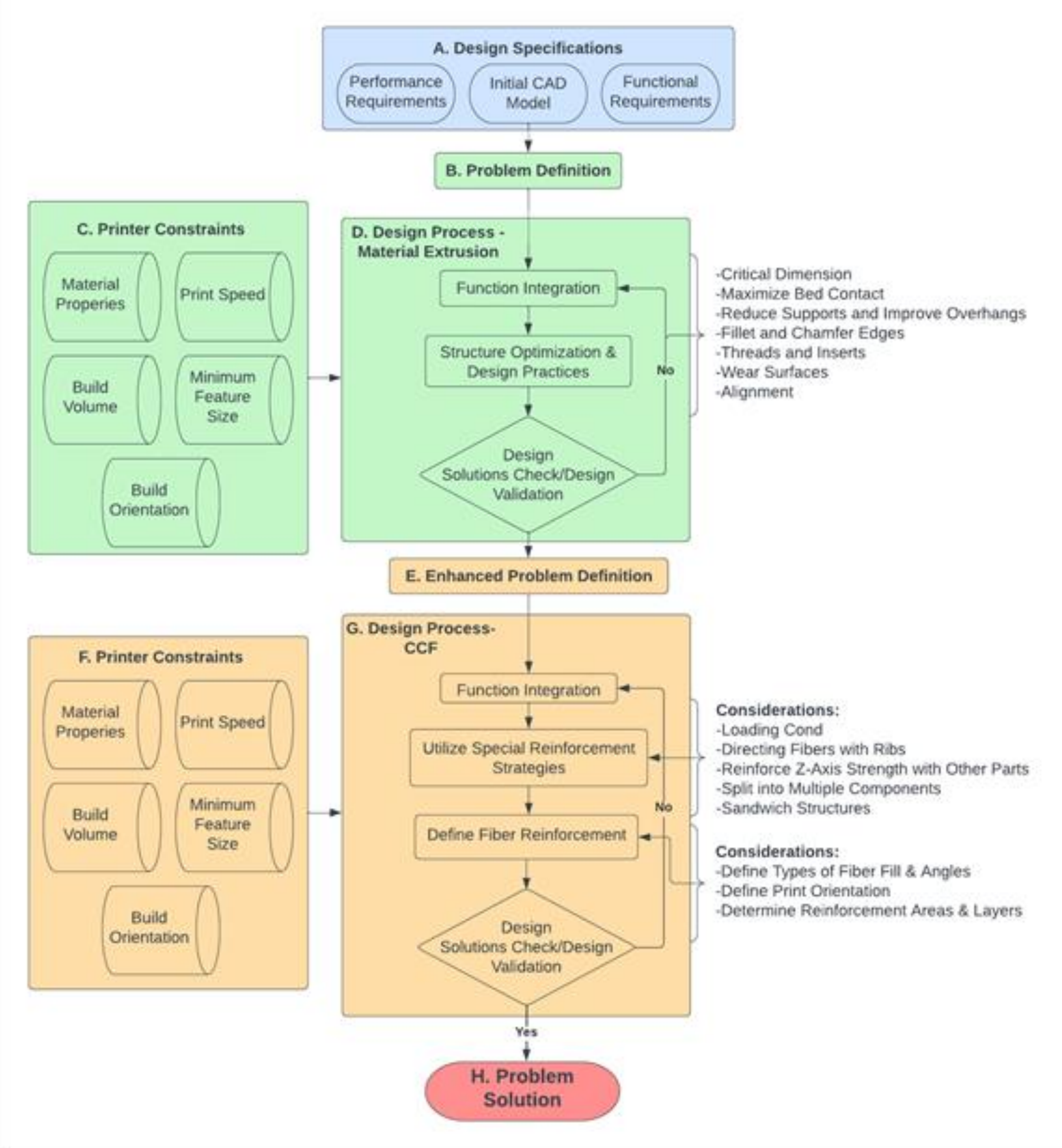

Figure 2. DfAM Workflow for CCF

Utilizing this design workflow can serve as a tool to help engineers the enhanced mechanical properties CCF can enable in end-use products. Following this workflow can also help reduce design error by characterizing and understanding the effects printing parameters and design decisions have on the final properties of the 3D printed composite parts for specific applications [8]. This workflow is split up into two different sections: standard material extrusion and CCF reinforcement. The primary focus for the two categories is to clarify each process's problem definition while accounting for its respective process constraints. The material extrusion section of the workflow is designed to adhere to the constraints of printing a part solely out of Onyx, while the CCF section aims to develop a multi-material solution that exploits the multi-material capabilities of the Markforged X7. The goal of splitting up the workflow is to ensure each specific design solution successfully captures the intended problem without introducing bias of differing process constraints. Intrinsic design decisions may be missed if attempting to capture both processes in one iterative workflow.

2.1. Design Specification

Clear specifications are important to engineering solutions. A typical performance requirement for designs requiring the use of the Markforged X7 may include (1) a load capacity, (2) safety factor, and/or (3) number of duty cycles. Clearly understanding the functional requirements is also critical to ensure successful performance of the design and may include mating features, final part weight/size, or user features (e.g., an ergonomic way to handle a part).

2.2. Problem Definition

Developing a clear problem definition is a vital step to this DfAM workflow. It establishes the foundation for design thinking and influences critical design decision-making. This initial problem statement should be outlined without the influence of design constraints for CCF and be strictly focused on designing a solution for a specified material extrusion printer. The problem definition should dictate a clear understanding of the specific issue the design will solve. This section defines the problem to be solved by outlining the design challenges, incorporating functional requirements and design constraints, and setting the stage for the development of a solution.

2.3. Process Constraints (Material Extrusion)

This section captures the constraints of the printing process. These constraints must be balanced with the design process workflow, which is why they are shown in parallel. These process constraints include material properties, printing speed, build volume, minimum feature size, and build orientation. For both the material extrusion and CCF Process Constraints sections of this DfAM workflow, the chosen system is assumed to have a print volume of 13.00"x10.63"x7.87" as it is the volume of the Markforged X7. The minimum feature size constraint is a design principle that can be carried across most material extrusion printers. Some general design principles for minimum feature size includes a minimum wall thickness ranging between 0.047" to 0.06" and hole diameters should be greater than 0.04" in order to retain a circular shape [17].

2.4. Design Process (Material Extrusion)

Function Integration. Functional solutions, such as part consolidation, may be applied at this step. A "shell" design is created initially which achieves critical dimensions [10]. Other functional decisions are integrated into the design based off the problem definition. The hierarchy of design decisions are a qualitative choice for the designer and should be weighed based off the defined problem. Other features such as threads and inserts are included based off the workflow. These may not yet be required after the initial pass, but a design solution check could require the engineer to general a new mating solution.

Structure Optimization & Design Practices. After a functionally successful design that adheres to mating conditions and other specifications is completed, structure optimization methods should be applied to achieve enhanced performance such as lighter weight, better heat dissipation, or improved dynamic properties [10]. As with function integration, the structure optimization hierarchy is weighed as a function of the initial problem definition. Topology optimization, a form of structure optimization, should be considered during this step. Leveraging the functionally successful design to produce a design which is lighter weight is advantageous and an effective step as AM provides near unlimited geometric complexity to a design. A parametric design should then be produced from the topology optimization results as an easily manipulable computer aided design (CAD) model is desirable in later stages of this workflow. This can be done by comparing the topology optimization results with the existing CAD model and removing material until a relatively similar representation is met. Though this may reduce the optimality of the final design, it is often still preferable to the initial designed topology. It may also require some initial effort to set up a parametric design, but it can ultimately save time and effort in later stages of the workflow. As an example, a topology optimization mesh may contain features which are under the minimum feature size threshold and do not adhere to the process constraints of the material extrusion printer. Manipulating the mesh to allow for proper sized features is challenging and unwieldy; more rapid design modifications can be achieved with a similar parametric model.

Design Solutions Check/Design Validation. Design solution check involves an analysis of the product to ensure that it meets the functional requirements and design constraints determined earlier. It also verifies that the design solution is feasible and will produce the desired results. The approach for a design solution check may vary depending on the specific application, especially for additive manufacturing. Finite element analysis (FEA) within most CAD software is a challenging step due to the AM material not functioning as a uniform homogenous solid. Designers must determine the necessary assumptions and acceptable format for defining a successful solution. This is an iterative step and may take a several attempts. A feedback loop to function integration or structure optimization may be necessary. If topology optimization was utilized in the Structure Optimization phase, FEA should still be conducted on the final redesigned structure to determine stress concentrations and identify how forces are dispersed within the part. This step also serves a formal check to review the CAD model, confirming the part meets the process parameters and design specifications successfully.

2.5. Enhanced Problem Definition

After the completion of the previous Design Solutions Check/Design Validation step*,* the DfAM workflow now transitions to the CCF design process. The main objective of the CCF section is to integrate the Markforged X7's multi-material capabilities and enable the use of reinforcing fibers. This section differs from the previous material extrusion section because it requires a more complex design process that leverages the advantages of CCF AM. This area of the design process requires an in-depth understanding of the material properties, print parameters, and design principles to create an optimal design that meets the enhanced problem definition. This section is also critical to ensuring the final design meets all functional requirements and is feasible for the CCF AM process. The enhanced problem definition for CCF should be defined at this step; problem definition for CCF will include the combination of a lightweight, robust design with the enhanced mechanical properties that the process offers. The material extrusion workflow should have set the stage for how a solution will need to be enhanced with CCF. For example, the material extrusion solution may need CCF to enable the mechanical performance in the design specification. CCF may also be utilized simply to provide additional confidence in a design due to the increased durability of the material.

2.6. Process Constraints (CCF)

While the CCF process constraints share similarities with material extrusion printing, it is important to note that they differ in terms of the ideal build orientation. The printer is limited to the depositing in the XY plane for CCF. Also, CCF slows down the printing process thus increasing build time. Designers must find a balance between incorporating the right amount of CCF within the part to address this balance. Some layers may require increased isotropic CCF while others may only need concentric rings or no fiber at all. The selection between concentric and isotropic fiber fills is dictated by the type of force applied to the part. Concentric fiber rings carry the load path in a specific direction and work best when routed in tension with the load direction. Isotropic fibers provide best reinforcement in all directions resulting in a uniform distribution of the stress throughout the part. This makes isotropic fibers ideal for uniform stress distribution and balanced parts that need strength in all XY directions [12].

General minimum feature sizes still follow the material extrusion design principles, but if a region requires CCF, the minimum feature sizes are increased. The minimum fiber reinforcement width for an open feature should be 0.15”, and 0.11” for a closed loop. Also, the minimum part height should be at least 0.04” to produce a part at least nine layers thick. This is due to the slicing software requiring four roof and four floor layers of Onyx above and below fiber groups. The smallest area to reinforce would be a square region of 0.14 inches^2 and a minimum post diameter of 0.38”. Sometimes, holes are too small to reinforce due to the given number of concentric fiber rings and minimum fiber length. After slicing and seeing a hole missing concentric fiber rings, this constraint may be the reason fiber is missing. Increasing the concentric fiber rings in Eiger can address this issue [13,14]. While press-fits, close-fits, and free-fits can be utilized in both CCF and material extrusion printing, they can prove to be particularly advantageous for joining split CCF parts. For material extrusion printing, a key DfAM objective is to minimize part count. However, in CCF DfAM of functional artifacts, the emphasis shifts to splitting parts in order to arrange fibers effectively. As a result, these fits play a crucial role in joining segmented parts together. Nominal clearances for the designed CAD model should be 0.000”-0.002” inch for press-fit, 0.002”-0.004” for close-fit, and 0.004”-0.008” inch for free-fit. Press fitting will require some force applied via cold pressing to assemble, close fitting can be assembled or disassembled by hand with minimal clearance, and free fits will allow for parts to slide and/or rotate easily when assembled [13].

2.7. Design Process (CCF)

Function Integration. Function integration may not be needed on the first iteration, but it will be necessary and serve as a check before moving to special reinforcement strategies on future iterations. Most function integration accommodations may have been applied already in the material extrusion cycle; however, feedback loop design modifications for CCF may eliminate this integration and need to be readdressed. New areas of function integration may arise based off this feedback loop as well.

Utilize Special Reinforcement Strategies. Special reinforcement strategies for CCF should initially focus on creating a design where the load is directly transferred through the fibers. To achieve this, the previous solution may need to be split into multiple components or printed in a different build orientation. Some examples of reinforcement strategies include directing the fibers with ribs, reinforcing the z-axis strength with other parts such as a fastener or sandwiching structures. This step may serve as a step backwards from standard material extrusion. While topology optimization is a worthwhile step for material extrusion, concessions in the original optimized design may need to be made to account for special reinforcement strategies needed for multi-material CCF.

Define Fiber Reinforcement. With a clear path to direct the fibers defined, the reinforcement strategy should begin. There are two main considerations for fiber reinforcement: direction layers and direction type. The designer should consider which regions require fibers. Some sections of a design may not carry a load or may be able to produce a successful design using only the single Onyx material. Other areas may require CCF at every layer; this is where the fiber fill should be considered, balancing between concentric outer rings and fully isotropic layers. Choosing between fiber fill paths can be done by analyzing the type of load for each component.

Design Solutions Check/Design Validation. Defining an acceptable means by which to identify a successful solution is important due to the non-homogenous nature of CCF additive manufacturing. The CCF DfAM approach builds upon the design principles and best practices established in the material extrusion section, but also introduces new challenges and considerations specific to the use of CCF. Multiple iterations through the design workflow are recommended to ensure all possible orientations, fiber directions, and part splits have been considered.

2.8. Problem Solution

The output may be introduced in the form of a CAD model, STL, model-based definition (MBD), or 2D drawing format. The MBD or 2D drawing can serve as a tool to display functional requirements, inspection, or capture any post-processing requirements. It Is worth noting that rarely is an engineering solution complete after the first pass. This workflow may need to be repeated after the first print of the design. This solution may be benchmarked against the material extrusion solution or previous revisions of the design. It can prove to be a worthwhile practice to step away from a design and compare solutions to help ensure nothing obvious was missed.

3. Case Study

A relevant case study was selected to demonstrate the use and effectiveness of the proposed framework for designing CCF parts. It will show how the framework can be used to identify key design parameters, such as defining fiber orientation and part splitting, and how to utilize these parameters effectively to improve the overall performance of a final part. By using an industry-focused application, this case study provides insight into the practical applications of this framework and how it can be used to produce high performance CCF parts. This case study will be focused on applying the proposed DfAM workflow towards the design of a load-bearing component of a hoist sling. This hoist sling will be used to lift a machined housing around an industrial shop floor between different machining operations. Safe lifting of this component is critical as not only is it an expensive and long-lead component, but it also weighs upwards of 125 pounds. Failure of any part on the hoist sling will likely damage the product and is a safety risk for people and machinery. Figure 3 shows the existing weldment through which the lifting component must successfully mate, alongside a representation of the housing to be lifted with the weldment assembly. The interface lifting surface is highlighted in the model. For the additively manufactured lifting component to successfully mate with the interfaces on the weldment assembly, it must align with two ball-lock pins and fit withing an opening between two plates.

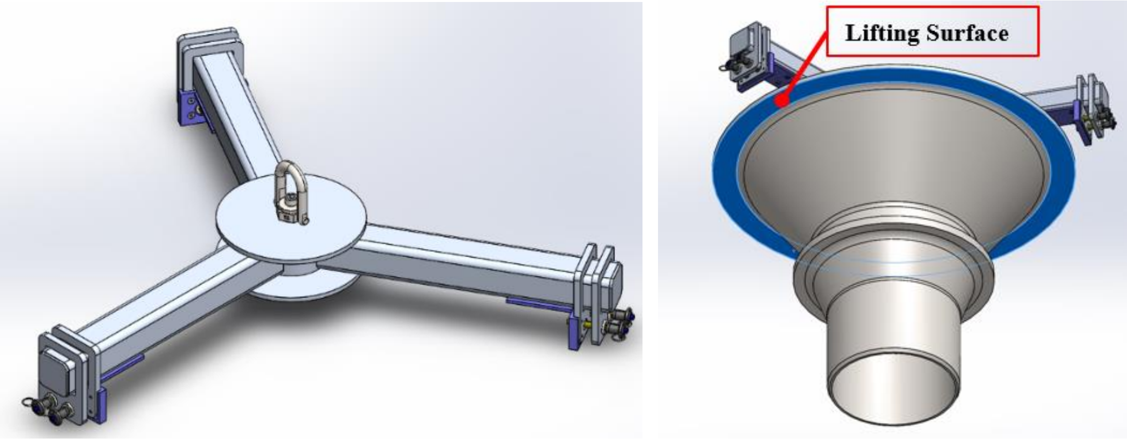

Figure 3. Weldment Assembly and Lifting Surface

3.1. Design Specification

The requirements for a redesigned hoist sling are as follows:

- A redesigned sling should be able to support a load of 125 pounds. This accounts for 33% of the working weight with a desired safety factor of 2.5.
- Due to the nature of the industrial environment this is used in, the design should have maximum impact resistance due to it being subjected to impacts or rough handling. Measures should be taken to enhance the toughness of the final part by material selection and minimizing regions susceptible to breaking.
- The AM solution should have mounting points compatible and consistent with the hoist sling weldment and not drive a redesign of this subassembly. The part should reliably mate with these two ball-lock pins and double shear interface.
- The AM solution should interface on the defined contact surface in Figure 4.
- A redesigned component should not damage the lifted component when in use or during assembly and disassembly.

3.2. Problem Definition

The material extrusion solution will be examined against the performance and functional requirements. This initial approach will attempt to create a part that mates to the critical surfaces yet is able to support the required load of 125 lbs., as determined by an initial FEA estimate. The structure should also be optimized for a material extrusion printing process.

3.3. Process Constraints (Material Extrusion)

The main process constraints associated with this solution are print bed size and build direction. The correct build orientation is critical to both printing this design in one part and providing ideal part strength. The decision between these two trade-offs should be based off the design specification. For this application, a part with advantageous mechanical performance is preferred over reducing support material. The part requires two holes with a diameter of 0.500” to join the part to the weldment assembly at the double shear interfaces. This mating requirement will not create an issue with minimum feature size. This design should have a free-fit interface with the two ball-lock pins to ensure easy installation and removal of the pin and consistent mating with the weldment assembly due to tolerance stack-ups. Meanwhile, maximum print volume will drive the allowable surface contact between the hoist sling component and machined housing. This design solution should attempt to produce as much surface contact as possible with the machined component to help disperse the load applied while lifting the machined housing.

3.4. Design Process (Material Extrusion)

Function Integration. Figure 4 shows the initial concept which applies the function iteration of the design workflow as it mates with the weldment assembly and interfaces with the machined housing. For this design there are two main interface regions: the pin interface and the mounting surface. For the pin interface, this design provides two holes which align with the holes of the weldment assembly while also providing a slip-fit interface with the ball lock pins. The pin interface thickness is driven by the opening in the weldment assembly and was selected to have a nominal 0.010” clearance between the two mounting faces. This will allow the bracket to be easily inserted into the groove of the weldment assembly while also having minimal movement when in use. The part then transitions towards the mounting surface. A shelf was designed for the housing assembly to rest on. There is a lip between the mounting surface and the transition region to help keep the machined housing captive during lifting. A 0.040” clearance from the outer diameter of the machined housing was used to account for the tolerance stack-up of the weldment assembly while also providing an easy and consistent fit with the machined housing. Maximum surface area on the mounting surface was designed to help distribute the load when the housing is mounted; as previously discussed, this surface area was dictated by the maximum build volume of the printer. Additional mounting surface also helps the machined housing rest securely on the designed part. No minimum feature sizes are of concern with this design as all holes and walls are well over the printer’s minimum feature size constraints.

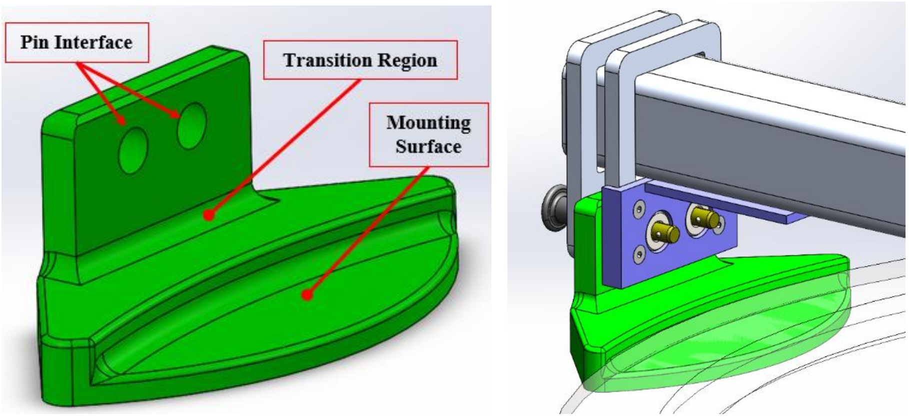

Figure 4. Initial Material Extrusion AM Solution

Structure Optimization & Design Practices. The structure optimization phase utilized topology optimization and performed through Autodesk Fusion 360. For this topology optimization design, the objective was to minimize mass subject to the loading conditions and factor of safety discussed in Section 3.1. Figure 5 displays the topology optimization mesh results with the initial concept transparent, alongside it is the parametric redesigned structure based off these results. The intent with the topology optimization was to determine areas to remove unnecessary material and utilize the free complexity of AM. This new structure provides a solution which not only has less material, but also will print faster.

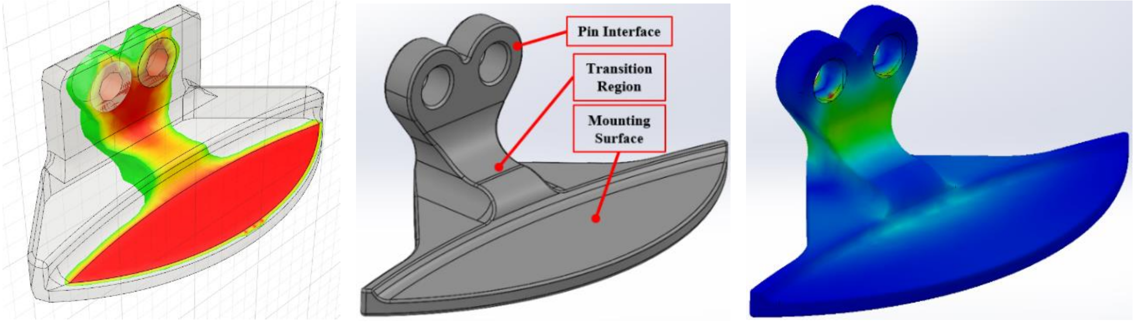

Figure 5. Topology Optimization Results and Redesigned Structure with FEA (Regions of Higher von Mises Stress Noted in Green)

Design Solutions Check/Design Validation. The iterative feedback loop between the Structure Optimization and the Design Solutions Check helped determine the ideal build direction. While FEA within Solidworks is not considered reliable at predicting design AM parts tensile performance due to parts being anisotropic as opposed to isotropic [18], it is a valuable tool to determine how the force will be transmitted through a component with an applied load. Utilizing this to visualize the areas of stress concentration are critical to determining the proper build direction to mitigate delamination between layers. The rightmost image in Figure 5 displays the stress-strain FEA results which shows the region bearing the largest stress is at the pin interface. This was deemed the region which should provide the most strength. Because of this, the build direction was selected to be perpendicular to the pin interface surface. This will ensure that the region which experiences the largest load will not be susceptible to delamination between those layers. The design tradeoff with this selection is there will be an increase in support material due to the overhanging features on the mounting surface. To minimize the support material, 45-degree extrusions were created in the transition region as this is the minimum angle which does not drive support generation in Eiger. The design specification to create a part for maximum part strength over reducing support material guided this design decision. The region between the mounting surface and transition region also experiences some load and will be susceptible to delamination in this region. To increase the part's strength in this region and minimize the possibility of delamination, the fillet size was maximized to provide as much material as possible. Figure 6 displays the build surface for the material extrusion design alongside the required support material and a visualization of the impact of the 45-degree angled extrusions.

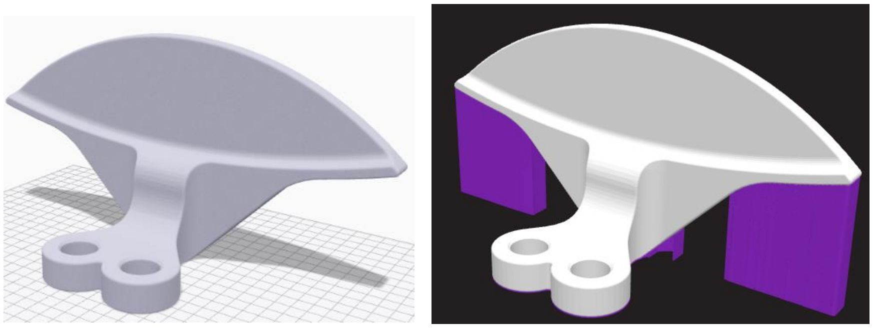

Figure 6. Material Extrusion Solution Loaded onto Build Plate in Eiger

3.5. Enhanced Problem Definition

After analyzing the material extrusion design, the decision was made to create a solution that incorporates CCF to further improve the mechanical properties of the design and provide increased robustness and reliability. As detailed previously, CCF offers improved strength, stiffness, and toughness compared to an Onyx-only solution. This CCF-tailored solution should use best practices in both fiber layering and direction to produce a robust and reliable design. Following the proposed CCF design workflow, reinforcing fibers should be laid in directions that enable it to achieve the maximum mechanical properties of the material and printing process.

3.6. Process Constraints (CCF)

The build direction plays a critical role in the process constraints for CCF, as reinforcing fibers must be deposited in the XY plane. Because of this, fiber orientation is key and drives most decisions during the design process. To correctly select and design a part with CCF, the force directions and types of forces in each region must be correctly defined. For this part, the pin interface region will be experiencing a load under tension while the mounting surface will be experiencing a uniform bending force. The pin interface should have concentric fiber rings routed to support the load while the mounting interface should have isotropic fiber fill. Because of these differing load paths, this indicates splitting the material extrusion part into two components to be the best approach. This will allow for having two separate parts each designed with the correct fiber routings for their specific load paths. A strategy of mating these two components together will also be necessary in this design stage. Utilizing a press-fit and close-fit interface will be an efficient way to adhere the parts together and successfully transfer the lifting load on the weldment assembly to the machined housing. Using and designing this fit correctly will reduce post-processing as well as create a consistent finished part.

3.7. Design Process (CCF)

Function Integration. As stated in previous subsection, it was determined to be necessary to split this design into two separate components due to the load paths. The pin interface region exhibits a force under tension when pulled upwards and having a load applied at the mounting surface. The transition region is where the force changes to bending as the mounting surface pulls downward while the lifting force of the weldment assembly pulls upward. This transition region and differing force types is what drives the requirement to no longer design this in one piece and instead create two different components with two different fiber path routings. The split structure for CCF is shown in Figure 7. Part One was designed with the approach of providing a part which delivers concentric fiber rings around the pin holes while also performing well under tension. The structure of Part One is similar to the pin interface region of the material extrusion solution, except it does not have a transition region. This ensures the entire part experiences a uniform load under tension and the part will be strongest where it experiences the largest load. It is also structured in a way to press-fit with the female square interface on Part Two and have press-fit dowel holes for a double shear interface to secure the parts together in the interface region. The functional parameter of the part width was kept the same as the material extrusion solution to provide a similar mounting scheme in the weldment assembly.

Part Two was redesigned to provide a region advantageous for isotropic infill. Again, the structure of the mounting surface when compared to the material extrusion solution was kept relatively similar. The important distinction is this structure is now intended to be built perpendicular to its bottom surface. As a result, the 45-degree extrusions in the transition region were no longer required since their function was only to reduce support material. A female press-fit region is provided to interface with Part One. The functional intent with the dowel holes is to press-fit with Part Two at their interface points. Unlike Part One, where the dowel holes can have concentric rings around their interface points, Part Two cannot have these concentric rings as it will be built in a stair-stepped manner, perpendicular to the centerlines of the holes. This is where the square press-fit interface between the two parts comes into play. Due to the moment created from the loaded part, there will be an angular force at this interface surface when the tool is in-use making it unlikely for this fit to come loose. The function of the dowel holes is then to act as a secondary interface joint and provide added rigidity to the region. The interaction between the two parts will be spread across the face of the square interface instead of being distributed entirely to the dowel holes. To increase the surface area of the interface between the two parts and help disperse the load across a larger surface, the interface joint on Part Two was raised higher. This justifies not providing a solution which has concentric rings in this area.

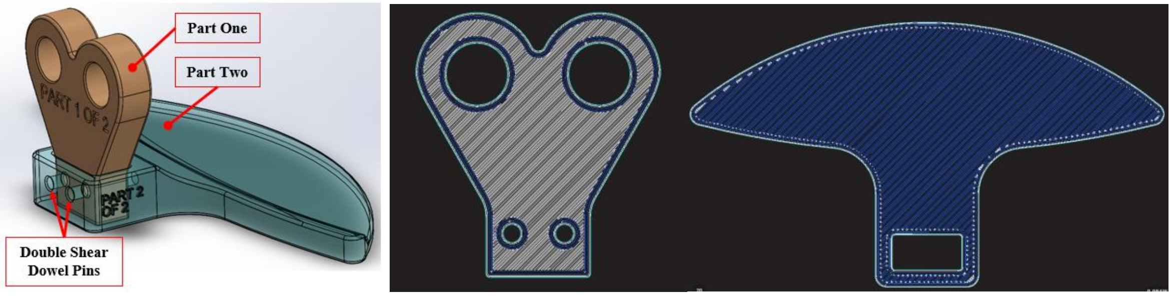

Figure 7. CCF AM Solution with 2D-Sectioned View of CCF Routing

Utilize Special Reinforcement Strategies. Splitting the design into two different components allows for the parts to be reinforced with CCF along their ideal directions for each respective part. As discussed previously, Part One provides concentric fibers through all layers. Part Two provides isotropic fiber fill for all layers. Figure 7 shows the sectioned view for Part One and how the concentric fibers route. The blue lines are the strands of carbon fiber while the white lines are the Onyx shell and infill. Figure 7 also shows a detailed view of Part Two's isotropic layers where the fibers are routed at 45-degree angles. There are still two concentric rings defined for these layers to help provide rigidity to the structure [13].

Define Fiber Reinforcement. Both solutions will be printed with 100% infill and have two wall layers before the CCF begins being deposited for each layer. Part One utilizes a sandwich panel approach for placing the layers of isotropic CCF. Isotropic fibers are used for the first five layers and last five layers. Concentric fiber is then only deposited along the remaining layers along the middle of the part to create a sandwich structure of CCF. This approach will help reduce the print time while also providing a sufficiently strong part. Increasing the amount of deposited CCF drastically increases print time as the extruder deposits fiber strands much slower than Onyx. Also, routing isotropic fibers for every layer will provide minimal increase to mechanical properties.

For this application, the distance the dowel pins were from the edge of part also required a feedback loop with the Function Integration portion of the design workflow for Part One. If the dowels are too close to the edge of part, they do not have enough clearance from the outer shell fiber strands. As a result, Eiger will not slice the desired amount of concentric fiber rings for the dowel pin holes.

Figure 8 displays the dowel holes too close to the edge of part for Part One resulting in this issue compared to Figure 7 which shows the concentric rings properly routed. Part Two utilized isotropic infill for all available layers. This was required due to the bending forces distributed between the dowel pin interface and loading surface. No other special accommodations were required for the fiber reinforcement in this part as the dowel holes cannot be laid with concentric fiber rings.

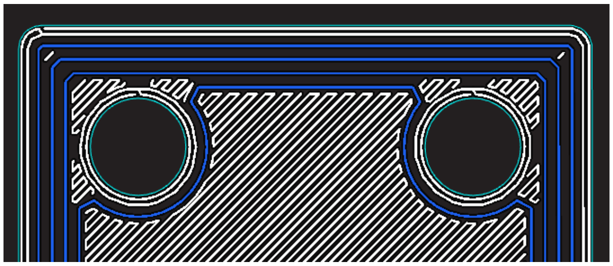

Figure 8. Incorrectly Routed Concentric Fiber Rings

Design Solutions Check/Design Validation. Markforged's Eiger software includes simulation capabilities to predict the mechanical results of a CCF part. After defining the printing parameters, CCF reinforcement, loads, and anchors, the simulation software provides a safety factor and expected maximum deflection. Both parts of the CCF reinforced solution were loaded into the simulation software to verify their performance. The simulation software indicated that Part Two initially had a failure point in the transition from the mounting surface towards the square interface between the two parts. Material in this region was increased and the fillet size was adjusted to help distribute the load evenly. Regions where the critical load was indicated were investigated as areas to increase the amount of material. Both final iteration of the parts passed their simulation checks with maximum deflections of 0.01mm and 0.89mm and safety factors of 10.74 and 2.94 for Part One and Part Two, respectively. This meets our performance requirement for the design. Figure 9 displays the output simulation results from Eiger.

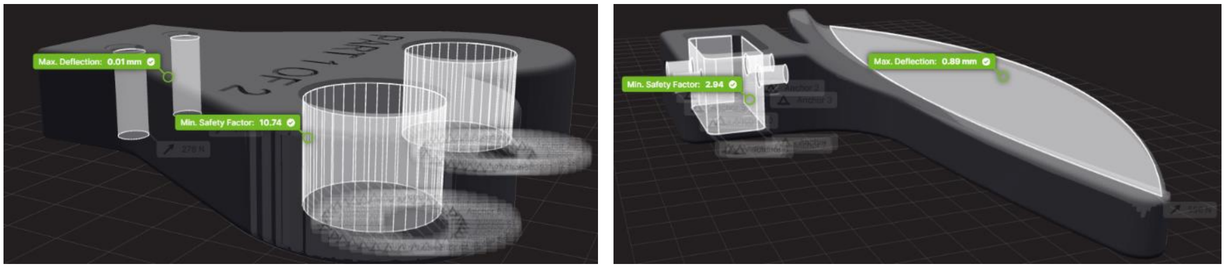

Figure 9. Eiger Simulation Results

3.8. Problem Solution

Though physical testing of the case study has not yet occurred, to validate the final design resulting from this workflow, a comparison between a traditionally manufactured part (based on the initial material extrusion design) and the two-part CCF design was conducted. The traditional design was loaded into FEA in Solidworks with 6061-T6 aluminum; a factor of safety for the design was determined to be 8.58, below the factor of safety provided by Part One, but above the factor of safety in Part Two. This shows how a part's performance may be improved as a result of considering CCF throughout the design workflow.

4. Conclusion

This study explored the potential of using a CCF material extrusion process to design and manufacture high-strength functional parts. A DfAM framework was proposed, analyzed, and then followed through a case study to demonstrate the importance of a design focused on fiber routing and orientation. The proposed framework also identifies how and where to account for CFF concerns within the design process. The case study in this paper provides a clear demonstration of how DfAM principles can be effectively applied to produce complex, high-performance parts towards a real-life application. As shown in the case study, a CCF design can potentially exceed the mechanical results of a similar aluminum part. Part One in the CCF design exceeded the factor of safety results seen in the metal solution. Part Two did not as the fibers were unable to be routed in an orientation that provided tension with the applied load; however, the part was still able to pass the factor of safety requirement.

There are some limitations which must be noted, and future research should be conducted to understand their impact. The fatigue life of Onyx and CCF designs must be better understood. These parts should be closely monitored for minor cracks or other defects when used in a real-life environment. Tensile testing must be done to compare the lifecycle of these parts against a respective subtractive metal solution. The impacts of these findings should be noted and the proposed DfAM workflow updated accordingly. The feedback on the fatigue life of these parts may impact the Function Integration or Utilize Special Reinforcement Strategies sections of the CCF workflow as additional design considerations may be required. Also, the Design Solutions Check sections for both material extrusion and CCF sections should be iterated further as additional software analysis packages and design verification methods become available.

5. References

[1] Ning, F., Cong, W., Qiu, J., Wei, J., and Wang, S., 2015, “Additive Manufacturing of Carbon Fiber Reinforced Thermoplastic Composites Using Fused Deposition Modeling,” Composites Part B: Engineering, **80**, pp. 369–378.

[2] Chee Kai, C., *Rapid Prototyping: Principles and Applications in Manufacturing*.

[3] Wong, K. V., and Hernandez, A., 2012, “A Review of Additive Manufacturing,” ISRN Mechanical Engineering, **2012**, pp. 1–10.

[4] Bárnik, F., Vaško, M., Handrik, M., Dorčiak, F., and Majko, J., 2019, “Comparing Mechanical Properties of Composites Structures on Onyx Base with Different Density and Shape of Fill,” Transportation Research Procedia, **40**, pp. 616–622.

[5] Jayashankar, D. K., Devarajan, A., Dong, G., and Rosen, D., “Design and Manufacture of a Continuous Fiber-Reinforced 3D Printed Unmanned Aerial Vehicle Wing,” p. 16.

[6] Baumann, F., Scholz, J., and Fleischer, J., 2017, “Investigation of a New Approach for Additively Manufactured Continuous Fiber-Reinforced Polymers,” Procedia CIRP, **66**, pp. 323–328.

[7] Dickson, A. N., Barry, J. N., McDonnell, K. A., and Dowling, D. P., 2017, “Fabrication of Continuous Carbon, Glass and Kevlar Fibre Reinforced Polymer Composites Using Additive Manufacturing,” Additive Manufacturing, **16**, pp. 146–152.

[8] Naranjo-Lozada, J., Ahuett-Garza, H., Orta-Castañón, P., Verbeeten, W. M. H., and Sáiz-González, D., 2019, “Tensile Properties and Failure Behavior of Chopped and Continuous

Carbon Fiber Composites Produced by Additive Manufacturing," Additive Manufacturing, **26**, pp. 227–241.

[9] Prüß, H., and Vietor, T., 2015, "Design for Fiber-Reinforced Additive Manufacturing," Journal of Mechanical Design, **137**(11), p. 111409.

[10] Yang, S., and Zhao, Y. F., 2015, "Additive Manufacturing-Enabled Design Theory and Methodology: A Critical Review," Int J Adv Manuf Technol, **80**(1–4), pp. 327–342.

[11] "Introducing Our New Markforged Material: Onyx."

[12] Markforged, 2022, "Material Datasheet."

[13] Markforged, "Design Guide for 3D Printing with Composites," Design Guide for 3D Printing with Composites.

[14] Zhang, Y., De Backer, W., Harik, R., and Bernard, A., 2016, "Build Orientation Determination for Multi-Material Deposition Additive Manufacturing with Continuous Fibers," Procedia CIRP, **50**, pp. 414–419.

[15] Saeed, K., McIlhagger, A., Harkin-Jones, E., McGarrigle, C., Dixon, D., Ali Shar, M., McMillan, A., and Archer, E., 2022, "Characterization of Continuous Carbon Fibre Reinforced 3D Printed Polymer Composites with Varying Fibre Volume Fractions," Composite Structures, **282**, p. 115033.

[16] Goh, G. D., Dikshit, V., Nagalingam, A. P., Goh, G. L., Agarwala, S., Sing, S. L., Wei, J., and Yeong, W. Y., 2018, "Characterization of Mechanical Properties and Fracture Mode of Additively Manufactured Carbon Fiber and Glass Fiber Reinforced Thermoplastics," Materials & Design, **137**, pp. 79–89.

[17] Paulsen, G., 2017, "Best Practices for FDM 3D Printing," MachineDesign.

[18] Abbot, D. W., Kallon, D. V. V., Anghel, C., and Dube, P., 2019, "Finite Element Analysis of 3D Printed Model via Compression Tests," Procedia Manufacturing, **35**, pp. 164–173.