Improving Quality of 3D Printed Components for Remotely Piloted Aircraft Systems with Curved Layer Fused Filament Fabrication

by

Mila Kanevsky

A Thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial fulfilment of the requirements for the degree of Master of Applied Science in Aerospace Engineering

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The undersigned recommend to
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Master of Applied Science

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Carleton University
2022
Abstract

The work in this thesis, explores methods of Additive Manufacturing applied to Remotely Piloted Aircraft Systems. The objective was to implement and test an alternate method of Fused Filament Fabrication using non-planar/curved layers. This was met by adapting a desktop 3D printer with an adapted nozzle and using a software offering non-planar layers. Both planar and non-planar prints were made to compare the strength using tensile and bend specimens. By completing flexural testing, it was determined that including non-planar layers did not provide a benefit to flexural strength with four or six non-planar top layers. Through printing different types of samples and angles, it was determined that using thicker layers and at low angles, non-planar printing provided improved surface quality. Recommendations for future work includes testing samples with different parameters, and improvements of printing hardware such as a custom printing nozzle or software.
This thesis is dedicated in loving memory of my father Vladimir Kanevski, who would have been proud to have seen my accomplishments.
Acknowledgments

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<tr>
<th>Acronyms</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ABS</td>
<td>Acrylonitrile Butadiene Styrene</td>
</tr>
<tr>
<td>ASA</td>
<td>Acrylonitrile Styrene Acrylate</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>AM</td>
<td>Additive Manufacturing</td>
</tr>
<tr>
<td>CARs</td>
<td>Canadian Aviation Regulations</td>
</tr>
<tr>
<td>CAM</td>
<td>Computer Aided Manufacturing</td>
</tr>
<tr>
<td>CLFDM</td>
<td>Curved Layer Fused Deposition Modelling</td>
</tr>
<tr>
<td>CLFFF</td>
<td>Curved Layer Fused Filament Fabrication</td>
</tr>
<tr>
<td>FDM</td>
<td>Fused Deposition Modelling</td>
</tr>
<tr>
<td>FFF</td>
<td>Fused Filament Fabrication</td>
</tr>
<tr>
<td>LOM</td>
<td>Laminated Object Manufacturing</td>
</tr>
<tr>
<td>PC</td>
<td>Polycarbonate</td>
</tr>
<tr>
<td>PETG</td>
<td>Polyethylene Terephthalate- Glycol Modified</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
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<tr>
<td>--------------</td>
<td>------------------------------------------------</td>
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<tr>
<td>PLA</td>
<td>Polylactic acid</td>
</tr>
<tr>
<td>RPAS</td>
<td>Remotely Piloted Aircraft System</td>
</tr>
<tr>
<td>SULSA</td>
<td>Southampton University Laser Sintered Aircraft</td>
</tr>
<tr>
<td>STL</td>
<td>Stereolithography</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
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Chapter 1

Introduction

The use of both Remotely Piloted Aerial Systems (RPAS) and Additive Manufacturing (AM) has grown significantly in the past decade, becoming more easily accessible for a variety of industries [1, 2].

The use of RPAS can be seen in many sectors such as agriculture, fire safety and forestry, search and rescue, information services, local authorities, oil companies, and traffic companies for a variety of purposes including surveying, pollution and land monitoring, telecommunications, imaging, photography, and monitoring [3]. RPAS offer many benefits such as: being able to fly in conditions that may pose a high risk to pilots; low altitude flight capabilities; relatively low price point; long flight endurance; and short takeoff and landing capabilities.

Similarly, the use of AM can be seen across many industries. Allowing for a low cost, accessible, and fast manufacturing method. Uses for AM are also seen across many sectors ranging from plastic filament extruders for individuals to metal printers used in machine shops and larger scale factories. Additive manufacturing allows a quick turnaround from the design to the manufacturing stage and allows for increased complexity with little to no extra cost.


1.1 Motivation

Over recent years, there has been an increased interest in both RPAS and AM as individual technologies but also combined into novel applications. Fused Filament Fabrication (FFF) is one method of AM that involves material extrusion to form a part. A literature review on FFF for RPAS highlighted a dozen research projects using, primarily prints of the frame or wing profiles for fixed-wing, rotary-wing, and blended wing RPAS. The review highlighted benefits including, multi-material manufacturing, optimized structures, and reduction of parts. Challenges were also discussed including the limited range of materials, build size limitation, and surface finish [4].

RPAS components are for the most part mass manufactured and purchased to design an RPAS or work with an already existing RPAS. When manufacturing an RPAS, different designs and configurations are used for different applications of the aircraft. AM presents the opportunity for users to add components and make changes to the aircraft performance on demand; such as replacing a broken part, or changing the design like adding a custom camera mount or more complex enhancements including mission-specific propellers or winglets for example.

Using AM for RPAS offers the benefits listed above as well as being able to have mission-specific design. Being able to manufacture in the field in the case of any broken part, AM allows more flexibility with the design, therefore, the users are able to select specific part qualities. This can also help decrease waste if a part is broken and cannot be purchased or fixed, as AM has the ability to create spare parts on demand. AM can meet some requirements for RPAS but a newer method of AM with curved layers referred to as Curved Layer Fuse Filament Fabrication (CLFFF) offers a potential better surface finish which may benefit aerodynamic performance which is important to RPAS.

The motivation comes from the increased ability to design and manufacture parts
of high quality. Moulds for specific parts can be expensive to make and are typically used for mass manufacturing.

1.2 Objective

The research will examine the application of an emerging method of AM, focusing specifically on a method of Fused Filament Fabrication (FFF) with non-planar layers, referred to as Curved Layer Fused Filament Fabrication (CLFFF). CLFFF will be examined for its effect on part mechanical properties, surface quality, and potential application for RPAS.

1.3 Organization of Thesis

The thesis is organized in the following manner:

- Chapter 2 includes a literature review and background on topics related to the thesis and completed work in the field. First an overview of AM followed by a summary CLFFF and current developments in the field. Lastly the application of CLFFF for RPAS.

- Chapter 3 discusses the methodology and test methods, including the experimental proposal, manufacturing methods, design of experiments, material selection, and methods of testing and analysis.

- Chapter 4 outlines the results and discussion of testing including tensile testing and three and four point flexural testing. Followed by results of parts printed for proof of concept including a wave, an airfoil section and a propeller section.

- Chapter 5 summarizes the work with conclusion and recommendations for future work.
Chapter 2

Literature Review and Background

This literature review presents previous work done in the fields related to the topics of AM and RPAS.

2.1 Additive Manufacturing

Additive Manufacturing (AM) has steadily grown in popularity over the years and has been used by a range of consumers from everyday hobbyists to large corporations. The Statista Research Department predicts consistent growth in the global AM market with an expected 17% increase from 2020-2023, 23.7% growth from 2023-2025, and 20.4% growth from 2025-2026 [5]. Another report, by the company Protolabs, estimates the AM market at $12.6B USD in 2020 and projected it to grow to $37.2B USD by 2026 [6].

AM is also commonly referred to as 3D printing based on the concept of being able to use methods similar to conventional printing and create a 3D object. The terms are often used interchangeably and in this thesis, it will be referred to as AM.

Unlike common methods of manufacturing that are subtractive, where the material is removed until the desired form is achieved, AM as the name suggests, is an additive method, starting with nothing and adding material incrementally to build a part. AM
is primarily broken down into a total of seven categories and can be classified by the material form used as described in Table 2.1, depicted in Figure 2.1.

Table 2.1: AM methods as described in ASTM 52910 [7].

<table>
<thead>
<tr>
<th>Method</th>
<th>Material Form</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vat Polymerization</td>
<td>Liquid-Based</td>
<td>Material (liquid photo-polymer) in a vat is cured with light-activated polymerization.</td>
</tr>
<tr>
<td>Material Extrusion</td>
<td>Liquid-Based</td>
<td>Filament is heated to flow throw a nozzle to deposit material.</td>
</tr>
<tr>
<td>Material Jetting</td>
<td>Liquid-Based</td>
<td>Material is selectively deposited with droplets.</td>
</tr>
<tr>
<td>Powder Bed Fusion</td>
<td>Powder-Based</td>
<td>Material is fused with thermal energy.</td>
</tr>
<tr>
<td>Binder Jetting</td>
<td>Powder-Based</td>
<td>Material is joined by selectively depositing a liquid bonding agent.</td>
</tr>
<tr>
<td>Direct Energy Deposition</td>
<td>Powder-Based</td>
<td>Material is fused by melting as it is being deposited with focused thermal energy.</td>
</tr>
<tr>
<td>Sheet Lamination</td>
<td>Sheet-Based</td>
<td>Material sheets are bonded to form an object.</td>
</tr>
</tbody>
</table>

For the research presented, material extrusion with plastic filament was selected. Material extrusion is a process that uses a filament and melts it, allowing it to pass through a nozzle as a liquid to be deposited in the desired location. Material extrusion was first invented and patented by Scott Crump, co-founder of Stratasys, Ltd in 1988 [8]. This type of AM was named Fused Deposition Modelling (FDM ©), the patent for which expired in 2009, expanding the market of material extrusion machines available. The RepRap project introduced the term Fused Filament Fabrication (FFF) which is also commonly used to refer to material extrusion and is not trademarked or patented.
FFF is typically carried out on machines that use either a Cartesian system or a delta system as shown in Figure 2.2, with the former being most common. Machines primarily work in three degrees of freedom with the translation of all three axes, some machines offer five degrees of freedom with the rotation of the printing head.

The main mode of printing an object on both types of machines is by using planar layers. Printers comprise a print bed and a hot end which includes a heating block and a nozzle. The printer bed may be heated and often moves in one direction of translation. The heating block heats the filament, allowing it to extrude from the nozzle, depending on the machine the hot end can move in translation in the x,
y, or z directions. When printing, each layer is created in the x and y direction, ultimately creating a 2D drawing. Movement in the Z-direction is used to stack the layers creating a 3D model.

Delta printers are adapted from robots used for pick and place systems, three arms manoeuvre allowing for precise location, and have seen increased use for FFF [11]. As shown in Figure 2.2, there are three arms that move in the z direction allowing for translation in all three axes and the printer bed is stationary. The Cartesian printer shown has each axis of motion from a different component, with the printer bed moving in the y direction and the hot end moving in the x and z directions.

FFF has now become an accessible and affordable method of printing, some companies developing AM machines including Prusa and Creality which offer printers with print beds as small as 180 mm x 180 mm (Prusa Mini) or 300 mm x 220 mm (CR10 mini).

With popular print beds roughly the size of an A3 (297 mm x 420 mm) paper
and open-source software available, this method of manufacturing is easily available to many people. Some other benefits of material extrusion include:

- It is an AM method, therefore, less material is wasted in the manufacturing process as material is built up instead of removed
- Low part cost, allowing for multiple design iterations
- Low barrier to entry in regards to cost and software availability
- Allows for a higher part complexity at no extra cost, contrary to regular manufacturing methods
- Quick transition from design to manufacturing process making it a good option for prototyping

With the benefits listed above, as with any manufacturing methods, there are drawbacks to be considered as well:

- Many process variables that can be adjusted by the user, and a variety of machines, result in difficulty to create consistent results
- Inconsistency between prints, time of print and repeat-ability
- Large selection of the same filament from different manufacturers with varying mechanical properties
- Mechanical properties may vary on how the material is stored after opening
- Due to the low cost per part, more material may be used making prototypes, in turn creating more waste
- Stair-stepping effect
One review by Liu et al. [12] of AM methods highlighted that some criticisms of the viability of AM for large scale manufacturing, as the study indicated that the energy cost associated with manufacturing a component via AM methods is greater than that of a traditional manufacturing process such as injection moulding [12]. With large-scale manufacturing, it is important to weigh the options if developing a mould for injection molding is more beneficial. AM may not be the best option for large-scale manufacturing, there are factors to consider for specific projects.

More research in the field still needs to be done to compare the environmental impacts between types of AM and the specific energy use that is required for FFF.

2.1.1 Computer Aided Manufacturing (CAM)

The manufacturing method used for the majority of AM methods and used specifically for FFF is Computer Aided Manufacturing (CAM). CAM, as the name entails is a method using computer software to execute the manufacturing process.

To be able to print a part using FFF a 3D model must be made. There is a variety of software that can be used for FFF. The software used in this research was a slicer named "Slic3r" and requires a .stl file.

STL is short for stereolithography, this type of file divides the part file which can be a .step or .part file, down into a tessellated file, comprised of many triangles that are easy to manipulate by computer software. The STL format was developed in 1987 by Hull and is commonly used for FFF [13], with the idea of a 3D object being built by stacking 2D layers. Stereolithography, also known as laser lithography creates an object using directed exposure to ultraviolet (UV) radiation to a liquid photosensitive polymer to create the model and was an important technology in the advancement of AM [14]. While the AM methods and platforms have expanded far from only stereolithography, the .stl file format name grew in popularity and is primarily used.

The slicer allows the user to generate a code, known as G-code, with commands to
the printer necessary to execute the print. G-code and CAM in general originated with
the introduction of Computer Numerical Control (CNC) machining. CNC machining
was the first development into automated machining where G-code was used to control
components and manufacture parts.

The goal of the research presented in this thesis was to improve the print quality of
a readily available desktop FFF printer to produce RPAS components. The following
sections will discuss an adaptive method of FFF seen in Figure 2.3, referred to as
Curved Layer Fused Deposition Modelling (CLFFF). CLFFF is often referred to as
non-planar printing, in the context of the thesis, CLFFF will be used to describe
the method, and non-planar or curved will be used to describe the layers that are
printed.

Figure 2.3: Planar printing with FFF (left) and non-planar printing with CLFFF
(right).
2.1.2 Curved Layer Fused Deposition Modelling (CLFFF)

CLFFF Background

Adaptive slicing and various alternate printing methods have been around since the 1990s. Adaptive slicing is any slicing method implementing layers of different thicknesses or orientations to increase the capability and quality of 3D printing; it has been adopted across many methods of AM techniques.

With changing geometries, AM can result in a stair-stepping effect which is depicted in Figure 2.4. The stair-stepping effect can impact the fidelity of the actual model and can reduce the mechanical and aerodynamic performance of the printed part [15].

![Airfoil with different layer thicknesses](image)

(a) Airfoil with 0.4 mm layer thickness.

(b) Airfoil with 0.2 mm layer thickness.

(c) Airfoil with 0.1 mm layer thickness.

Figure 2.4: Slicer preview of airfoil and stair-stepping effect with different layer thicknesses (chord length=53 mm).

Research conducted in 1997 by Sabourin et al. [16] included thicker lower density layers as the infill and thinner layers on the top and bottom to decrease the
manufacturing or build time. Another similar method of adaptive slicing to improve the surface quality of printed parts includes reducing the layer thickness in areas with curvature to reduce the stair-stepping effect. While this method can reduce the stair-stepping effects as can be seen from Figure 2.4b and 2.4c, it is still present and print time would, in turn, increase manufacturing time. Additional methods and history of adaptive slicing through the years 1994-2012 can be found in [17] and [18].

The adaptive slicing technique of interest for this study is Curved Layer Fused Filament Fabrication (CLFFF). The method was introduced by Chakraborty [19], specifically Curved Layer Fused Deposition Modelling (CLFDM) in the early 2000’s. A non-planar printing method takes advantage of all three axes for curved layers, the x, y, and z directions move throughout the print following the curvature of a given surface. This creates a smooth surface for curved top layers and reduces the stair-stepping effect. Other curved layer AM methods were studied before methods for FFF, Klosterman et al. [20] developed curved layer Laminated Object Manufacturing (LOM) for monolithic ceramics and ceramic matrix composites in 1999. This application by Klosterman et al. for curved thin shells proved to eliminate the stair-stepping effect, increase build speed, reduce waste and maintain the continuity of the composite fibers in the direction of curvature [20].

One factor affecting the strength of printed parts is the inter-layer versus intra-layer strength, the inter-layer strength being lower than intra-layer strength. The inter-layer strength is the bonding within individuals layers, and intra-layer strength is the bonding of each subsequent layer that is stacked. Parts made using FFF often suffer from anisotropy and low adhesive strength between layers. This is due to the building process, as each layer is printed with mainly continuous filament with higher adhesion and then stacked to the next layer with lower adhesion as cooling of the layer previously deposited has begun. Studies by Perez et al. [21] indicate that the
tensile strength in the build direction of the FFF component could be as low as 50% of the strength loaded parallel to build orientation [21]. Tests conducted by Zeltmann et al. [22] showed that ABS loaded in the inter-layer direction, perpendicular to the build orientation resulted in brittle failure, whereas tests parallel to build direction showed ductile fracture with significant deformation before fracture [22].

Chakraborty [19] introduced the use of CLFFF for thin curved shell-type parts. Introducing curved layers increases the amount of continuous filament, resulting in higher strength and bonding. This can be seen in Figure 2.5a, with more continuous filament along the top of the modelled part than can be seen in Figure 2.5b, the pink represents the top layers, the yellow lines are layers below.

![Figure 2.5: Model of a part sliced using curved layer and regular FFF.](image)

(a) Model with curved top layer. Continuous filament in the same direction.  
(b) Model with FFF (planar) layers. Filament is placed in various directions.

Developments of CLFFF algorithms and machines

With the growing interest in CLFFF, many researchers are working to design machines and algorithms to be able to handle it but there is not yet one universally available option. The research completed by various groups is discussed in the following section.
In 2009 Huang [23] successfully printed a curved part using CLFFF, by adapting a desktop FFF printer and creating a slicing software in MATLAB to print non-planar layers. The software was able to take an STL file, obtain the Cartesian coordinate value of each point, and recorded it in the form of matrices. A Four Vector Cross Product algorithm was used to determine the offset of each surface, it used four vectors to solve new locations for each point on the layers. Using this method, each point on the surface was calculated and the curved surface was generated from these points [23, 24]. Singamneni et al. [25] continued research using the algorithm to manufacture parts and study the mechanical properties of Fabepoxy and ABS, three-point bend testing was conducted on curved surfaces. The Fabepoxy testing resulted in a failure deflection load of 227 N and 320 N for flat and non-planar layers respectively [25]. The ABS was found to fail at 626.5 N for regular planar slicing, 764.7 N for adaptive slicing, and 951.4 N for non-planar slicing [26]. Other research expanding on the platform developed and the algorithm is presented in [17, 27].

The work by Allen and Trask et al. [11, 28] developed a proof of concept of CLFFF of different types of printed surfaces using a modified delta FFF platform. Three case studies printing concave curved surfaces included a vehicle body panel, a shoe insole, and a dished sandwich panel, outlined in [28]. To create a tool path, the surface was converted to an array of data points, the z-value for the surface was calculated using the surface equation and creating a vector field following the part shape [11].

Lim et al. [18] highlighted the benefits of CLFFF for large-scale AM with concrete. This research used a scripting language to produce a code for the printer rather than a single mathematical model [18].

The work presented by Jin et al. [29] focused on the development of an accurate model for CLFFF. The work targeted the tangent point for filament deposition. The study took the data of the surface as a B-spline. The extruder path was obtained in two steps. First, a surface was obtained by offsetting the design surface with a
distance of half a layer thick and this was the filament target. The filament target paths were generated based on a given path and the void depth requirement [29]. Zhao and Guo [30] presented extruder path generation for CLFFF for an extruder with multiple degrees of freedom, by using methods outlined by Jin et al., the offset surface was obtained by offsetting the curved surface along the normal direction by a distance of the layer thickness. First, the slicing surface was offset with respect to the previous layer to determine the filament target and the next location of the extruder, and the filament target paths were created based on the select infill pattern [30].

A different method of extruding filament is investigated by Tsao et al. [31]. The intent here was to examine traditional forming and joining processes by using the print head to directly deposit material to the part. This research looked at the effects of changing both the direction and dimension of the printed part simultaneously. A plastic filament was used with a soldering station as a heat source. A 4-axis CNC tabletop system was used to test a setup. Different nozzles were designed and tested to be attached to the tips of a soldering head [31].

In 2018, Ahlers [32] developed a non-planar slicing adaptation that can be used in the open-source software named “Slic3r”, which was made available online, this program will be used for the parts presented in this thesis. The toolpath generation presented by Ahlers used projection. Potential non-planar layers are identified and moved to the highest layer of the part. The non-planar surface was modelled above the part as a 2D surface floating above the part, this was then projected down onto the top of the surface. Extrusion paths are generated from 2D points, but the non-planar surface has a different z value which is the distance from the projected layer to the surface, this creates the non-planar layers [15, 32].

The projection of the top surface was based on the facet geometry, the printed pattern is made up of extrusion paths which are a vector of points. The tool path was projected to follow the geometry of the surface, each point of the identified non-planar
layers touching a planar layer in the tool path is processed. The z component must be set to the same height to achieve a non-planar path, this was done by searching the facet of the non-planar surface. Each point was checked against each facet, the edges of which were defined by three vectors, a point was checked with the three vectors if it lies in the facet. Line plane intersection was used to determine the point that needs to be projected onto the facet [32]. The following calculations were derived by Ahlers [32] to determine the projected distance of the non-planar layer. The plane was first converted into the following forms:

\[ ax + by + cz + d = 0 \]  \hspace{1cm} (2.1)

Where \( a \) and \( b \) are the \( x \) and \( y \) components that remain unchanged, the \( z \) component is the only component that changes, and \( d \) is defined as:

\[ d = -(N \ast V) \]  \hspace{1cm} (2.2)

Where \( N \) is the normal vector and \( V \) is any vertex from the facet. The projected distance for \( z \) is then determined by:

\[ P(z) = P(z) + u \]  \hspace{1cm} (2.3)

Where \( u \) is defined as:

\[ u = -\frac{N \ast P + d}{N \ast z} \]  \hspace{1cm} (2.4)

This projection results in a tool path that intersects previous planar layers which can be seen in Figure 2.6b. Each line is then checked against every edge of the facet on the non-planar surface to get the intersection. The intersection is first checked in the \( x \) and \( y \) with a two-line intersection algorithm and the \( z \) component is added when there is an intersection to achieve a tool path with no collisions to the layers previously placed as shown in Figure 2.6c [32].
Another program recently developed is the Curvi Slicer which uses an algorithm to optimize the deformation of the object, resulting in a toolpath to be curved along with the object as shown in Figure 2.7 [33].

One shortcoming of CLFFF on 3-axis machines involves the bonding of extruded material; to achieve the strongest bond, having the print head perpendicular to the layer it is depositing is ideal as shown in Figure 2.8a. For CLFFF the normal vectors of the surface at deposition points are constantly changing so the distance between the height of the filament is larger than in flat printing, therefore the layers do not bond as well to the material surface. This can be seen in Figure 2.8, Figure 2.8a is
a planar printing tool path, where the filament is deposited directly perpendicular to the end of the nozzle, the nozzle is close enough to the material to help lightly press it onto the surface to achieve the desired layer thickness. The issues of CLFFF with a 3-axis machine can be seen in Figure 2.8b and 2.8c, a larger angle is used to better portray the effect. In both cases, the filament has a further path to travel from the tip of the nozzle down to the part than in Figure 2.8a. In Figure 2.8b, the left side of the tip of the nozzle interferes with the filament and can cause scraping of the top surface. In Figure 2.8c, the filament is not pressed down onto the surface and can result in a rough surface finish.

![Diagram](image)

(a) Regular/planar printing.

(b) Non-Planar, nozzle travelling down.

(c) Non-Planar, nozzle travelling up.

**Figure 2.8: Nozzle position relative deposited filament when extruding.**

CLFFF can provide benefits by reducing/eliminating the stair-stepping effect but also improving mechanical properties due to better inter-layer bonding. Much research is still ongoing to develop an algorithm, method, and machine to best execute CLFFF. Some mechanical tests have been conducted, but no extensive work has been
completed to validate the benefits of CLFFF. This thesis stands to fill the gap in research on CLFFF part strength and determine if non-planar top layers offer a benefit to part quality including surface finish and mechanical properties.

### 2.1.3 AM Materials

There are a wide range of materials available to be used for FFF ranging from plastics to composites and even wood or metal in some cases. For FFF, material is available in the form of pellets or filament, which are fed into a heated nozzle to extrude the material in the desired shape for deposition. This thesis was based on FFF for RPAS applications, therefore, thermoplastic materials are considered to increase weight savings and for use on a desktop 3D printer. Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) were initially popularized with the start of FFF printing, but many other materials have surfaced in recent years. Some materials of interest are listed in Table 2.2.

**Table 2.2: Materials Suitable for AM of RPAS [34, 35].**

<table>
<thead>
<tr>
<th>Material</th>
<th>Printer Bed Temperature (°C)</th>
<th>Printer Nozzle Temperature (°C)</th>
<th>Ultimate Strength (MPa)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylonitrile Butadiene Styrene (ABS)</td>
<td>96-110</td>
<td>220-265</td>
<td>33-40</td>
<td>1.04</td>
</tr>
<tr>
<td>Acrylonitrile Styrene Acrylate (ASA)</td>
<td>90-110</td>
<td>235-260</td>
<td>43-55</td>
<td>1.07</td>
</tr>
<tr>
<td>Nylon</td>
<td>70-90</td>
<td>220-270</td>
<td>40-85</td>
<td>1.1</td>
</tr>
<tr>
<td>Polycarbonate (PC)</td>
<td>80-120</td>
<td>260-310</td>
<td>62-72</td>
<td>1.2</td>
</tr>
<tr>
<td>PET glycol-modified (PETG)</td>
<td>70-90</td>
<td>230-250</td>
<td>30-53</td>
<td>1.23</td>
</tr>
<tr>
<td>Polylactic Acid (PLA)</td>
<td>25-60</td>
<td>190-230</td>
<td>46-65</td>
<td>1.24</td>
</tr>
</tbody>
</table>
Research by Maricic et al. [36] completed a weighted trade study including the listed materials scoring them on various categories and weighing them with importance related to use for RPAS. The categories included ultimate tensile strength, durability, density, price, printability, and recyclability. The materials highest ranked in the study were PETG, Nylon, ASA, and PC.

As mentioned, one highlighted benefit of FFF is the reduced amount of material waste in manufacturing. However, failed prints, short life cycle parts, and support structures still account for large amounts of waste from FFF. Plastic production has grown significantly over the last decades and is set to increase to 850 million tons of plastic waste by the year 2050, and many plastics are made from fossil fuels and are not biodegradable [37]. More research has been done over the last decade on the recycling of materials and new materials with more environmental benefits.

With a focus on the environmental impact, more research is being done looking at the capability of recycling used filament. The Protocycler, designed by the Canadian company ReDeTec is a material recycler that grinds up used material and extrudes new filament [38]. Researchers from the University of Michigan and Aalto University designed an open-source RepRapable Recyclebot. The Recyclebot is affordable and many of the parts can be made with a 3D printer [39]. An issue with recycling printed parts is the deterioration of mechanical properties over time after several melting and cooling cycles. Depending on applications and use of printed parts, recycled filament could be suitable. There are also some plant-based plastic becoming more popular and post-consumer/post-user recycled filaments are offered directly from manufacturers. Due to the requirements of mechanical properties being consistent and known for use of RPAS structural components, the recycled filament was not explored in this thesis, but the recyclability of the material was taken into account.
2.2 Remotely Piloted Aircraft System (RPAS)

RPAS also commonly known as Unmanned Aerial Vehicle (UAV) or drones; offer many benefits such as being able to fly in conditions that may pose a high risk to pilots; low altitude flight capabilities; being able to fly in conditions not safe or not possible for manned aircraft; relatively low price point; long flight endurance; and short takeoff and landing capabilities. RPAS have a wide range of applications and are increasingly being used commercially and recreationally.

Since the 1990s the market for RPAS has been significantly growing. Initially beginning as a military technology, it is now possible for anyone to have a small RPAS for recreational purposes. With the increased use of RPAS, Transport Canada released new regulations effective June 1, 2019, and are continuing to progress on the regulations which are found in the Canadian Aviation Regulations (CARs) SOR/96-433 Part IX [40]. The new regulations implement different classes of RPAS, any aircraft with a maximum take-off weight below 250 g is considered a micro RPAS, between 250 g, up to 25 kg is classified as small RPAS, and aircraft above 25 kg are large RPAS and require a special flight operations certificate for flight.

Small RPAS listed by Transport Canada allow for basic drone operations and will be the focus of this research. Small RPAS allow for an accessible platform for recreational, educational, research, and commercial use of aircraft.

The two most common aircraft configurations are a fixed wing aircraft and a rotary wing aircraft, but there are also many other aircraft such as flapping wing, hybrid, or blimp-type RPAS platforms. The focus was primarily on fixed and rotary wing aircraft as those are used for research at Carleton University as shown in Figure 2.9.
2.2.1 RPAS and Additive manufacturing

Advancing AM methods have evolved to allow for “low cost” manufacturing that a variety of people can access whether it be large companies or individuals in their homes. The focus of this work outlines the use of AM for developing RPAS, allowing for flexibility within the design aspect itself as well as the ability to print in many locations and on demand.

The benefits of AM are being recognized by many researchers in the field of RPAS, with much work in the last 5-10 years analyzing benefits and challenges, optimizing materials and RPAS designs. For more detail the work presented in [36],[43], [44], [45], and [46] is some of the work highlighting the use of AM and RPAS. This thesis will highlight some key moments within the RPAS and AM fields.

The primary benefits of AM to applications of RPAS include: being able to manufacture complex parts that are difficult to achieve with traditional manufacturing, being able to tailor materials and designs depending on the mission requirements, and being able to manufacture parts on site.

The first 3D printed RPAS to take flight was developed at the University of Southampton. The Southampton University Laser Sintered Aircraft (SULSA)
shown in Figure 2.10 was designed and manufactured using laser sintering. The technology allowed for tailoring of the aircraft and quick production going from concept to manufacturing within days. AM allowed for the SULSA to have elliptical wings, which have decreased induced drag as compared to straight or elliptical wings but are difficult to make with common manufacturing methods and are therefore not commonly seen on modern aircraft [47]. The aircraft was designed in 2011 and in 2015, the Royal Navy flew tests with the SULSA to demonstrate the potential use of such aircraft for maritime use [48].

Figure 2.10: SULSA (Southampton University Laser Sintered Aircraft) [47].

AM allows for faster production of RPAS and increased weight savings with the use of reinforced and unreinforced plastics over conventional metals. Many companies are taking advantage by adopting this technology directly into their manufacturing line; the Tundra Windform, for one is a quadcopter RPAS developed by CRP Technology using laser sintering as well and is shown in Figure 2.11a [49]. Another company, 3D Robotics, released an aircraft in 2014 named the IRIS+, and in 2016 the company teamed up with My Mini Factory, making all the 3D part files of the aircraft available to the public for them to be able to manufacture it themselves.

It is not uncommon to see unique and customized additions to RPAS custom designed to meet requirements whether it is mounts for a variety of payloads from sensitive electronics, cameras, or even packages. Figure 2.12 shows the Carleton University Pawnee aircraft with printed wing tip pods to hold sensitive magnetometers.
AM has evolved to the point that there is a printed jet powered RPAS that can fly at 240 km/hr, shown in Figure 2.13. Developed by Aurora Flight Sciences, the goal was to show how quickly a design can be brought from concept to reality [51].

2.2.2 RPAS Propellers

Propellers on RPAS, perform the same role as on a regular aircraft, but on a smaller scale. For a fixed wing aircraft, propellers can either be placed on the front, back or wings and provides thrust to the aircraft. For a rotary wing aircraft, the rotating
Figure 2.13: World’s first jet powered RPAS made with AM [51].

propellers often called rotors, are responsible for both the lift and thrust of the aircraft.

Propellers have been a part of aircraft from the start of aircraft design to offer thrust, much work was done studying aircraft propeller design in 1930. Propellers use classic momentum theory. The energy of the rotation of the blade is converted into the force produced for thrust or lift of the aircraft. Propellers used for small RPAS tend to have low efficiency of around 30-70% [52].

Flight conditions depend on the total weight, which may vary based on the application of an RPAS. In flight, the induced and forward velocity will change, and the efficiency of the propellers changes through flight due to this. Aircraft propellers, are not always operating at peak efficiency, and changing the pitch of the blade helps maximize the thrust-to-power ratio [53]. Take-off speed requires a large amount of lift to get the aircraft off the ground, requiring propellers with a small pitch. While cruising, higher pitch propellers are required [54].

One key benefit of AM is being able to design mission specific propellers, a process to design and manufacture propellers to meet user defined performance requirements was designed by Rutkay [53].

With the increased use of RPAS, regulations have been developing. Many of them as general guidance, specifically ASTM F3298-19 for the “Design, Construction, and Verification of Lightweight Unmanned Aircraft Systems” which outlines many design requirements for propellers and rotors [55]. The standard provides guidance on the
propellers speed and pitch, structural strength, safety factors, mass balance, blade clearance, and maximum damage and wear. The guidelines are broad for example “Propeller speed (RPM) and pitch shall not be allowed to exceed safe operating limits established by the manufacturer under normal conditions” [55]. Meeting requirements is therefore up to the design/manufacturer for safe use of the RPAS. The guidelines are broad, which is due to the many applications and in turn sizes and configurations of RPAS.
Chapter 3

Methodology

This chapter discusses the methodologies employed to prepare samples using AM, and to conduct mechanical testing. Testing included uni-axial tensile testing, three-point bend test, and four-point bend test.

3.1 Experiment Proposal

The purpose of the work presented is to address and identify the benefits of current CLFFF capabilities on readily available desktop FFF printers, as well as mechanical testing of specimens manufactured with CLFFF.

Various specimens are printed using uniform and adaptive FFF specifically CLFFF, this research intends to fill a gap in material testing knowledge. CLFFF has been shown as a promising method to increase part quality and performance. There is not yet a reliable platform for CLFFF and much of the research being conducted is in developing the foundation for such a program as discussed in Section 2.1.1. This work proposes experiments using CLFFF for curved specimens.

The primary objectives of the work are to:

- Use open-source FFF desktop printer to execute non-planar printing
- Test specimens to compare the impact of CLFFF on part strength and quality
• Proof of concept printing various specimens using CLFFF

The following sections will outline the methodologies to reach the objectives listed. First the material selection will be discussed. Next the manufacturing methods will be discussed including the steps required for FFF and the software and hardware selected to complete the research. Once coupon manufacturing is complete, methods of testing and analysis are detailed, various testing was conducted to determine material properties including tensile and bend testing. Statistical methods are outlined that were used in analyzing the data to determine if there are statistically significant variations in the results.

3.2 Material Selection

By selecting RPAS components as the case study, it brings some challenges in selecting a material to withstand the operating environment. Some requirements for the material include:

• Must withstand forces and provide sufficient lift
• Must be stiff enough to hold its shape to provide sufficient lift
• Be able to withstand impact from potential crashes
• Withstand natural environment, including rain and sun
• Be able to print on the printer capabilities. Limited by heated bed of 80°C and nozzle of 260 °C

Considering the materials presented in Table 2.2, the following section outlines certain advantages and disadvantages and the material ultimately selected.
PLA is an appealing material as it is considered bio-degradable, bio-compatible, and is also made from plant starch as opposed to fossil fuels. However, PLA has a low fracture toughness and low impact strength. PLA is also highly hygrothermal, meaning it absorbs moisture and heat from the environment resulting in hydrolysis that degrades the part [56]. PLA has poor resistance to ultraviolet (UV) light as the energy of the UV outdoors is higher than the bond of the molecular change of PLA, therefore when exposed to sunlight it can become brittle and result in a shorter life-cycle [57]. For those reasons, PLA was not selected.

ABS does have a low density and moderate impact strength but, ultimately was not selected due to the high printer bed temperature required and the increased fumes from ABS of potentially dangerous volatile organic compounds when heated [58]. ABS also breaks down with UV radiation losing colour and becoming brittle [59] and was ultimately not selected.

Carbon Fiber Filled polymers offer great mechanical properties and as a material with fibers may have increased benefits from non-planar printing. Non-planar printing increases the amount of continuous filament and filament in the same direction rather than vari-directional. Ultimately, it was not selected as it could be abrasive to the nozzle and could lead to more clogging issues with the printer.

Nylon offers great impact resistance due to its flexibility and has a low density. However, nylon is often a tricky material to print which raised concerns with a longer nozzle. Nylon is also hygroscopic and absorbs moisture from the surrounding air, which can affect print quality and nylon should be pre-dried to remove any excess moisture [60].

PC, and ASA offer a high ultimate strength but were not selected due to the high temperatures that are required for printing.

PETG is often seen as a good balance between ABS and PLA. It is hygroscopic but not as much as Nylon or PLA.
The material selected was PETG by Polymaker. PETG was selected as it does not have the same off-gassing effects of ABS and although it is hygroscopic, it is less so than other materials. The material was stored out without a dehumidifier, material was placed in a bag with silica when not being used for extended periods of time.

3.3 Coupon Manufacturing

AM, specifically a desktop FFF printer was selected as the technology for this project because it is cost-effective, accessible, and portable. The method used to create the objects with the 3D printer is Computer Aided Manufacturing (CAM). Where a computer program, breaks down and plans the manufacturing of the part. The following steps are required to obtain a printed part:

1. Design a part in a CAD software and obtain an .stl file
2. Upload the .stl file into a program referred to as a slicer
3. Set printing parameters in the slicer for the specific printing material and preferred part quality
4. Obtain a G-code from the slicer
5. Load G-code onto the printer and print the part

The process listed above is iterative and repeated until the desired part quality is achieved as illustrated in Figure 3.1.

3.3.1 Computer Aided Manufacturing (CAM)

The computer program used, called a slicer, ultimately breaks down the STL, layer by layer and creates a code allowing the manufacturing machine, in this case a FFF
printer to execute the print. The slicer often allows the user to visualize what the print looks like. Figure 3.2 shows what can be seen in the slicer, the part can be seen layer by layer how it will be printed.

(a) First layer of propeller.  
(b) Propeller sliced 1/4 of the way.  
(c) Propeller sliced 3/4 of the way.  
(d) Fully sliced propeller.

Figure 3.2: Slicer visualization of a propeller, snapshots taken at various point of slice.

The slicer takes the STL and generates a G-code file, which is the common name for the text file that contains all the commands for the machine to execute the print. The code is a combination of G-code, indicating the tool path with a sequence x, y and z coordinates, as well as M-code which are commands to the machine such as temperature and acceleration. The series of G-code coordinates are what map out each layer of how the print head moves. A sample of G-code is shown in Figure 3.3, the code included is for a non-planar part, one thing to note is the value of the z component. It remains the same for planar layers (Figure 3.3b), but across non-planar layers it changes with each coordinate (Figure 3.3c).
The following sections highlight the specific hardware (printer) and software (slicer) used to manufacture the components.

### 3.3.2 Hardware- Selected FFF Printers

The printers used were the Anycubic MegaX and a custom-built printer, the Dewar Made-Experiment One. Two printers were selected to meet timeline requirements. While printing parameters were set to be the same for both printers, some aspects of the printer itself may influence the print quality, Table 3.1 outlines each printer’s specification and indicates if the parameter could influence the part quality.

Parameters not marked in Table 3.2, do not have an impact on the print quality as they do not directly influence the print or can be set to be the same on both printers. The parameters that may affect the final part quality will be discussed.

The maximum print speed may affect quality as it is the upper limit of the printer’s capability. The controller also may have affect the print as with a larger controller comes more precision to where the filament is being placed, resulting in stronger parts.

```plaintext
G28 ;Home
G92 E0 ;Reset Extruder
M190 S85 ; set bed temperature and wait for it to be reached
M109 S255 ; set temperature and wait for it to be reached
G21 ; set units to millimeters
G90 ; use absolute coordinates
```

(a) Initializing G-code, before extrusion begins.

(b) G-code of planar layer, z value is consistent. (c) G-code of non-planar layer, z value changes.

**Figure 3.3: G-code sample.**

The following sections highlight the specific hardware (printer) and software (slicer) used to manufacture the components.
Table 3.1: Printer specifications of the two printers used in the research work.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Anycubic Mega X</th>
<th>Dewar Made</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>300 x 300 x 300 (mm)</td>
<td>166 x 176 x 171 (mm)</td>
</tr>
<tr>
<td>Maximum Print Speed +</td>
<td>100 mm/s</td>
<td>800 mm/s (recommended 300-400 mm/s)</td>
</tr>
<tr>
<td>Bed and Nozzle Temperature</td>
<td>85°C, 250°C</td>
<td>110°C, 300°C</td>
</tr>
<tr>
<td>Filament feed -</td>
<td>Bowden Tube</td>
<td>Direct Drive</td>
</tr>
<tr>
<td>Controller +</td>
<td>8-bit</td>
<td>32-bit</td>
</tr>
<tr>
<td>Nozzle -</td>
<td>Extended Nozzle</td>
<td>Regular Nozzle</td>
</tr>
</tbody>
</table>

+ parameter has higher influence on final part quality.
- parameter has a lower influence on part quality.

The filament feed type can affect how well the filament is flowing into the nozzle, the two types of are shown in Figure 3.4. A bowden tube, is a tube that connects the gear box pushing the filament to the nozzle. A direct drive assembly has the gears directly above the heating block, therefore the material is pushed directly into the extruder rather than through a tube first.

One last component that may have an impact on the part quality is the nozzle. A longer nozzle was installed on the Anycubic to ensure enough clearance when printing non-planar layers. The extended nozzle results in a temperature drop from the heating block to the point of extrusion. The assembled nozzle of the Anycubic is shown in Figure 3.5a and the long and short nozzles are shown side by side in Figure 3.5b.

While several factors can cause discrepancies, printing parameters will be set to be the same on both printers and will be outlined in the following section. These differences in printers should be accounted for in the results.
3.3.3 Software- Slic3r

The software used for FFF as previously mentioned, is commonly referred to as slicing programs or “slicers”. Within the slicer various settings can be changed, the high level settings are shown in Figure 3.6.

Within each category, specific parameters may be adjusted. The print settings are the primary settings of the print including layer height, perimeters, the type of infill,
the first layer, speed, support material, and some more advanced settings as well. Filament settings include diameter of the filament, and the temperature of the nozzle and print bed, as well as cooling fan settings. The printer settings set the hardware limits such as the size of the print bed, if the print bed can be heated, the size of the nozzle, and offsets.

The specific printing parameters used for the Polylite PETG by Polymaker used in this research are outlined in Table 3.2, the settings were selected after running various test prints to determine what produced the best and consistent prints.

The rectilinear infill was selected as it can be used with 100% infill, it is a diagonal pattern that switched directions each layer as shown in Figure 3.7. It also offers higher yield strength when compared to concentric and honeycomb infill [62, 63]. The rest of the settings were determined based on the recommendations from the manufacturer with changes made to improve the printability. The temperature settings were tested several times and the printer bed heat was selected to allow for good adhesion, the infill overlap was selected after some prints had stringing and over extrusion.
Table 3.2: Printing parameters selected for printing PETG specimens

<table>
<thead>
<tr>
<th>Printing Parameter</th>
<th>Set Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>55 mm/s</td>
</tr>
<tr>
<td>Filament Temperature</td>
<td>255 °C</td>
</tr>
<tr>
<td>Bed Temperature</td>
<td>85 °C</td>
</tr>
<tr>
<td>Acceleration</td>
<td>X500, Y500, Z100 (mm/s)</td>
</tr>
<tr>
<td>Layer Height</td>
<td>0.1 mm (excluding 4-point bend specimens at 0.2mm)</td>
</tr>
<tr>
<td>Layer Width</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Infill Percentage</td>
<td>100% (excluding 4-point bend specimens at 90%)</td>
</tr>
<tr>
<td>Infill Overlap</td>
<td>10%</td>
</tr>
<tr>
<td>Infill Pattern</td>
<td>Rectilinear</td>
</tr>
</tbody>
</table>

Figure 3.7: Rectilinear printing extruder path for two layers, one would be on top of the other.

As mentioned in Section 2.1.2, no widely used software currently exists with curved layer (non-planar) settings within the program specifically for FFF printers. This means that the programs will slice the part, building with only 2D layers (x and y) that are built up in the third direction (z), with no options for other ways of printing. Ahlers worked to develop a non-planar software to integrate into the open-source slicing program Slic3r [15]. The work done by Ahlers allows the user to directly add a
non-planar slicing option into the program as shown in Figure 3.8 and is the software used in this research. The program curvislicer was explored but the program did not compile when the .stl files of interest were uploaded and therefore that program was not used.

(a) Regular (planar) slic3r print settings.  
(b) Non-Planar slicing print settings.

Figure 3.8: Slic3r print setting options.

The non-planar setting in Slic3r allows the user to set a select number of top layers to be printed with non-planar layers. The remainder of the part is sliced as a regular planar print, with only the selected number of top layers set to be curved. The Slic3r visualization of a curved coupon is shown in Figure 3.9. A cut version of the part is shown in Figure 3.9c, showing how both Figure 3.9a and 3.9b look on the inside.
3.4 Methods of testing and analysis

Various methods of testing were selected to validate and determine the effects of CLFFF. First, tensile testing was conducted to confirm the material characteristics provided by the material manufacturer and is outlined in Appendix A, Figure A.1. Second, flexural testing of three types of specimens was complete, including three-point and four-point bend tests to assess the impact of non-planar printing on mechanical properties. Lastly, samples of segments of propellers and airfoils are printed for proof of concept.

Three-point bend tests on 10° and 20° specimens are to compare the strength of different top layers comparing planar layers to two, four, and six non-planar top layers which correspond to approximately 5%, 10%, and 15% of the part thickness.

Four-point bend tests with 90° samples were complete and samples were printed in three orientations, upright for completely planar printing, sideways with linear infill,
and sideways with rectilinear infill as shown in Figure 3.10.

![Figure 3.10: Orientation of printing of 90° specimens.](image)

(a) Upright orientation (fully planar).  (b) Sideways (non-planar) orientation.

The testing and number of experiments complete is outlined in Table 3.3.

### 3.4.1 Tensile Testing

Tensile testing followed ASTM D638 standards, type I dog bone specimens were selected as suggested by the standards for rigid and semi-rigid plastics [64]. The dimensions of the coupons were adapted by extending the gripping section to allow the grips of the hydraulic press machine to better hold the specimen, dimensions are shown in Figure 3.11. The setup for the tensile testing is shown in Figure 3.12.

The force and displacement is recorded by the hydraulic servo system for the duration of the test, the speed of testing was selected as suggested by ASTM for type I dog bone as 5 mm/min. The tensile strength was calculated using the force at the break and cross-sectional area of the coupons within the gauge section. Young’s modulus is calculated within the linear portion of the stress-strain graph, and the elongation at break is also determined from the recorded values.
Table 3.3: Design of experiments.

<table>
<thead>
<tr>
<th>Mechanical test</th>
<th>Non-Planar or Planar</th>
<th>Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile</td>
<td>Planar</td>
<td>10 total (5 per printer)</td>
</tr>
<tr>
<td>Three-point bend</td>
<td>Planar</td>
<td>5</td>
</tr>
<tr>
<td>Three-point bend</td>
<td>Non-Planar</td>
<td>15 total</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5 per 2, 4, and 6 top layers)</td>
</tr>
<tr>
<td>Three-point bend</td>
<td>Planar</td>
<td>5</td>
</tr>
<tr>
<td>Three-point bend</td>
<td>Non-Planar</td>
<td>15 total</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5 per 2, 4, and 6 top layers)</td>
</tr>
<tr>
<td>Four-point bend</td>
<td>Planar</td>
<td>5</td>
</tr>
<tr>
<td>Four-point bend</td>
<td>Non-planar</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 3.11: Tensile dog bone type I specimen (dimensions are in mm).
3.4.2 Three and Four Point Bend Testing

Two types of testing were selected for flexural testing to be able to assess both shallow and large curves. A three-point bend test in accordance with ASTM D790-17 “Standard Test Method’s for Flexural Properties of Unreinforced and Reinforced Plastic and Electrical Insulating Materials” and a four-point bend test in accordance with ASTM D6415 “Standard Test Methods for Measuring the Curved Beam Strength of Fibre-Reinforced Polymer-Matrix Composite” [65, 66]. Both test setups are shown in Figure 3.13. The force and displacement are recorded by the hydraulic servo system.

The test jig was designed and manufactured by Carette [67]. The jig was made in accordance with ASTM D790-19, meant for testing flat specimens. The samples used in this research were adapted for curved samples and with similar dimensions as Carette tested to ensure they fit the jig.
Three-point bend test

A three-point bend test was done on two types of specimens, $10^\circ$ and $20^\circ$ curved arcs, with dimensions as shown in Figure 3.14.

![Three-point set up and Four-point set up](image)

Figure 3.13: Three and Four point flexural test set up on a 25 kN servo-hydraulic machine.

Figure 3.14: Dimensions of $10^\circ$ specimen (dimensions are in mm).

The ASTM D790-17 standard is developed for straight beams, therefore it was only used as a guideline for testing. The suggestions for cross head motion and span
Figure 3.15: Dimension of 20° specimen (dimensions are in mm).

were used from the standards and were 2.9 mm/min and 81.3 mm respectively. The equations of the stress and strain are outlined below [65]:

$$\sigma = \frac{3FL}{2bd^2}$$  \hspace{1cm} (3.1)

Where $F$ is the force, $L$ is the distance of the supports, and $b$ and $d$ are the width and depth of the sample. With the recorded displacement $\delta$, the strain is defined as:

$$\epsilon = \frac{6\delta d}{L^2}$$  \hspace{1cm} (3.2)

A limitation of the formulas presented above is that they are applicable to flat beams, the standards for curved beams are associated with a four-point bend test which is covered in the next section. Therefore formulas from ASTM D790-17 must be adapted for curved specimens.

There are some assumptions made in completing the calculations. The specimens are assumed to be loaded in the plane of symmetry, the cross-sections are perpendicular to the neutral axis, the material is homogeneous, stresses are below the elastic limit and the segment has pure pending.

As shown in Figure 3.13a, the specimen in the jig is simply supported by two rollers on the bottom surface, the loading point is located in the center placed on top
of the specimen. The reaction forces on the roller are estimated by taking a section of the beam and assuming roller support at the middle point to determine the moment, which is illustrated in Figure 3.16.

![Free body diagram of one section of the beam split in half.](image)

**Figure 3.16:** Free body diagram of one section of the beam split in half.

Where \( d_x \) and \( d_y \) are the distance from the contact point of the bottom roller to the neutral axis. The angle \( \alpha \) which varies throughout testing is defined as:

\[
\alpha_i = \tan^{-1}\left(\frac{d_y - \delta}{d_x}\right) \quad (3.3)
\]

\[
Fx = F/2 \quad (3.4)
\]

\[
Fy = \frac{F/2}{\tan(\alpha)} \quad (3.5)
\]

\[
\rho_o = \tan^{-1}\left(\frac{r_n - d_y}{dx}\right) \quad (3.6)
\]

Both \( \alpha \) and \( \rho \) will change during testing, but the angle between them is assumed to be constant, defined as:

\[
\theta = \alpha_{\delta=0} + \rho_o \quad (3.7)
\]

Figure 3.17 shows a segment of a curved beam in pure bending. Where \( (r_o) \) and \( (r_i) \) represent the radius to the outer and inner edges of the part, and \( h \) is the height.
of the cross-section. The distance from the neutral axis to the inner and outer edge is defined as \( c_i \) and \( c_o \) respectively. The centroidal axis (\( r_c \)) depends on the geometry of the part, the neutral axis is the place along which there are no stresses (\( r_n \)), for a straight beams these axes line up, for a curved beam that is not the case.

![Figure 3.17: Diagram of a curved beam in bending [68].](image)

The central and neutral axis distance is defined as [68]:

\[
r_c = r_i + \frac{h}{2} \tag{3.8}
\]

\[
r_n = \frac{h}{\ln(r_o/r_i)} \tag{3.9}
\]

The distance between \( r_c \) and \( r_n \) is defined by the difference of the values and is denoted as \( e \) [68].

The stress is determined by the following equations defined in [69].

\[
\sigma_o = \left( \frac{M}{c_o} \right) \left( \frac{c_o}{r_o} \right) \tag{3.10}
\]

The strain is determined by [69]:

\[
\epsilon_o = \left( \frac{M}{c_o} \right) \left( \frac{c_o}{r_o} \right)
\]
\[
\epsilon = \frac{c_o r_n}{r_n + c_o \left( \frac{1}{r_n^*} - \frac{1}{r_n} \right)} 
\]  \hspace{1cm} (3.11)

where \( r_{n^*} \) is the deformed radius of curvature to the neutral axis and is determined by:

\[
r_{n^*} = \frac{d_x}{\cos(\theta - \alpha_i)} 
\]  \hspace{1cm} (3.12)

### Four-point bend test

A four-point bend test was complete with guidance from ASTM D6415, the specimen was designed as shown in Figure 3.18. The standards are meant for composites consisting of layers of unidirectional fabric. In the case of testing for this research, testing was done to compare fully non-planar and fully planar printing. Two of three orientations printed, as shown in Figure 3.10 were not as indicated for the standards. The standards served as guidance for the specimen design, test set up and calculations.

![Figure 3.18: Dimension of 90° specimen (dimensions are in mm).](image)

The fixture was set up in the MTS machine as shown in Figure 3.13b. The load
and deflection were recorded for the duration of the test, the selected test speed was 6 mm/min. Calculations were complete to determine the curved bending strength as outlined in ASTM D6415, equations are outlined below with notation of setup outlined in Figure 3.19.

\[ d_y = d_x \tan(\phi_i) + \frac{D + t}{\cos(\phi_i)} - \delta \quad (3.13) \]

Where D is the diameter of the roller and t is the thickness of the beam. As the test begins, the angle will change so the angle (\( \phi \)) at any point during the test is:

\[ \phi = \sin^{-1} \left( \frac{-d_x(D + t) + d_y \sqrt{d_x^2 + d_y^2 - D^2 - 2Dt - t^2}}{d_x^2 + d_y^2} \right) \quad (3.14) \]

The curved bending strength (CBS) is the associated load on one leg of the specimen and is defined as:
\[ CBS = \frac{M}{w} \]  

(3.15)

\[ CBS = \frac{P}{2 \ast w \ast \cos(\phi)} \ast \left[ \frac{d_x}{\cos(\phi)} + (D + t)\tan(\phi) \right] \]  

(3.16)

Where \( P \) is the force, and \( w \) is the width of the beam. The inter laminar strength is defined as the maximum radial strength \( (\sigma_r) \) at failure, which is defined as:

\[ \sigma_r = \frac{3CBS}{2t\sqrt{\rho_i \rho_o}} \]  

(3.17)

Summary of methods for stress calculations in are further expanded in [70].

### 3.5 Statistical Analysis

#### 3.5.1 Outlier Test

The inter-quartile test is conducted to determine an outlier within a data set prior to statistical analysis.

The lower and upper bounds of the data are:

\[ \text{LowerBound} = Q1 - (1.5 \ast IQR) \]  

(3.18)

\[ \text{UpperBound} = Q3 + (1.5 \ast IQR) \]  

(3.19)

Where \( Q1 \) and \( Q3 \) and the first and third quartile and the IQR is:

\[ IQR = Q3 - Q1 \]  

(3.20)
3.5.2 Statistical Analysis- Tensile test

The statistical analysis used for the tensile testing was a t-test because only two separate data sets were compared. From the difference of the means the estimated difference between the two groups is obtained. Assuming the groups are independent, the t-value is determined by:

\[
t = \frac{(\overline{X}_1 - \overline{X}_2)}{\sqrt{\frac{S^2_1}{n} + \frac{S^2_2}{n}}} \tag{3.21}
\]

Where \( S \) is the standard deviation, \( n \) is the degree of freedom and \( \overline{X} \) is the mean.

3.5.3 Statistical Analysis-Bend Test

Analysis of Variance (ANOVA) was selected as the analysis method between tests for the bend test specimens as there more than two groups to analyze. This analysis is done by calculating the f-statistic and comparing it to the f-critical. The f-statistic is determined by:

\[
F = \frac{MSS_B}{MSS_w} \tag{3.22}
\]

Where \( MSS_B \) and \( MSS_W \) represent the mean sum of square between and within groups, which are determined by the following:

\[
MSS_B = \frac{\sum(n * (X_i - X_m)^2)}{k - 1} \tag{3.23}
\]

\[
MSS_W = \frac{\sum(X_m - X_G)^2}{n - k} \tag{3.24}
\]

Where \( k \) is the number of groups and \( n \) is the total number of variables. The value of the data point is \( X_i \), the mean of the group is \( X_m \) and the grand mean is \( X_G \).
Chapter 4

Results and Discussion

The following section summarizes the results and provides a discussion on the research completed. This starts with the coupon manufacturing on the two machines followed by the results of mechanical testing and statistical analysis of the results.

4.1 Coupon Manufacturing

The specimens were printed on two printers due to the variability of machines, obtaining repeatably of prints is challenging. Two machines were used to increase the speed of manufacturing of all parts. Some prints had differences or defects that will be discussed in this section as well as an initial assessment of the printed parts.

Tensile specimens from the Dewar Made printer had some surface defects as shown in Figure 4.1, impact on the part strength will be discussed in the following section. The defects on the dog bones were from removing the parts from the printer bed surface and the defects were primarily superficial.

Testing was conducted on different size arcs at 10° and 20°. As the printing angle is increased, the filament lines became more raised as the material could not be pushed onto the surface as well, resulting in a rougher surface at spots with higher angles that were on the edges of the samples. A sample set of printed 10° and 20° arcs are shown
in Figure 4.2 and Figure 4.3 respectively. The stair-stepping effect is visible in the planar print appearing at the bottom of both images. For the non-planar prints, the edges of the part are noticeably not as smooth as in the planar print. Over extrusion can be seen in the image, however, to not affect variability of prints, the settings were not adjusted for each sample after being set with calibration samples. Some parameters which can cause over extrusion were selected to allow better prints with the long nozzle such as a lowering the printing speed and an increasing the nozzle temperature.

Figure 4.1: Tensile specimens with visible surface defects from print bed surface.

As mentioned in Section 3.4, 90° samples were printed in three orientations. The prints that were printed completely planar, showed some warping on the legs during the print. The print on the side with linear infill had some noticeable gaps in between layers.

Challenges of printing

During the process of printing samples, many complications and issues occurred. This is due to the nature of FFF itself as well as some challenges with the specific CLFFF software and hardware that will be discussed.

One issue noticed upon printing was that printed parts were more prone to cracking when being removed from the printer bed. When printed, the PETG was brittle,
Figure 4.2: Non-planar and planar $10^\circ$ printed samples before testing.

Figure 4.3: Non-planar and planar $20^\circ$ printed samples before testing.
resulting in some failed prints upon removal from the bed. When selecting material PETG was chosen by a reliable company, but the material can vary from company and even between each batch made by the company. Different fillers or manufacturing conditions, can be used for the same material depending on the manufacturer to adjust the material properties. This is another issue with FFF as exactly how the material will print is not fully known until it is tested.

A hardware issue was the assembly of the nozzle, and issues with material leaking. Hot end nozzles come assembled from the manufacturer, they can be removed and changed but it comes with some challenges. The standard hot-end of the Anycubic was disassembled to mount the extended nozzle. Due to the design of the nozzle, it was harder to tighten and had some issues with material leaking.

One issue with non-planar slicing is that it was not compatible with the slicer created supports. Because of this, custom supports were created to be imported to Slic3r, the two supports are shown in Figures 4.4a and 4.4b.

When supports are selected in the slicer a lower infill is used for that section as well as a different pattern separating it from the part, allowing for faster printing time and making it easier to remove the supports. The two patterns within the generated support are shown in Figure 4.4d. The custom supports however, had to be printed at the same infill as the part, due to this some of the support structure did not come off as easily as others, which can lead to increase part strength. Edge cutters were used to remove the support material from the part. It was found that the prints from the Dewar Made had larger sections of support fused to the actual part which can be another factor attributing to increased part strength.
4.2 Material Validation with Tensile Testing

This round of testing was designed to confirm material properties with the manufacturer’s datasheet.

Specimens A1 through A5 were made on the Dewar Made, and specimens A through E were printed on the Anycubic. An outlier test was conducted and an outlier in each group was determined, the outlier samples were A3 and E, sample A3 is included in the images for comparison as it was the only sample with a clean break. The average breaking load of the parts made on the two printers was 2.03 kN and 1.44 kN respectively, the load-deflection data of the specimens is shown in Appendix B, Figure B.1. This discrepancy in strength of the parts from the two printers may be due to several reasons.

Looking at the differences outlined between printers in Table 3.1. One factor is the
difference in nozzles, with the extended nozzle, the temperature of the plastic would be lower when deposited than with a regular shorter nozzle. Another factor that could affect this is that the Dewar Made has a faster operating system as mentioned before which increases accuracy which can increase the strength of the part. This may increase strength due to a higher accuracy in filament placement and resolution, resulting in a more accurate print with fewer voids.

All but one specimen broke in a diagonal, at the onset of failure, the fibers could be seen breaking in the direction they were printed on a diagonal as can be seen in Figures 4.5 and 4.6. Sample A3, had a fully tensile failure and had a straight line.

![Figure 4.5: Tensile specimens after failure manufactured on the Dewar Made machine.](image)

The average Ultimate Tensile Strength (UTS) was 45 MPa for specimens from the Dewar Made and 35.1 MPa for specimens from the Anycubic, the stress-strain curve is shown in Figure 4.7. Some specimens had minor surface defects as mentioned in the previous section, however, this did not appear to have an influence on the tensile strength.

A t-test of the two groups was conducted with a null hypothesis that there is no statistically significant difference between samples. The results are listed in Table 4.1.
Figure 4.6: Tensile specimens after failure manufactured on the Anycubic MegaX.

Figure 4.7: Stress strain results of tensile specimens.

The t-value calculated was higher than the critical t-value, therefore the null hypothesis is rejected and there is a statistically significant difference between the groups.

This tensile test was completed to validate the material datasheet and to note
Table 4.1: Results and statistical analysis of tensile testing.

<table>
<thead>
<tr>
<th></th>
<th>Mean Tensile Strength</th>
<th>Variance</th>
<th>Observations</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anycubic</td>
<td>35.1 MPa</td>
<td>0.28</td>
<td>4</td>
<td>0.49</td>
</tr>
<tr>
<td>Dewar Made</td>
<td>44.9 MPa</td>
<td>0.25</td>
<td>4</td>
<td>0.53</td>
</tr>
<tr>
<td>T-test</td>
<td>degree of freedom</td>
<td>T-calculated</td>
<td>T-critical</td>
<td>P value</td>
</tr>
<tr>
<td>Results</td>
<td>6</td>
<td>27</td>
<td>2.45</td>
<td>1.7E−7</td>
</tr>
</tbody>
</table>

any differences between printers. The findings determined that there is a discrepancy between the quality of parts manufactured by the printers with the Anycubic providing results that closely reflect the manufacturer information. The percent difference between the UTS and Young’s modulus of parts created on the printers is 12.3 % and 10.3 % respectively.

The reported mechanical properties from the manufacturer are a Young’s Modulus of 1472 ± 270 MPa and an ultimate breaking strength of 31.9 ± 1.1 MPa, the manufacturer datasheet can be found in Appendix A. The percent difference of the results for the Anycubic and Dewar Made machines to the manufacturer’s data were 4.7% and 17% for UTS, and 0.7% and 11% for Young’s Modulus respectively. The manufacturer data is used as the baseline and this difference is taken into account in further testing.

4.3 Three and Four Point Bend Testing of Curved Coupons

As mentioned in the previous section, there was a discrepancy in the strength of the parts printed using the Dewar Made and Anycubic printers. This will be reflected in
the bending strength as well and will be taken into consideration for the results in this section.

As expected from the results seen in tensile testing, the samples printed on the Dewar Made withstood higher loads under flexural testing. The tensile and bending strength of the material for this testing is assumed to be proportional. In theory, the two should be proportional to each other but, the relationship varies depending on the material [71]. While there are models that determine the relationship of the tensile to bending strength for the material it is out of the scope of the research and a detailed process is outlined in [71]. For the work presented in the following sections, the percent difference of the ultimate strength between the specimens on the two printers and the manufacturer will be applied to the results. This is to help diminish the variance of results due to the performance of the printers and to focus on the properties that are related to the method of planar and non-planar manufacturing more accurately.

4.3.1 Three-Point Bend Test

10° and 20° samples were tested in the MTS load frame, the samples were printed fully planar and compared to parts printed with two, four, and six top non-planar layers.

Once testing was completed, several failure modes were seen across the parts. Figure 4.8 and 4.9 show the samples after testing. The naming convention of the specimens is the angle followed by the number of non-planar top layers.
(a) $10^\circ$ planar samples (Dewar Made).

(b) $10^\circ$ planar samples (Anycubic).

(c) $10^\circ$ non-planar, 2 top layers. (d) $10^\circ$ non-planar, 4 top layers. (e) $10^\circ$ non-planar, 6 top layers.

Figure 4.8: $10^\circ$ samples after testing.

(a) $20^\circ$ planar samples.

(b) $20^\circ$ non-planar, 2 top layers.

(c) $20^\circ$ non-planar with, top layers. (d) $20^\circ$ non-planar with, top layers.

Figure 4.9: $20^\circ$ samples after testing.
The stresses were calculated using both the linear and curved solutions in Equations 3.1 and 3.10. The failure point was calculated as the point of load drop. The difference between the results was an average 1.2% for the $10^\circ$ specimens and 0.997% for the $20^\circ$ specimens. An issue arose for the $10^\circ$ specimens when calculating the strain with Equation 3.11 because in the test case presented, the curved specimen increases in radius, approaching infinity as it approaches the horizontal. The linear portion of the stress-strain curve was plotted to determine the bending modulus using the linear portion of the graph with the linear strain equation in Equation 3.2. The linear regression of the stress-strain relationships can be seen in found in Appendix B. The load-displacement graphs are shown in Figures 4.11-4.18 for the $10^\circ$ and $20^\circ$ samples. The resulting maximum stress on the outer surface is listed in Table 4.2.

![Figure 4.10: Planar $10^\circ$ load-deflection (Dewar Made) curve.](image)
Figure 4.11: Planar $10^\circ$ load-deflection (Anycubic) curve.

Figure 4.12: Load-deflection for $10^\circ$ samples with two top layers.
Figure 4.13: Load-deflection for 10° samples with four top layers.

Figure 4.14: Load-deflection for 10° samples with six top layers.
Figure 4.15: Load-deflection of planar 20° samples (20b-d: Deware Made; 20a,20e: Anycubic)

Table 4.2: Results of three-point bend test for 10° specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$\sigma(MPa)$</th>
<th>Specimen</th>
<th>$\sigma(MPa)$</th>
<th>Specimen</th>
<th>$\sigma(MPa)$</th>
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<tbody>
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<td>42.1</td>
<td>104a</td>
<td>43</td>
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<td>10c</td>
<td>81</td>
<td>102c</td>
<td>34.3</td>
<td>104c</td>
<td>36.7</td>
<td>106c</td>
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<tr>
<td>10d</td>
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</tr>
</tbody>
</table>
Figure 4.16: Load-deflection for 20° samples with for two top layers.

Figure 4.17: Load-deflection for 20° samples with for four top layers.
Figure 4.18: Load-deflection for 20° samples with for six top layers.

Table 4.3: Results of three-point bend test for 20° specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>σ(MPa)</th>
<th>Specimen</th>
<th>σ(MPa)</th>
<th>Specimen</th>
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<td>49.9</td>
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<td>35</td>
<td>204a</td>
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<td>206a</td>
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<td>206a</td>
<td>36.9</td>
</tr>
<tr>
<td>20e</td>
<td>31.4</td>
<td>202e</td>
<td>34.8</td>
<td>204a</td>
<td>32.9</td>
<td>206a</td>
<td>29.9</td>
</tr>
</tbody>
</table>

A statistical analysis was conducted on the results from the testing. The results were first adjusted in accordance with the percent difference from the manufacturer’s datasheet determined from the tensile testing. After, an outlier test was conducted on the results listed in Table 4.2 and 4.3, then a single factor ANOVA was conducted.
to determine if there is a statistical difference between groups with a null hypothesis that the means are equivalent. Results of the ANOVA are listed in Table 4.4.

Table 4.4: Statistical analysis of three-point bend test results.

<table>
<thead>
<tr>
<th>Sample</th>
<th>SS_b</th>
<th>SS_w</th>
<th>DoF_b</th>
<th>DoF_w</th>
<th>F calculated</th>
<th>F critical</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>2228</td>
<td>1567</td>
<td>4</td>
<td>15</td>
<td>5.3</td>
<td>3.05</td>
<td>0.007</td>
</tr>
<tr>
<td>20°</td>
<td>419.9</td>
<td>278</td>
<td>4</td>
<td>14</td>
<td>5.2</td>
<td>3.1</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Table 4.5: Mean values of three-point bend tests.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Average Stress</th>
<th>Variance</th>
<th>Deformation</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 (Dewar Made)</td>
<td>61.1 MPa</td>
<td>54 MPa²</td>
<td>14.5 mm</td>
<td>5</td>
</tr>
<tr>
<td>10 (Anycubic)</td>
<td>35 MPa</td>
<td>3.9 MPa²</td>
<td>12.7 mm</td>
<td>2</td>
</tr>
<tr>
<td>102</td>
<td>55.5 MPa</td>
<td>301 MPa²</td>
<td>13.1 mm</td>
<td>5</td>
</tr>
<tr>
<td>104</td>
<td>44.6 MPa</td>
<td>25.1 MPa²</td>
<td>13.2 mm</td>
<td>4</td>
</tr>
<tr>
<td>106</td>
<td>34.7 MPa</td>
<td>22.5 MPa²</td>
<td>10.6 mm</td>
<td>4</td>
</tr>
<tr>
<td>20 (Deware Made)</td>
<td>45.8 MPa</td>
<td>21.6 MPa²</td>
<td>19.3 mm</td>
<td>3</td>
</tr>
<tr>
<td>20 (Anycubic)</td>
<td>35 MPa</td>
<td>9.5 MPa²</td>
<td>13 mm</td>
<td>2</td>
</tr>
<tr>
<td>202</td>
<td>40.5 MPa</td>
<td>18.3 MPa²</td>
<td>15.1 mm</td>
<td>5</td>
</tr>
<tr>
<td>204</td>
<td>33.6 MPa</td>
<td>14.9 MPa²</td>
<td>13.6 mm</td>
<td>4</td>
</tr>
<tr>
<td>206</td>
<td>34 MPa</td>
<td>16.2 MPa²</td>
<td>11.1 mm</td>
<td>5</td>
</tr>
</tbody>
</table>

As seen in Table 4.5 the average maximum stress for the specimens did not follow the hypothesis that increased non-planar layers would increase the strength of the part. The calculated F-value is higher than the critical value, therefore there is a statistically significant difference between groups.
A trend can be seen across both samples with a higher bending strength exhibited by the specimens with two non-planar layers, and the lowest with specimens with six non-planar layers. One reason for this can be explained by the phenomenon in Figure 2.8 and that the non-planar layers are not being deposited optimally onto the surface leading to lower adhesion between layers and ultimately lower strength.

The failure point in bend testing is the bottom of the arc, which followed regular planar printing as only the top of the print was non-planar. The assumption was the non-planar layers would help distribute the load along the fibers of the top surface, therefore, increasing the load that can be withstood, but this was not the case.

One interesting characteristic to note is that the specimens with curved layers that did not break did not have permanent plastic deformation and is shown in Figure 4.19 and 4.20.

Figure 4.19: 20° samples after testing.
4.3.2 Four-Point Bend Test

A four-point bend test was conducted on fifteen samples, five samples in each orientation as described in Figure 3.10. The infill for the samples was set as different orientations, but the same 90% for all samples. The results for each sample group are discussed in the following sections.

Non-Planar with rectilinear infill

The load-deflection curve for samples printed with non-planar printing but rectilinear infill are shown in Figure 4.21. As can be seen, all five samples follow a similar trend, the exponential rise at the end can be associated with the metal rollers of the jig making contact, running the sample to its full range of motion.

One notable feature in Figure 4.21 is the noticeable drop in force just below 1000 N of sample 90e, this can be associated with delamination. While loading, cracking could be heard but is not seen in the graph, therefore the small delamination within the layers did not have a severe impact on the part strength. The samples from this round of testing did not have any visible cracks or damage in the corner of the sample, however, permanent plastic deformation had occurred in the legs of all the samples and can be seen in Figure 4.22. Sample B had visible delamination on the top layer as shown in Figure 4.22b.
Figure 4.21: Load-deflection for 90° samples printed on the side with rectilinear infill.

(a) 90° samples after testing. (b) Visible delamination on the corner or sample 90b.

Figure 4.22: 90° samples permanent deformation after testing.
Non-Planar with linear infill

Samples printed with linear infill sustained lower loads than with rectilinear infill. As opposed to the rectilinear infill, linear infill follows the shape of the part, when tested, the part with linear infill is expected to flex more. In the load-deflection graph shown in Figure 4.23 delamination is noticeable with visible drops in load during the test. This method of printing had significant gaps between the layers resulting in higher deformation under lower loads as compared to with rectilinear infill.

Figure 4.23: Load-deflection curve for 90° non-planar parts with linear infill.

Planar printing

The final round of testing with 90° specimens was fully planar prints. Each of the samples broke in testing and the load-deflection curves are shown in Figure 4.24. Higher drops in force are observed in the load-deflection compared to the other types of samples as delamination of layers was occurring.
Comparison of results of 90° specimens

All three tests highlighted the different bending strengths of parts with different infills used. Table 4.6 highlights the maximum radial stress of all the samples. The results are an estimation, as porosity due to 90% infill instead of 100% infill was not taken into account in the calculations.

The purpose of the four-point bend testing was to highlight the differences in printing orientations and the potential application of non-planar printing. The samples printed sideways with rectilinear infill performed significantly better than the other two groups. The planar prints did have a higher strength than the fully non-planar ones, but they all fractured and the non-planar ones did not. Therefore, parts made with non-planar can undergo higher deformation than with planar printing. Further testing is required to determine the potential impact resistance. For practical use of a RPAS propeller withstanding a crash.
Table 4.6: Results of four-point bend test.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Radial Stress (MPa)</th>
<th>Specimen</th>
<th>Radial Stress (MPa)</th>
<th>Specimen</th>
<th>Radial Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90a</td>
<td>8.1</td>
<td>NPa</td>
<td>1.6</td>
<td>Pa</td>
<td>2.2</td>
</tr>
<tr>
<td>90b</td>
<td>7.7</td>
<td>NPb</td>
<td>1.59</td>
<td>Pb</td>
<td>5.2</td>
</tr>
<tr>
<td>90c</td>
<td>7.5</td>
<td>NPC</td>
<td>1.59</td>
<td>Pc</td>
<td>3.5</td>
</tr>
<tr>
<td>90d</td>
<td>7.2</td>
<td>NPD</td>
<td>1.46</td>
<td>Pd</td>
<td>1.9</td>
</tr>
<tr>
<td>90e</td>
<td>7.1</td>
<td>NPE</td>
<td>1.17</td>
<td>Pe</td>
<td>2.5</td>
</tr>
</tbody>
</table>

4.4 Proof of Concept

In addition to assessing the basic mechanical performance of parts made using CLFFF, it is important to investigate the general manufacturability of such parts for specific applications. This section summarizes select designs that were chosen for proof of concept and to determine which are most suitable for CLFFF. To determine the best angles of use for non-planar printing, two wave shaped samples with varying curves were printed, for application to RPAS both fixed wing and rotary wing sections were printed. These designs and outcomes will be discussed in the following section.

4.4.1 Determining Optimal Angle For CLFFF

A part was designed with various angles to be included in one print, the piece is used to demonstrate types of curves or surfaces that can benefit from curved versus planar layers. The sample was printed with 0.2 mm thick layers for each and at an infill of 70%. The wave of both planar and non-planar is shown in Figure 4.25.

As can be seen, non-planar printing was best for the small curves ranging from approximately 2°-10°, the curves remained smooth and left a better finish than the planar version. This is due to the nozzle contact as illustrated in Figure 2.8. At
Figure 4.25: Wave shaped sample to highlight planar and non-planar printing at various angles.

At higher angles, with CLFFF, the extruded filament is not placed on the surface as well causing a rough surface finish. For higher angles ranging from 25°-40° planar layers are preferable as they result in a smoother surface finish. The angles in between from 10°-25° it is up to the designer to make a decision on which type of printing would be most beneficial.

4.4.2 RPAS Propeller and Wing Section

DJI Mavic Mini propellers printed are shown in Figure 4.26. The printer was set to print with a layer thickness of 0.1 mm, one realization was for small surfaces, the final non-planar layer, while eliminating the stair-stepping effect is not as smooth as the planar layers.

Additionally, a propeller and airfoil section were printed. Given the surface quality
of the DJI Mavic Mini propeller, thicker layers of 0.3 mm were selected to see if non-planar layers would be better or if it is not recommended for small parts at all. As can be seen in Figure 4.27 and 4.28, the non-planar surface does provide a better surface finish. Therefore, it is shown that non-planar layers are not as beneficial if the part is manufactured with thinner layers, but in cases with thicker layers, non-planar printing presents a higher benefit. Non-planar printing thus allows the designer to print using thicker layers which saves time and results in a better surface finish.
Figure 4.28: Airfoil printed with planar (left) and non-planar (right) printing.

The proof of concept was successful and various types of samples were printed to validate the application of CLFFF for RPAS components. General ease of printing is simple, as generating the G-code is the same process as for standard FFF. Depending on the clearance required for prints, non-planar slicing can be executed on a printer with a regular nozzle, not requiring to change to the extended nozzle.
Chapter 5

Conclusions and Recommendations

5.1 Conclusion

In this research different parts and sections of parts for RPAS were printed and non-planar printing was successfully implemented with the use of CLFFF.

Tensile testing was successfully conducted, confirming the properties from the manufacturer’s data sheet. Parts manufactured with the DewarMade performed better than those manufactured on the Anycubic, with a percent difference of 12.3% between the UTS.

Three point-bend tests were completed on samples of 10° and 20°, with planar printing and non-planar layers, including prints with two, four, and six top layers. The results of the testing were statistically significant between the data sets of the stress on the outer layer. The parts with more non-planar layers (six and four layers) performed worse than those with less (two), or planar layers. This is assumed to be due to the low adhesion between the top layers. Four-point bend tests determined that non-planar printing resulted in parts that could withstand higher deformation without breaking.

It was also determined through samples with varying angles and propeller sections that non-planar printing does not always provide a better surface finish, the cases for
5.2 Recommendations for Future Work

Recommendations for future work are outlined below, including suggestions for additional testing, hardware upgrades, and exploring other software.

The research in this thesis focused on adaptive printing with thin layers, comparing prints with a thickness of 0.1 mm. In this case, it was found that CLFFF did not stand to add any significant benefits to the part strength or quality at present. More research should be done to compare thicker layers and their effect on part strength.

This thesis explored non-planar thickness of up to 15 % of the part thickness, the recommendation is to increase that amount by increasing the number of non-planar layers or increasing the layer thickness. This work may be a benefit to material that includes reinforcing fibers such as carbon or glass. Composites rely heavily on anisotropy and can benefit from filament being placed in the same direction as is done with non-planar layers. At the time printing was being conducted, only brass extended nozzles were available that are not suitable for such materials, since then, stainless steel hot ends have become available allowing for research into that topic. Other mechanical testing is also suggested including fatigue and impact resistance.

Another improvement to be made is to have different types of samples that do not require printed support structures. The printed support structure had an effect on the bottom of the sample, which has a direct relation to the bending strength. Other suggestions include designing a four-point bend test specimen with a smaller angle than was explored in this work.

From a hardware aspect, suggestions include manufacturing a nozzle for non-planar printing that is not as long as the one purchased. The nozzles used in this research provided more than enough surface clearance, a shorter nozzle would benefit
in helping the materials extrude and decreasing the potential for clogs. Another improvement would include having a head that could also rotate and pivot which would result in a much better surface finish of curved surfaces, allowing perpendicular filament deposition during the print.

As mentioned, no widely used open-source software exists “as is” for this type of printing in existing slicers. With the growing popularity and more research in the space, and as more software becomes available, it is suggested to compare more samples printed with other software such as the curvislicer or even to develop a custom software.
List of References


[34] “Polymaker.” polymaker.com.


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“2011: Revolutionising aircraft design with the world’s first printed aircraft.”
https://www.southampton.ac.uk/engineering/about/making-history/3d-printed-unmanned-aircraft.page.

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“World’s first jet-powered, 3d printed uav tops 150 mph with lightweight stratasys materials.”


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Appendix A

PolyLite™ PETG

PolyLite™ PETG is an affordable PETG filament with balanced mechanical properties and ease of printing.

### Physical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Testing method</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>ASTM D792 (ISO 1183, GB/T 1033)</td>
<td>1.25 (g/cm³ at 21.5 °C)</td>
</tr>
<tr>
<td>Glass transition temperature</td>
<td>DSC, 10 °C/min</td>
<td>81 °C</td>
</tr>
<tr>
<td>Vicat Softening temperature</td>
<td>ASTM D1525 (ISO 306 GB/T 1633)</td>
<td>84 °C</td>
</tr>
<tr>
<td>Melt index</td>
<td>220 °C, 2.16 kg</td>
<td>3.9 (g/10 min)</td>
</tr>
<tr>
<td>Melt index</td>
<td>240 °C, 2.16 kg</td>
<td>10.8 (g/10 min)</td>
</tr>
</tbody>
</table>

All testing specimens were printed under the following conditions:
- nozzle temperature: 230 °C
- printing speed: 40 mm/s
- build plate temperature: 80 °C
- infill: 100%

All specimens were conditioned at room temperature for 24h prior to testing.

### Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Testing method</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus (X-Y)</td>
<td>ASTM D638 (ISO 527, GB/T 1040)</td>
<td>1472 ± 270 (MPa)</td>
</tr>
<tr>
<td>Tensile strength (X-Y)</td>
<td>ASTM D638 (ISO 527, GB/T 1040)</td>
<td>31.9 ± 1.1 (MPa)</td>
</tr>
<tr>
<td>Elongation at break (X-Y)</td>
<td>ASTM D638 (ISO 527, GB/T 1040)</td>
<td>6.8 ± 0.9 (%)</td>
</tr>
<tr>
<td>Bending modulus</td>
<td>ASTM D790 (ISO 178, GB/T 9341)</td>
<td>1174 ± 64 (MPa)</td>
</tr>
<tr>
<td>Bending strength</td>
<td>ASTM D790 (ISO 178, GB/T 9341)</td>
<td>53.7 ± 2.4 (MPa)</td>
</tr>
</tbody>
</table>

### Recommended printing conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle temperature</td>
<td>230 - 240 °C</td>
</tr>
<tr>
<td>Build Surface material</td>
<td>Glass, BuildTak™ (recommended)</td>
</tr>
<tr>
<td>Build surface treatment</td>
<td>None</td>
</tr>
<tr>
<td>Build plate temperature</td>
<td>70-80 °C</td>
</tr>
<tr>
<td>Cooling fan</td>
<td>Turned on</td>
</tr>
<tr>
<td>Printing speed</td>
<td>30-50 (mm/s)</td>
</tr>
<tr>
<td>Raft separation distance</td>
<td>0.14 (mm)</td>
</tr>
<tr>
<td>Retraction distance</td>
<td>1-3 (mm)</td>
</tr>
<tr>
<td>Retraction speed</td>
<td>20 - 60 (mm/s)</td>
</tr>
<tr>
<td>Recommended environmental temperature</td>
<td>Room temperature</td>
</tr>
<tr>
<td>Threshold overhang angle</td>
<td>60 (°)</td>
</tr>
<tr>
<td>Recommended support material</td>
<td>None</td>
</tr>
</tbody>
</table>

Based on 0.4 mm nozzle and Simplify 1040. Printing conditions may vary with different nozzle diameters.

Figure A.1: Polymaker PETG material data sheet
Appendix B

The load deflection curves are shown in the figures below.

Figure B.1: Tensile test load deflection curve.
Figure B.2: Stress-strain linear trend line for 10° samples (DewarMade).

Figure B.3: Stress-strain linear trend line for 10° samples (Anycubic).
Figure B.4: Stress-strain linear trend line for 10°, with two non-planar layers.

Figure B.5: Stress-strain linear trend line for 10°, with four non-planar layers.
Figure B.6: Stress-strain linear trend line for 10°, with six non-planar layers.

Figure B.7: Stress-strain linear trend line for 20°, with planar layers.
Figure B.8: Stress-strain linear trend line for 20°, with two non-planar layers.

Figure B.9: Stress-strain linear trend line for 20°, with four non-planar layers.
Figure B.10: Stress-strain linear trend line for 20°, with six non-planar layers.