The Development of Feedstock for 3D Printing and 3D Knitting of Continuous Carbon Fibre Composite Filaments

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Abstract

The main purpose of this research was the development of a composite filament comprising of a thermoset resin and long/continuous carbon fibre reinforcement for the use with additive manufacturing applications. Currently, there are composite materials available that consist of fibre reinforcement but none that utilise long/continuous fibre reinforcement with a thermoset resin in a controlled manner. A series of prototypes were developed to determine the production processes required to produce the composite filament. Specimens were produced from these prototypes were subjected to cross-sectional analysis to analyse the quality of composite filament being produced. The results from this research is a production method that consistently produces the composite filament with the desired material properties.

The secondary purpose of this research was to analyse a commercially available 3D printer, the Mark One, that can produce composite parts using long/continuous fibre reinforcement and a thermoplastic matrix. An analysis into the capabilities and limitations of the Mark One was conducted prior to analysing specimens produced by the Mark One. An analysis of the tensile properties of parts produced by the Mark One was conducted using fibreglass and carbon fibre long/continuous fibre reinforcement. Tensile specimens made in accordance with the standard ASTM D638 for Type I specimens were produced and tensile tested. The Taguchi method was used to analyse the effect and contribution that three parameters had on the tensile properties of specimens. Complications with specimens fracturing incorrectly lead to a redesign of the tensile specimens to ensure the specimens would fracture correctly. Several design iterations were tested until a final design was chosen. This final design was used for both fibreglass and carbon fibre specimens. The results from the tensile specimens showed the effect that changing certain parameters had on the tensile properties and the contribution that each parameter had on the tensile properties produced using the Mark One. These results were confirmed by producing tensile specimens using the optimal combination of parameters and provided insight into the capabilities of the Mark One.

Acknowledgements

Now this has been a project that has lasted many years, has resulted in many late nights and has generated a rollercoaster of up and down moments that I am surprised that I made it to the end of it all. With all the work involved with finishing this project, I cannot take all the credit and I must acknowledge those that have helped me along the way.

The first people that have helped me in more ways than they can know are my parents, David and Lara. My parents have provided me with more support than I could have ever expected, the guidance and insight to manage my life throughout this project and a surprising amount of meals for those late-night work sessions. Thank you both for everything, as I would not have finished this project without your support.

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List of Abbreviations

2D	-	Two Dimensional
3D	–	Three Dimensional
ABS	–	Acrylonitrile Butadiene Styrene
AM	–	Additive Manufacturing
CAD	–	Computer Aided Design
CFRP	–	Carbon Fibre Reinforced Polymer
DLP	–	Digital Light Processing
EBM	–	Electron Beam Melting
FDM	–	Fused Deposition Modelling
FRP	–	Fibre Reinforced Polymer
IPA	–	Isopropyl Alcohol
LED	–	Light Emitting Diode
PLA	–	Polylactic Acid
SEM	–	Scanning Electron Microscope
SLA	–	Stereolithography
SLM	–	Selective Laser Melting
SLS	–	Selective Laser Sintering
UV	–	Ultraviolet

1. Introduction

The research presented in this thesis is based on identifying the required processes and materials needed to fabricate a composite filament for a range of additive manufacturing (AM) technologies. The defining properties of this filament were that the filament had to comprise of long/continuous unidirectional fibre reinforcement and that the filament had to integrate the fibre reinforcement with a thermoset resin to create the composite filament.

Based on research conducted prior to the start of this research project, additive manufacturing technologies have not utilised a composite filament comprising of a thermoset resin and long/continuous fibre reinforcement effectively. This is partly due to the difficulties that come with handling a thermoset resin compared to a thermoplastic polymer and the difficulties with controlling the orientation of long/continuous fibre reinforcement within a thermoset resin. As such, the work presented in this thesis is the beginning towards developing a composite filament comprising of a thermoset resin and long/continuous fibre reinforcement for AM applications.

A secondary aspect of this research project involves analysing the current forms of integrating fibre reinforcement within AM technologies, with a focus on AM technologies that utilise thermoplastic polymers with long/continuous fibre reinforcement. Researchers have already integrated fibre reinforcement into various AM technologies, but these have mainly been restricted to using short fibre reinforcement as the short fibres are easier to handle. Analysing the current methods of incorporating fibre reinforcement into AM technologies will provide insight that will assist with the development of the composite filament comprising of a thermoset resin and long/continuous fibre reinforcement.

1.1 Aims and Objectives

The main aim of this research was to develop a carbon fibre composite filament that would be suitable for AM applications. Currently, there are no available materials that comprises of long/continuous fibre reinforcement and a thermoset resin that is designed specifically for AM technologies. Therefore, a manufacturing process for producing the composite filament, with the required materials, will have to be developed. Additionally, there are no AM technologies that are currently designed to utilise a composite filament made using a thermoset resin. Therefore, an AM technology would have to be developed to use the composite filament, but the development of that AM technology is outside the scope of this research project.

The secondary aim of this research project is to analyse the methods for incorporating fibre reinforcement into current AM technologies, with a focus on carbon fibre reinforcement. The recent advances in commercial 3D printers that can produce composite parts using a thermoplastic polymer with a range of materials for the fibre reinforcement provides an opportunity to gain insight into the current available technologies. Analysing the available technologies will greatly assist with the development of the composite filament made using a thermoset resin and long/continuous fibre reinforcement.

Based on the aims stated above, a series of objectives were drawn up to guide the research into completing each of these aims. The objectives for this research are stated below:

- Generate a literature review that focuses on the relevant technological areas.
- Identify a set of processes required to fabricate the composite filament comprising of the required materials and properties.
- Develop a flowchart that details the required sequence of processes to fabricate the filament to be suitable for additive manufacturing technologies.
- Design and develop numerous prototypes, based on the developed flowchart, to produce the composite filament.
- Utilise the prototypes to produce a multitude of composite filament specimens for analysis.
- Conduct an analysis of a commercially available 3D printer that can fabricate composite parts that utilise long/continuous fibre reinforcement.
- Provide a list of recommendations that will aid further research onto this area.

2. Literature Review

2.1 Current State of Carbon Fibre

Carbon fibre is a material that is utilised across a wide range of industries as a result of the inherent mechanical properties with carbon fibre parts. Carbon fibre has many desirable material properties including, excellent tensile properties, high strength-to-weight ratio, high chemical and thermal stability, high specific strength, high stiffness, good thermal and chemical conductivities and good corrosion resistance [1]. These material properties make carbon fibre a highly desirable material for a range of industries including aerospace [2], medical [3] and automotive [4, 5].

There are several limitations that are problematic when it comes to utilising carbon fibre parts, regardless of application. Foremost amongst those limitations is the material cost involved with using carbon fibre. Carbon fibre is an expensive material due to the manufacturing process required to produce carbon fibres. The manufacturing process for producing carbon fibre involves several processes of heating the carbon fibres to several hundreds of degrees Celsius for several hours. This production process requires significant amounts of energy and time to produce carbon fibre and is the main contributor to the cost for carbon fibre parts [6].

One of the other significant limitations with utilising carbon fibre, and other fibre types, is the weak transverse strength of carbon fibres [7]. Carbon fibres exhibit high longitudinal strength under tensile load which makes the fibres highly desirable, but the weak transverse strength is problematic. Therefore, carbon fibres are often combined to create a composite material using a different material that will assist with weak transverse strength.

Carbon fibre parts are almost always used in the form of composites. A composite is a material that comprises of at least two materials bonded together and the composite materials are divided into two phases. The phases for a composite material are the reinforcement phase and the matrix phase. For a carbon fibre part, the carbon fibres are the reinforcement phase and the matrix phase can be several different materials such as polymers, metals and ceramics, but the most popular matrix phase material for carbon fibre composites is a thermoset resin. The most commonly used thermoset resin with carbon fibres are epoxy resins, but there are other resins that are used with carbon fibres such as polyester and vinyl ester resins. The choice of material for the matrix phase is very important in determining some of the mechanical properties of the composite material.

The matrix phase for carbon fibre composites has several responsibilities. Some of the key responsibilities of the matrix phase is to separate the individual carbon fibres and homogenously distribute the individual fibres within the matrix material. It is important that the individual fibres are separated to ensure that the matrix material can fully encapsulate each individual fibre and increase the strength of the interfacial bonding between the fibre reinforcement phase and the matrix phase. If the fibres are not separated, this can create a weakness in the interfacial bonding which could cause the composite to fracture under stress. The importance of homogeneously distributing the individual fibres within the matrix material is to ensure that there is no section of the matrix phase is devoid of fibre reinforcement. Areas within the matrix material without fibre reinforcement will be weak points within the composite and will be the most prone to fracturing under stress.

One of the other main responsibilities of the matrix phase, for fibre reinforced composites, is to distribute the external stresses applied to the composite throughout the fibre reinforcement rather than the matrix phase. If a fibre reinforced composite does not distribute the external stresses to the fibre reinforcement, the weaker matrix material will undertake too much of the external stress, which will result in the matrix material fracturing and will cause the composite part to fail. Distributing external stresses throughout the fibre reinforcement is achieved by having a strong interfacial bond between the fibre reinforcement and the matrix material. One of the main reasons that a fibre reinforced composite part fails is due to debonding of the interfacial bond, particularly as a result of a transverse stress being applied to the composite [8]. Therefore, having a strong interfacial bond within a fibre reinforced composite will not only ensure that stresses are distributed throughout the fibre reinforcement, but will also reduce the chances of a fibre reinforced composite failing prematurely.

Another important responsibility for the matrix phase within fibre reinforced composites is to protect the fibre reinforcement from external factors. The fibres used within fibre reinforced composites are susceptible to fracturing due to external factors. Some of the external factors that the matrix phase will protect the fibre reinforcement against include mechanical abrasion, chemicals and preventing cracks from propagating from one fibre to another fibre.

Within carbon fibre reinforced composites, the carbon fibres are the reinforcement phase and the reinforcement phase does have several responsibilities. The reinforcement phase is responsible for providing the composite with either different mechanical properties to that of the matrix material or to enhance the mechanical properties shown by the matrix material [9].

Carbon fibre is generally used within fibre reinforced composites to increase the strength and rigidity of the matrix material.

2.1.1 Current Carbon Fibre Production Methods

Commercially, carbon fibre can come in multiple forms depending on the application. Carbon fibre can come in the form of pre-woven textiles, prepregs, continuous fibres and chopped fibres. One of the more common forms of carbon fibre is a spool of continuous fibres. These spools of continuous fibres typically have thousands of unidirectional carbon fibres that are bundled together and are wound onto a spool, but there are a couple of variations. These spools of carbon fibre can then be used for several carbon fibre production methods, including using multiple spools to weave a variety of textile patterns. Figure 2-1 shows some examples of the available carbon fibre textile patterns.

Prepreg is one of the most commonly available forms of carbon fibre used in industry. Prepreg consist of several pre-woven sheets of carbon fibre that have been bonded together and are coated using a thermoset resin. These sheets of prepreg can be cut into shape and used to create carbon fibre parts using a variety of production methods. Prepreg sheets need to be stored at temperatures below zero degrees Celsius to ensure that the thermoset resin within the prepreg sheets does not begin to cure. If the prepreg sheets are not stored at the appropriate temperature, the thermoset will eventually cure and will create a solid sheet of prepreg that cannot be used.

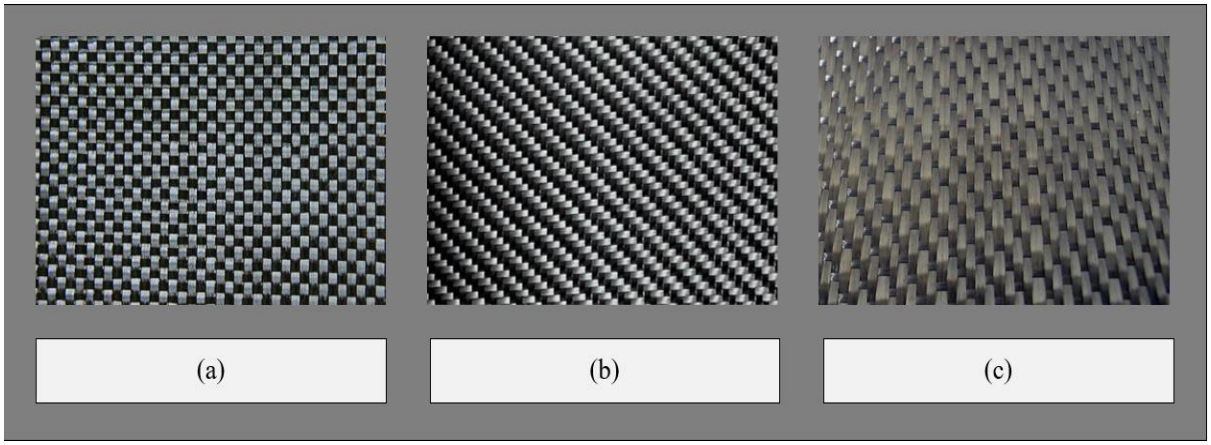

Figure 2-1 - (a) 1x1 Carbon Fibre Pattern, (b) 2x2 Twill Weave Carbon Fibre & (c) 8 Harness-Satin Carbon Fibre Pattern [10].

There are several production methods for producing parts using carbon fibre. Some of the production methods are designed to create parts with certain characteristics that take advantage of the strength provided by the carbon fibres. While other carbon fibre production methods are more versatile in the types of parts that can be produced. The production of carbon fibre parts is predominantly done using a range of thermoset resins.

One of the production methods for carbon fibre part production is filament winding, shown in Figure 2-2. Filament winding is a process for manufacturing open-end structures, such as cylinders, or closed-end structures, such as pressure vessels. The filament winding process takes continuous carbon fibre reinforcement from either a single spool or several spools and pulls the continuous carbon fibre reinforcement through a resin bath and onto a rotating mandrel. The resin bath is designed to combine the carbon fibre and the thermoset resin within the resin bath to make a composite material. The rotating mandrel is designed to rotate so that the continuous carbon fibre is constantly being pulled through the resin bath and then wound onto the mandrel. There are several patterns for winding the continuous carbon fibre reinforcement onto the mandrel. Each pattern provides different strengths along certain axis or axes. The chosen pattern can be repeated until the desired thickness is achieved. Once the desired thickness has been achieved, the thermoset resin is cured, and the mandrel is removed. For some applications, the mandrel cannot be removed as the removal will compromise the structural integrity of the structure made from the continuous fibre reinforcement. In this instance, the structure is designed to have the mandrel left within the structure indefinitely.

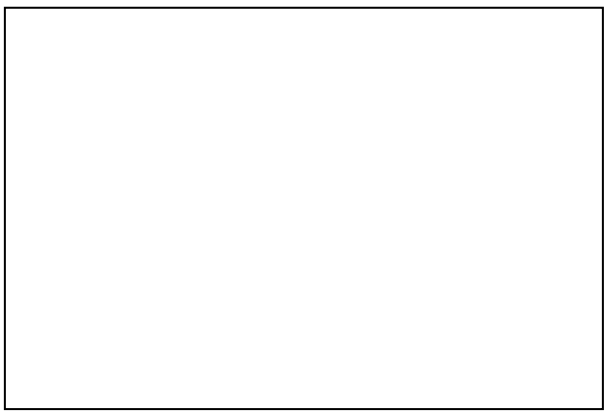

Figure 2-2 - Filament Winding Diagram [11].

One of the other methods for producing carbon fibre parts is known as pultrusion, shown in Figure 2-3. Pultrusion is a method for producing parts with a uniform cross-section, such as rods and tubes. The pultrusion process for carbon fibre production involves taking continuous fibre reinforcement, from several spools, through a series of processes to achieve a carbon fibre composite part. Pultrusion begins by first pulling the continuous fibre reinforcement through a resin bath, filled with a thermoset resin, and then through a series of dies to get the final shape of the chosen part. The first die is called the preforming die and is responsible for getting the continuous carbon fibre reinforcement, coated with the thermoset resin, into the desired shape. The second die is called the curing die and is responsible for heating the thermoset resin coating the carbon fibres to speed up the curing of the resin and to make sure the continuous carbon fibre reinforcement is in the desired shape for curing. After the composite material passes through the curing die, there is a mechanism for pulling the continuous carbon fibre reinforcement through the required processes and then a cutting mechanism is used to cut the composite material into the desired lengths.

There are several other production methods for producing carbon fibre parts. These production methods focus mainly on utilising pre-woven sheets of carbon fibre or sheets of prepreg, which are not are not suitable for creating a composite filament using long/continuous fibre reinforcement. Therefore, these production methods have not been analysed.

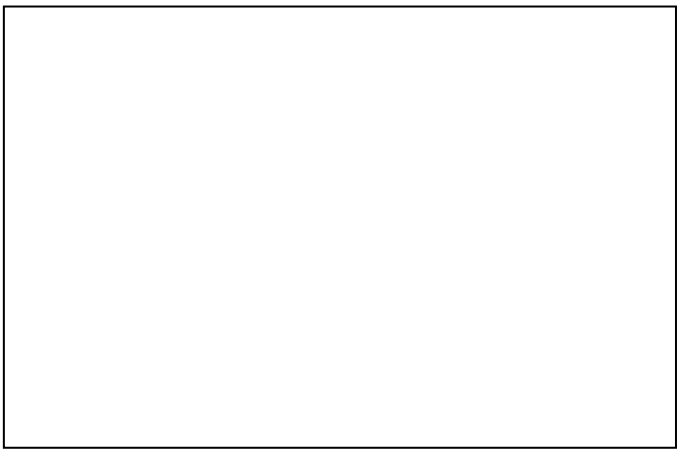

Figure 2-3 - Pultrusion Diagram [11].

2.1.2 Current Carbon Fibre Production Research Areas

One of the major areas of research for the carbon fibre industry is the recycling of carbon fibres within fibre reinforced polymer (FRP) parts [12]. This research is not limited to carbon fibres, but the intrinsic mechanical properties and the wide usage of carbon fibre reinforced polymer (CFRP) parts in industry make carbon fibre a focus of this research. Currently, CFRP waste is landfilled due to the difficulty of recycling the carbon fibres within CFRP parts. Recycling CFRP waste is inherently difficult as the thermosets commonly used in CFRP parts cannot be remoulded and the composites can have complex compositions. The common sources of CFRP waste are end-of-life components, manufacturing cut-offs, testing materials and production tools.

Another major area of research within the carbon fibre industry is improving interfacial bonding between the carbon fibres and the chosen matrix material. This area of research is common amongst several different types of fibres with the aim of strengthening the interfacial bonding is to reduce the chances of the interfacial bonds failing. This research area involves the pre-treatment of fibres and modifying the matrix material [8, 13].

2.2 Current State of Additive Manufacturing

Additive manufacturing, more commonly known as 3D printing, is a set of manufacturing technologies that is based on adding layers of materials on top of one another to create parts using a wide range of materials. These technologies have been utilised mainly to produce prototypes of parts during the product development process prior to mass manufacturing, but developments in the technologies and the materials available have led to AM technologies being used to manufacture end products [14]. Utilising AM technologies over conventional manufacturing technologies is one of the main areas of interest regarding the future of AM [15].

AM is utilised in a wide range of industries due to certain advantages that AM has over conventional manufacturing technologies [16, 17]. One of the main advantages of AM technologies over the conventional manufacturing technologies is the ease at which AM technologies can create intrinsically complex parts that would require multiple conventional technologies to recreate [18-20]. Parts that are designed with complex cross-sections or a complex internal structure can be made using a single AM technology, but conventional technologies would struggle to match [21, 22]. Other advantages that AM technologies have

over conventional manufacturing technologies are that AM can produce less waste material [23], AM technologies require less development time to manufacture complex parts [21], reduce the production costs for intricate parts and allows for the development of a competitive advantage [20, 22]. The industries that utilise the advantages of AM technologies include, but are not limited to, aerospace [24, 25], medical [26, 27], architectural [28], dentistry [29, 30] and automotive [31].

AM technologies can be used to manufacture parts using a wide range of materials including polymers, metals, ceramics and composites. AM technologies have been developed to provide a manufacturing technology that can produce complex parts using the materials desired by different industries. Therefore, one of the main areas of development for AM is the development of technologies that can utilise new materials or can improve the quality of parts or the speed of production of parts using the current materials [32].

Although AM technologies have advantages over conventional manufacturing technologies, there are several disadvantages towards using AM technologies. One of the main disadvantages of AM technologies are that the technologies are not as cost-effective when producing a large volume of parts, especially when the parts are simple in design [20]. AM technologies will not be able to come close to creating a similar cost per part for high volumes of parts compared to conventional manufacturing technologies. Another disadvantage for AM technologies is that the technologies are significantly slower when producing high volumes of parts compared to mass manufacturing [33]. Conventional manufacturing technologies are designed to produce large volumes of parts in as short a period as possible and AM technologies cannot compete when producing large volumes of simple parts. The advantages and disadvantages of AM technologies compared to conventional mean that AM technologies are unsuitable for the mass manufacturing of parts but AM technologies being an ideal option for producing low volumes of highly complex parts [18, 21].

When analysing the various AM technologies, there are a few challenges that are consistent across most of the available technologies. The foremost amongst these challenges is that a part produced using AM technologies can exhibit anisotropic mechanical properties and microstructure [34, 35]. The anisotropic mechanical properties and microstructure of parts produced using AM technologies is a result of the layer-by-layer construction inherent in AM technologies. The microstructure of parts built by a layer-by-layer construction process results in the microstructure being different when comparing the inside of each layer to the area where

the layers bond together. This difference in the microstructure is the cause of the anisotropic mechanical properties in parts produced using AM technologies. Parts that are produced using AM technologies will exhibit significantly different mechanical behaviour when subjected to tension or compression either parallel to the layers or perpendicular to the layers. Some AM technologies have utilised techniques to reduce the anisotropic nature of parts made using AM technologies, but these are limited to certain AM technologies [36]. The anisotropic behaviour shown in parts produced using AM technologies can be beneficial for certain applications that require this type of behaviour.

One of the other challenges apparent in AM technologies is the formation of voids between the layers of material. For some AM technologies, numerous voids can be generated within parts and these voids will increase the porosity of parts. Additionally, these voids can cause a reduction in the interfacial bonding between layers and will result in a reduction in the mechanical behaviour of AM parts [37]. These voids partially contribute towards the anisotropic mechanical properties of parts produced using AM technologies and can also result in the delamination or separation of layers after a part is produced and subjected to stress. The introduction of voids within the parts made using AM technologies can be utilised and expanded further for applications that require a complex part with a controlled porosity [38].

There are other challenges that are apparent in AM technologies but most of these challenges are mainly cosmetic. One of the cosmetic challenges with AM technologies is that parts can exhibit a layer-by-layer appearance which appears different to the initial design [34]. This layer-by-layer appearance is a concern for applications that have appearance as a priority, such as models or displays. The layer-by-layer appearance is dependent on several factors, including the chosen AM technology, the layer thickness, the orientation of parts during printing, the use of post-production techniques and several other factors. Some AM technologies can produce parts with little to no layer-by-layer appearance and are ideal for cosmetic applications.

2.2.1 Current State of 3D Printing Technologies

3D printing is a section of manufacturing technologies that are designed to create three-dimensional parts by building two-dimensions layers of material on top of each other [39]. The machinery that utilise these 3D printing technologies are referred to as 3D printers. Each 3D printing technology is designed to utilise a specific type of material and has advantages and

disadvantages when compared to other 3D printing technologies. Analysing the differences is important when designing parts to be made using 3D printing.

The main two areas of research within 3D printing focus on the materials being used within 3D printing technologies or focus on improving the current 3D printing technologies. Each of these areas is designed to increase the number applications and industries that 3D printing technologies can be utilised.

The area of research that focuses on the materials within 3D printing technologies can be split into two sections. The first section focuses on the introduction of new materials into current 3D printing technologies. An example of this can be the development of current 3D printing technologies to produce parts using fibre-reinforced composites [40, 41]. The second section is the development of new 3D printing technologies to either produce parts using materials that have not been utilised in current 3D printing technologies or produce parts using a material that is used in current 3D printing technologies but using a different production method. An example of using new materials within current technologies is the development of bio-polymers within current 3D printing technologies [42-44].

The other area of research within 3D printing technologies is focussed on improving the current 3D printing technologies. This area of research can be split into two sections. The first section is focussed on improving certain aspects of the current 3D printing technologies to increase the speed at which parts are produced or improve a specific property of the parts being produced. An example of this is the analysis would be improving the mechanical properties of metal 3D printed parts by analysing the print parameters [45]. The second section of this area of research is focussed on the development of new 3D printing technologies to produce parts of higher quality than current 3D printing technologies.

The market for 3D printers can be split into two major sections. The first major section of the 3D printing market is the industrial section and the second is the hobbyist section. The industrial section for 3D printers comprises of companies with in-house 3D printers to print parts on demand and 3D printing bureaus that have several 3D printers that print parts for customers and companies. The industrial section for 3D printer market typically utilises 3D printers that can produce high-quality parts, largescale 3D printers that can produce a large volume of parts and 3D printers that utilise expensive materials that are high quality and/or have desirable mechanical properties.

The hobbyist section of the 3D printing market typically utilises the smaller and cheaper 3D printers, including open-source 3D printers. These cheaper 3D printers are not able to produce parts with the same accuracy, mechanical properties or scale as the commercial 3D printers but are still suitable for prototyping parts for certain applications or within larger tolerances. The hobbyist 3D printers are generally designed to utilise cheaper materials that are easy to operate. The 3D printers aimed at hobbyists are improving and are branching into more complex 3D printing technologies due to the expiration of several key patents in recent years.

There are several different 3D printing technologies available that produce parts using a specific type of material. Some of the more commonly used 3D printing technologies are stereolithography (SLA), selective laser sintering (SLS) and fused deposition modelling (FDM). These 3D printing technologies are widely used in industry and are typically used to create parts using polymers but can also be used to make parts using composite materials. Other 3D printing technologies include selective laser melting (SLM) and electronic beam melting (EBM) and digital light processing (DLP). This research will focus on the more commonly used 3D printing technologies that utilise different forms of polymers and polymer-based composites.

2.2.1.1 SLA 3D Printing

One of the most commonly used 3D printing technologies in industry is the SLA 3D printing technology. SLA 3D printers utilise a high-powered ultraviolet (UV) laser to cure or solidify photosensitive resins to create three-dimensional parts. The photosensitive resins used in SLA 3D printers are thermoset polymers by nature and cannot be reshaped after being cured.

There are a wide range of resins on the market designed specifically for SLA 3D printers that have a variety of mechanical properties and colours. Some resins are designed to replicate some of the mechanical properties of commonly used polymers in industry, such as Nylon and polypropylene. The main consideration for a photosensitive resin for an SLA 3D printer is the wavelength at which the resin is designed to operate under. Ideally, the wavelength that the resin is designed to operate, and the wavelength generated from the high-powered UV laser need to be the same. Discrepancies in the wavelength generated by the high-powered UV laser and the resin can result in problems when producing parts. SLA 3D printers can still print parts of decent quality if there is a discrepancy in wavelengths, but the SLA 3D printers will need to be adjusted to compensate for this discrepancy.

There are a range of applications that SLA 3D printed parts can be utilised for different industries. The most common application for SLA 3D printed parts are as either a model or a final prototype to check the shape and fit of a part prior to producing the end products. Some of the more uncommon applications for SLA 3D printed parts are as patterns for a silicone mould and being used as a mould for silicone casting.

SLA 3D printers have several key advantages that make it a desirable option for industrial applications. Some of the key advantages of SLA 3D printers are that the parts are dimensionally accurate within 0.1mm or smaller, parts with flat surfaces will have smooth surface finish based on the orientation of the part during printing, parts are mostly impermeable and are not affected by thermal shrinkage. Other minor advantages for SLA 3D printing is that the parts produced are rigid except for parts with thin wall sections and SLA parts can be finished using a range of techniques for aesthetically pleasing parts.

Despite some of the advantages of SLA 3D printing, there are several disadvantages to using SLA 3D printing. Some of the main disadvantages with SLA 3D printing are that SLA 3D printed parts require significant post-production processes to achieve aesthetic parts, some part designs will require support material, which is waste, and SLA 3D printed parts cannot be recycled. The post-production processes for SLA 3D printing can include the removal of the support material, including the marks that support material can leave on parts, removing the excess resin on parts using a solvent, such as acetone or isopropyl alcohol (IPA), and subjecting parts to a final cure within a UV chamber. These post-production processes require a well-ventilated clean room for the handling of the excess resin and the flammable and toxic fumes generated from the resin and the solvents. These post-production processes are required to produce appealing parts and is one of the main reasons that it is uncommon for companies to have an in-house SLA 3D printer.

SLA 3D printers can come in two layout variations; top-down layout or bottom-up layout. The layout refers to the location of the high-powered UV laser relative to the resin and the direction that the platform, that parts are printed onto, will move to print consecutive two-dimensional layers. Each layout has its own advantages and disadvantages, but the overall process remains very similar. This section will focus on the top-down layout variant of SLA 3D printers. The layout for a top-down layout SLA 3D printer, shown in Figure 2-4, comprises of a vat of photosensitive resin, the high-powered UV laser is situated above the vat and a platform that can move vertically within and above the vat of resin. An SLA 3D printer will control the

position of the high-powered UV laser on the surface of the vat of photosensitive resin using two galvanometers, one each for the x-axis and the y-axis. Additionally, an SLA 3D printer can have a blade that is positioned to run across the surface of the resin inside the vat and is designed to remove bubbles on the surface of the resin and to ensure that there is enough resin available for every layer during the printing process.

The basic printing process for an SLA 3D printer begins by submerging the platform by a predetermined distance just below the surface of the resin within the vat. This predetermined distance can be used as the layer height or layer thickness of the parts being printed. The galvanometers will then be used to guide the laser to cure a layer of the part/s using the resin within the vat and onto the platform. The platform is then lowered by the predetermined distance and a recoater blade passes across the surface of the resin to remove surface bubbles and ensure there is enough resin to make the next layer of the part/s. The laser is then used to cure the next layer of resin and connect the current layer to the previous layer of cured resin. The processes of lowering the platform by a predetermined amount, using the laser to cure a layer of the part/s and the blade running across the surface of the resin is repeated until the part/s have been printed. This is the basic printing process for SLA 3D printing, but some SLA 3D printers will include extra steps for the printing process.

The main challenges with handling SLA 3D printing are the handling and storage of the photosensitive resins and solvents and having a dedicated room or area, that is well-ventilated, for the post-production processes to be conducted. These requirements reduce the feasibility of companies having an SLA 3D printer in-house, but the quality of SLA 3D printed parts make the parts desirable for a range of industries. Factoring in the high cost for commercial SLA 3D printer, only companies that will regularly utilise the SLA 3D printer, such as a 3D printing bureau, will see any benefit. There have been developments into desktop versions for smaller SLA 3D printers that would be more suitable for companies and hobbyists by reducing the cost for running an SLA 3D printer, but the requirements of a dedicated area and the handling of materials remains as an obstacle. Additionally, these desktop SLA 3D printers have made downgrades to reduce the cost and this can result in a reduction in part quality or a reduction in the capabilities of the SLA 3D printers.

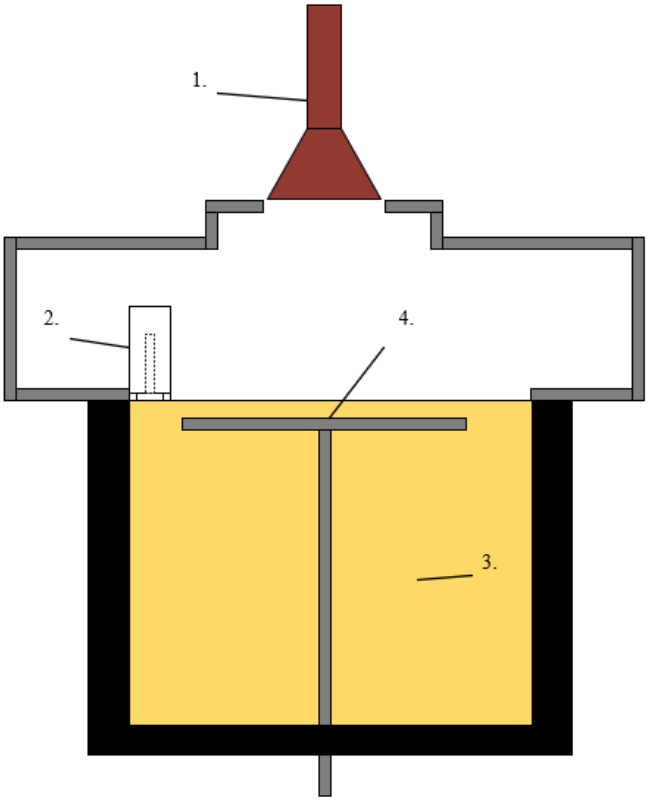

Figure 2-4 - Top-Down Layout SLA 3D Printer, 1. UV Laser, 2. Recoater Blade , 3. Resin Vat, 4 & Printing Platform.

2.2.1.2 SLS 3D Printing

One of the other more commonly used 3D printing technologies in industry is the SLS 3D printing technology. SLS 3D printers make three-dimensional parts using materials in powder form. SLS 3D printers typically utilise a high-powered carbon dioxide laser to sinter the powder to solidify and fuse a cross-section of powder to create a layer. The powder used for SLS 3D printing is heated just below the melting point of the powder and the high-powered laser is used to raise the temperature of powder to reach the melting point. Elevating the temperature of the powder prior to sintering the powder reduces the time it takes for the powder to reach its melting point and will extend the life of the laser.

There are a range of powders that are available for the SLS 3D printing technology. The types of materials in powder form that can be used with SLS 3D printing technology include polymers, ceramics and metals. Composite powders can also be utilised with SLS 3D printers, but these materials can require extra steps to the material preparation process. An example of a composite material for SLS 3D printing is a combination of a Nylon powder mixed with glass beads.

There are various applications that SLS 3D printed parts can be utilised for different industries. The main applications for SLS 3D printed parts are for complex functional end products and prototypes. Other applications include cosmetic display models and complex polymer parts that need to be stronger than parts produced using other 3D printing technologies.

The layout for an SLS 3D printer, shown in Figure 2-5, is similar to the layout of an SLA 3D printer but there are a few key differences. The high-powered carbon dioxide laser is situated above a print bed and two galvanometers, one each for the x-axis and y-axis, are used to control where the laser is situated on the surface of the print bed. The print bed is designed to move vertically within a removable chamber. The SLS 3D printing process will have the print bed near the top of the chamber and will be lowered a predetermined amount to create additional layers. The predetermined amount that the print bed is lowered determines the layer thickness for parts. The SLS 3D printing process requires the print bed to be filled with powder before a layer can be sintered and solidified.

For an SLS 3D printer, the powder used to create parts is stored in separate areas to the print bed. Two powder bins are situated above the print bed with one on each side of the high-powered laser. These powder bins hold the powder for the printing process and are stored away from the print bed so that the powder within the bins will not be subjected to same amount of heating as the powder on the print bed. The powder bins are designed to drop a predetermined amount of powder that will fill the print bed with powder after the print bed is lowered. The powder within the powder bins is aerated to ensure that the powder will drop.

The powder dropped from the powder bins is spread across the print bed using a recoater. The recoater can traverse across the top of the removable chamber that the print bed is situated within. During the SLS printing process, the recoater will receive the dropped powder from one powder bin and traverse across the print bed to fill the space left when the print bed is lowered. Additionally, the recoater will also ensure that the surface of the powder on top of the print bed is flat for the high-powered laser to pass over.

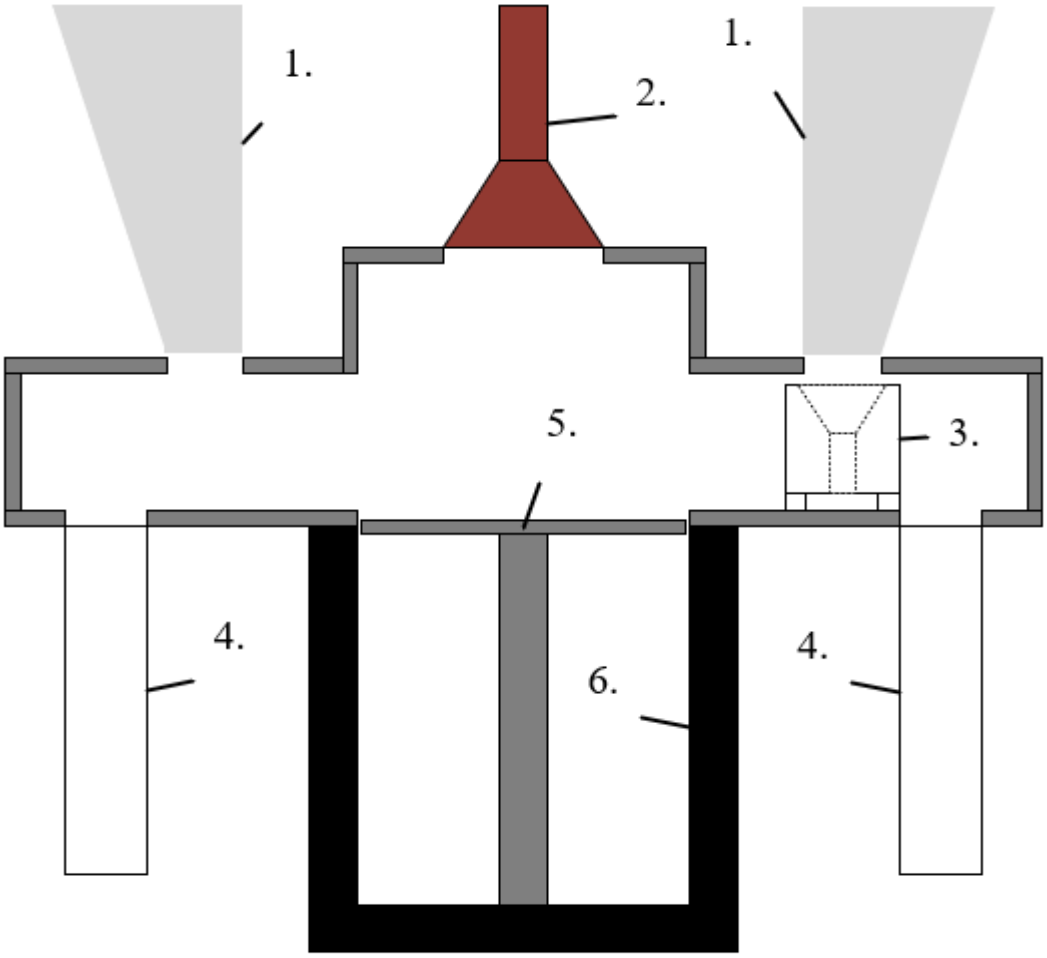

Figure 2-5 - SLS 3D Printer Layout. 1. Powder Bins, 2. Carbon Dioxide Laser, 3. Recoater, 4. Cache Bins, 5. Print Bed & 6. Removable Chamber.

SLS 3D printers will also have a two cache bins, that are situated on either side of the removable chamber, to collect any excess powder during the printing process. The recoater will collect excess powder during printing process. This excess powder needs to be removed to ensure the recoater does not become hindered or locked in place by a build-up of powder. The cache bins are situated further away from the print bed than the powder bins to ensure that the powder from the powder bins is spread across the print bed first before being dropped into the cache bins.

The basic 3D printing process for an SLS 3D printers starts by first having the print bed filled with powder and then a warmup process will begin to get the powder to just below its melting temperature. The SLS 3D printer will then maintain that temperature and then the high-powered laser will run across the surface of the powder on the print bed to raise the temperature of the powder to melting point. The powder that has been melted by the laser will then solidify due to cooling and a layer will be formed. The print bed will then be lowered and one of the

powder bins will drop powder into the recoater and the recoater will traverse across the print bed to provide a new layer of powder and remove any excess powder into one of the cache bins. The new layer of powder will then be heated to just below the powder's melting temperature and high-powered laser will then solidify the next layer. This process is repeated until all layers have been created. After all the layers have been created, a cooling period is required to ensure parts do not warp due to thermal shrinkage. This cooling period can be a couple of hours or over a day depending on the size of the build within the SLS 3D printer.

There are several advantages for using SLS 3D printed parts over other 3D printing technologies. One of the key advantages for SLS 3D printing is that the parts do not require any support material to be generated during the printing process. This advantage is inherent to the printing process and allows for parts to be orientated to be create the best surface finish or to provide strength along a specific axis without having to account for the removal of the support material and the marks left behind from the support material.

An additional advantage that SLS 3D printing has over other 3D printing technologies is the ability to print parts on top of one another. Due to the print bed being consistently filled with powder during the printing process, the powder that is not solidified acts as the support material for parts. Therefore, parts can be situated throughout the removable chamber provided that the parts are not too close to each other. This is a significant advantage over other 3D printing technologies for printing many parts that would require other 3D printers to run multiple times.

Despite these advantages, there are several disadvantages for utilising SLS 3D printers when designing parts for 3D printing. The main disadvantage of utilising SLS 3D printing is due to the inherent heating involved in the SLS 3D printing process. Due to the powder used within SLS 3D printers being heated to just below the powder's melting temperature, parts made using this powder will be subject to thermal shrinkage when the parts cool to room temperature. This problem is compounded when the parts that have thin walls or if the parts reach room temperature too quickly. The worst-case scenario is a large flat part that is a few millimetres thick as this part will not retain its shape due to the thermal shrinkage.

Another disadvantage with SLS 3D printed parts is that they have a rough surface finish that is similar to sandpaper. Having a smooth surface finish is a desirable property, especially for applications where aesthetics is important. The rough surface finish of SLS 3D printed parts can be removed using post-production process such as a media tumbler with a ceramic media.

Using a tumbler will result in some part dimensions being smaller and exposed sharp edges on parts becoming rounded.

One of the other disadvantages of utilising SLS 3D printed parts is that the parts are somewhat porous. SLS 3D printed parts are somewhat inherently water-resistant but will allow liquids to pass through. For applications that require a water-tight part, SLS 3D printed parts are not suitable without the use of post-production processes. The porosity of SLS 3D printed parts can be solved by providing a protective coating but this will lead to part dimensions being larger than intended [35].

Some of the disadvantages with SLS 3D printing are the cost of the SLS 3D printer and post-production processes, the cost of the raw materials and the space requirements for running an SLS 3D printer. The basic machinery required for running a commercial SLS 3D printer involves the SLS 3D printer, a sieving unit for used powder to be recycled and a machine for removing the excess powder attached to parts. This machinery can be very expensive, and the machinery requires significant room for housing these machines. One of the methods for reducing the cost of the raw materials is to recycle used powder with virgin powder [46]. Depending on the ratio between recycled powder and virgin powder, this can result in discolouration of parts, the surface finish of parts becoming rougher and parts being weaker.

Additionally, all these machines should be stored within a single area or room as using the machinery will generate spilled powder. These requirements make commercial SLS 3D printers unsuitable for companies except for companies that will consistently utilise the SLS 3D printer, such as a 3D printing bureau. There are some desktop SLS 3D printers that are smaller, cheaper and require less space, but these still require the same machinery and spilled powder will still be generated.

2.2.1.3 FDM 3D Printing

One of the mostly commonly used 3D printers are FDM 3D printers. FDM 3D printers utilise thermoplastic polymers, in the form of filament, to create three-dimensional parts. FDM 3D printers are commonly used by hobbyists as FDM 3D printers are significantly cheaper than other types of 3D printers, the raw materials are cheap and there are several open-source FDM 3D printers on the market. FDM 3D printers are also utilised in industry as they are suitable for printing initial part prototypes to check the fit and/or shape of a part prior to getting a more expensive prototype or beginning mass production.

The main materials that FDM 3D printers are thermoplastic polymers, such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and Nylon. There have been developments into developing composite filaments that utilise a thermoplastic as the matrix and using different types of fibres for the reinforcement [47, 48]. These composite filaments aim to provide additional mechanical properties that are not easily attained using just thermoplastic polymers.

The basis of FDM 3D printing is based on utilising the glass transition temperature for thermoplastic polymers. The glass transition temperature of a material is always below the melting temperature of a material and is the range of temperatures that will transition the material from a brittle solid state to a viscous or rubbery state. FDM 3D printers will heat the thermoplastic polymers, which are solid at room temperature, to the polymer's glass transition temperature and deposit the heated polymer onto a print bed. Once the heated thermoplastic polymer is deposited onto the print bed, the polymer will cool below its glass transition temperature and solidify.

There are various types of layouts for FDM 3D printers, but the overall layout is generally the same, shown in Figure 2-6. The first component for an FDM 3D printer is the extruder. The extruder is responsible for controlling the feed of thermoplastic polymer filament, for heating the polymer to its glass transition temperature and controlling how much of the polymer is deposited through a nozzle. For the different layouts for FDM 3D printers, extruders can either be stationary or will move along between one to three axes. For some FDM 3D printers, there can be more than one extruder for handling multiple filament materials. The next component for an FDM 3D printer is the print bed. The print bed is responsible for providing a platform for the heated thermoplastic polymer to bond onto and is often heated to help the polymer with bonding to the platform. Depending on the layout of the FDM 3D printer, the print bed can either be stationary or can move along between one to three axes.

Despite the cost and availability of FDM 3D printing, there are several other advantages that FDM 3D printing has over other 3D printing technologies. Firstly, there are a wide range of materials available for FDM 3D printers and these materials can often come in a wide range of colours or finishes. This range of materials makes FDM 3D printing suitable for cosmetic applications, such as models or figurines.

Figure 2-6 – FDM 3D Printer Layout [11].

Despite these advantages, there are several disadvantages with utilising FDM 3D printers. One of the key disadvantages with FDM 3D printed parts are the parts are susceptible to voids, which can result in delamination between the layers [49]. The bonding between the layers for FDM 3D printed parts are weaker than those in other 3D printing technologies and are likely to fracture under stress. These voids can also increase the porosity of FDM 3D printed parts and make them unsuitable for applications that need to be watertight.

There are other disadvantages with using FDM 3D printers that are related to aesthetics. One of the key aesthetic disadvantages of utilising an FDM 3D printer is the need for support material. Support material will need to be removed from parts and this can result in marks being left on the surface of parts. Another disadvantage of FDM 3D printed parts are that FDM parts do not have a smooth outer surface finish. FDM 3D printed parts show distinct layer lines based on the orientation of parts during printing process.

2.3 Current State of Fibre Reinforced 3D Printing

One of the developments with 3D printing over the past few years has been the incorporation of fibre reinforcement into 3D printing. The purpose of incorporating fibre reinforcement into 3D printed parts is to impart the mechanical properties of the fibre reinforcement into the 3D printed parts. There has been a focus on integrating fibre reinforcement within polymer 3D printing technologies to increase the mechanical properties of 3D printed polymer parts.

For incorporating fibre reinforcement into 3D printing, there are different methods for incorporating short and long/continuous fibre reinforcement in the different polymer 3D printing technologies. One of the more commonly utilised polymer 3D printing technologies for incorporating fibre reinforcement is FDM 3D printing, but there are other methods for incorporating fibre reinforcement into SLA and SLS 3D printing technologies.

The first common method for incorporating fibre reinforcement into FDM 3D printing involves the use of short fibres. The short fibres are introduced into FDM 3D printing by integrating short fibres into a thermoplastic polymer and creating a composite filament that is reinforced using the short fibres [50-52]. After the composite filament has been produced, the composite filament can be utilised with an FDM 3D printer, with a few adjustments, to produce parts that are reinforced with short fibres.

The advantages of incorporating short fibre reinforcement into FDM 3D printing is that the short fibres will increase the mechanical properties of parts compared to a completely thermoplastic polymer part and that short fibres can be incorporated into the FDM 3D printing technology with little adjustments. The main disadvantage of utilising short fibres to reinforce thermoplastic polymer parts is that there will only be a slight increase in the mechanical properties of parts [53].

The other common method for integrating fibre reinforcement into FDM 3D printing is based on utilising long/continuous fibres. The advantages of utilising long/continuous fibre reinforcement within FDM 3D printing is that there will be a significant increase in the mechanical properties of parts compared to parts made solely of a thermoplastic polymer [53]. The disadvantage of utilising long/continuous fibre reinforcement for FDM 3D printing is that current FDM 3D printers need to be adjusted to incorporate the fibre reinforcement without damaging the long/continuous fibre reinforcement.

The basic principle for integrating long/continuous fibre reinforcement into a thermoplastic polymer filament is to introduce the fibre reinforcement into the filament when the filament is heated to its glass transition temperature [54, 55]. When the thermoplastic polymer filament reaches its glass transition temperature and becomes viscous, the fibre reinforcement can then penetrate the viscous filament to become a composite filament that is reinforced with long/continuous fibre reinforcement. This composite filament can then be utilised by an FDM 3D printer.

Regarding incorporating fibre reinforcement within SLA 3D printing technology, there has not been as much development, compared to FDM 3D printing, as controlling the orientation of fibres within a vat of UV-curable resin is extremely difficult. Controlling the orientation of fibres with a nozzle-based 3D printing technology, such as FDM 3D printing, is possible by controlling the pattern that the nozzle moves to produce a layer, but a 3D printing technology that is not based on utilising a nozzle, such as SLA or SLS 3D printing, is difficult. Therefore, most of the work on incorporating fibre reinforcement within SLA 3D printing has involved the use of randomly orientated short fibres [56]. Some work has been done to utilise magnets to control the orientation of short fibres using a similar process to SLA 3D printing called magnetic 3D printing [57]. There is little to no significant developments that allow for the control over the orientation of long/continuous fibre reinforcement within SLA 3D printing.

Regarding SLS 3D printing, there have been developments into incorporating fibre reinforcement into SLS 3D printing, but the developments are focused on incorporating short fibres instead of long/continuous fibres [58]. The current method of providing the powder for each layer does not allow for control over the orientation and layout of long/continuous fibres. The basis for incorporating short fibres into SLS 3D printing is to mix short fibres with the powder. Mixing the short fibres and powder together can include numerous processes to prepare the materials, but the printing process is mostly the same [59].

2.3.1 Current Commercial Fibre Reinforced 3D Printing

There are a few commercial 3D printers available that can be used to produce parts that are reinforced with fibre reinforcement. These 3D printers can be roughly split based on the length of fibre reinforcement that is utilised during production. For long/continuous fibre reinforced 3D printed parts, a range of 3D printers have been developed by a company called Markforged. Markforged have developed several FDM 3D printers that can construct parts with fibre reinforcement. The printers from Markforged utilise a range of composite filaments, with the fibre reinforcement embedded within a thermoplastic matrix, using fibreglass, carbon fibres and Kevlar fibres. There have been some research that has been conducted into the capabilities of the first commercial 3D printer released by Markforged, called the Mark One [60, 61]. There have been several other FDM 3D printers release by Markforged that utilise either short or long/continuous fibre reinforcement, including the Mark Two, Onyx One and Onyx Pro.

Regarding commercially available 3D printers that can utilise short fibre for producing parts, materials have been developed with short fibres to be used with several 3D printing technologies. SLS 3D printing powder is combined with short fibres to create composite parts and SLA 3D printing resin can have short fibres within the resin to create composite parts. Special filaments are available with short fibres embedded within the filament for FDM 3D printers to create composite parts.

Currently there are no commercial 3D printers available that can print using thermoset resin within controlled/orientated long/continuous fibre reinforcement. Thermosets offer distinct advantages over thermoplastics such as being cheaper, are suitable for high-temperature applications and high fatigue strength [62]. The main hinderance is controlling the thermoset resin prior to curing as the process cannot be reversed as with thermoplastics. Incorporating long/continuous fibre reinforcement within thermoset resins into 3D printing technologies could allow for composite parts to be 3D printed with the mechanical properties offered from thermoset resins with customised/orientated fibre reinforcement.

2.3.2 Future Fibre Reinforced 3D Printing Research Areas

The main areas of research for 3D printing fibre reinforced composite parts is based on introducing the composite parts to industries. These areas include increasing the amount of materials that can be used to create 3D printed fibre reinforced composite parts, increase the mechanical properties of 3D printed fibre reinforced composite parts and reducing the time it takes to produce 3D printed fibre reinforced composite parts [37]. Development into each of these areas will aid with the incorporation of 3D printed fibre reinforced parts into industry.

3. Composite Filament Production Flowchart

One of the main objectives for this research is the development of a flowchart that details the required processes need to create a fibre reinforced composite filament comprising of long/continuous fibres and a thermoset plastic. Following the completion of the research detailed in the literature review, the key processes and materials for producing the composite filament, with the required material properties, have been identified.

The materials used to produce the fibre reinforced composite filament must adhere to the material properties chosen for the filament; long/continuous fibre reinforcement and a thermoset plastic. The chosen material to provide the long/continuous fibre reinforcement is carbon fibre yarn. Carbon fibre yarn consists of a several thousand unidirectional fibres bundled together and can come in a variety of tow sizes. Typically, carbon fibre yarn comes on a spool and will provide a source of fibres for the filament. Integrating the carbon fibre yarn into the filament will provide the long/continuous fibre reinforcement for the filament.

For the second material for producing the composite filament with the necessary material properties, a thermoset resin is needed. Considering the research conducted in the literature review, a UV-curable resin will be suitable as it allows for better control over the curing of the resin when compared to a two-part thermoset resin. A two-part thermoset resin can be used for preliminary testing, but the final solution will comprise of a UV-curable resin.

The processes required for producing the fibre reinforced composite filament must be designed to integrate the chosen materials and control the materials to create the filament with the desired properties. Following the research conducted in the literature review and the materials being chosen, the following key processes required to produce a fibre reinforced composite filament were identified and are listed below:

- Carbon Fibre Yarn Management.
- Thermoset Resin Management.
- Integrating the Fibre Reinforcement with the Thermoset Resin.
- Removal of Excess Resin from the Composite Filament.
- Controlling the Cross-Sectional Shape of the Composite Filament.
- Controlling the Curing of the Thermoset Resin.
- Application or Storage of the Composite Filament

Following the identification of the materials and processes required to produce the fibre reinforced composite filament with the required material properties, a flowchart was devised to illustrate how the materials and process interact with one another. Figure 3-1 shows the flowchart with each of the identified materials and processes. The flowchart is designed to combine the materials to create the composite filament and run the filament through a linear series of processes to achieve the desired material properties for the filament.

3.1 Flowchart Key Filament Parameters

Through the development of the flowchart and analysing the research conducted in the literature review, several materials properties for the composite filament were identified that would increase the overall performance of the filament and make the filament suitable for additive manufacturing technologies. Therefore, the processes within the flowchart would need to be designed while considering these material properties and how the filament will be utilised within additive manufacturing technologies. The material properties devised for the composite filament are listed as follows:

- Fibre Volume Fraction.
- Interfacial Bonding.
- Air Pockets/Voids.
- Impurities.
- Cross-Sectional Shape.

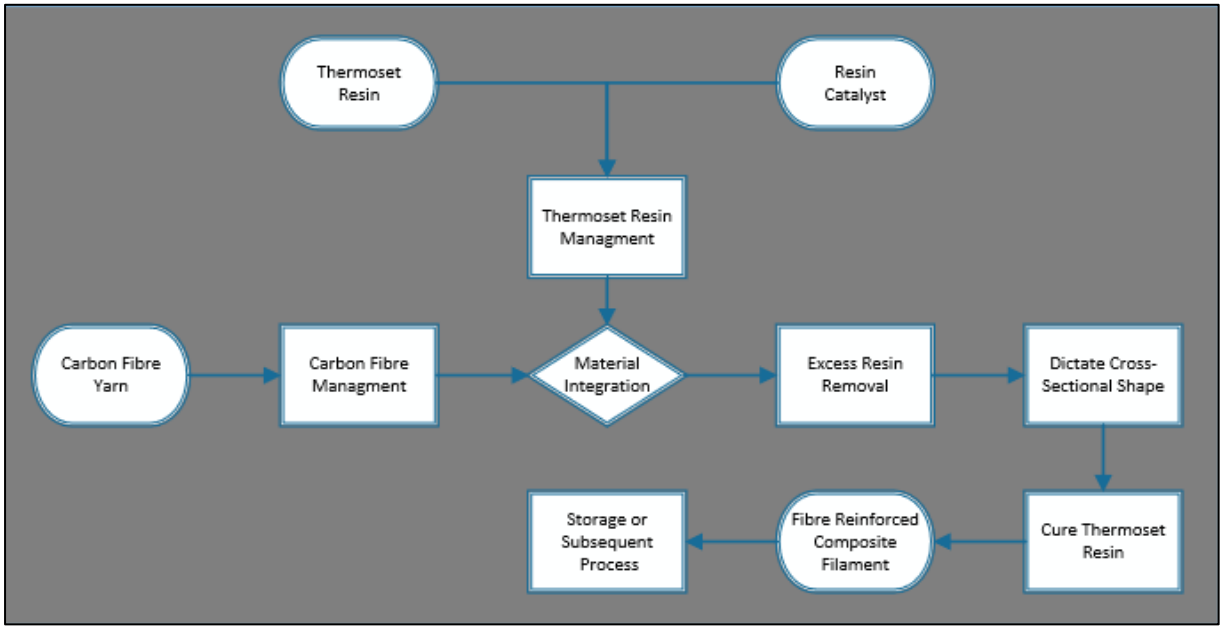

Figure 3-1 - Flowchart for Producing the Composite Filament.

3.1.1 Fibre Volume Fraction

Fibre volume fraction, or fibre volume ratio, is one of the most important material properties for creating a composite filament comprising of long fibre reinforcement. Fibre volume fraction can be defined as the percentage of fibre volume within the overall volume of a fibre reinforced composite material and is shown in the formula below.

$$V_f = \frac{v_f}{v_c}$$

V_f - *Fibre volume fraction*

v_f - *Volume of fibres*

v_c - *Volume of the composite*

Based on research regarding the fibre volume fraction for composite materials, composite materials with higher fibre volume fraction exhibit stronger mechanical properties compared to those with lower fibre volume fractions. This is due to the fibre reinforcement within the composite material contributing significantly more towards the mechanical properties of a composite material compared to the matrix material. This is very apparent in the tensile properties of composite materials. Composite materials with a lower fibre volume fraction will exhibit more areas that are devoid of the fibre reinforcement compared to those with a higher fibre volume fraction. Due to the mechanical properties of the matrix material being lower than the fibre reinforcement, the areas within the composite material that are devoid of fibre reinforcement are more prone to fail under load and could cause the fail to propagate throughout the composite material. Therefore, it will be ideal to have a high fibre volume fraction for the composite filament.

Although having a higher fibre volume fraction will be ideal for the composite filament, a secondary aspect of the fibre volume fraction needs to be considered. One of the main aspects of the matrix component of a composite filament is that the matrix material must protect the fibre reinforcement from external stresses. Regarding the composite filament, the long/continuous fibre reinforcement are prone to breaking when subjected to external stresses perpendicular to the length of the long/continuous fibres. These external stresses include, chemical erosion and mechanical abrasion. Therefore, it will be important for the composite filament to have sufficient matrix material to protect the fibres from external stresses whilst having a high fibre volume fraction.

3.1.2 Interfacial Bonding

One of the important material properties for a fibre reinforced composite material is the interfacial bonding. Interfacial bonding for fibre reinforced composite materials is the bonding between the fibre reinforcement material and the matrix material. It is important for the bonding between the two materials to be sufficient. Fibre reinforced composite materials that have insufficient interfacial bonding between the fibre reinforcement material and the matrix material will result in separation between the materials and this will create areas of weakness that will be prone to failure when subjected to load [63]. Therefore, it is important that the interfacial bonding between the fibre reinforcement and the matrix material for the composite filament is sufficient to reduce the possibility of the materials separating.

3.1.3 Air Pockets/Voids

One of the important aspects when producing fibre reinforced composite materials is to ensure that air pockets/voids are not apparent within the composite material. For composite material that utilise resin as the matrix material, air pockets are generally introduced into a composite material when the matrix material is prepared before being introduced to the fibre reinforcement. Air pockets within composite materials introduce areas of weakness within the composite material due to the absence of resin. These areas of weakness are prone to fail under load and could possibly propagate throughout the composite material. Therefore, the fibre reinforce composite filament must consider reducing the probability of air pockets entering the thermoset resin and subsequently, the composite filament. Otherwise, the composite filament could fracture prematurely under load.

3.1.4 Impurities

Impurities, for composite materials, are materials that are unexpectedly found within the composite material. These impurities generally come in the form of particles or grains and can cause some complications to the mechanical properties of the composite materials. These impurities within the composite material can take the place of the fibre reinforcement and/or the matrix material and can result in stress concentrations and microcracking within the composite material. Additionally, these impurities can also affect the conductivity of composite material. While it is not possible to remove all impurities from the composite material, the production process for creating the composite filament must be designed to introduce the least amount of impurities as possible.

3.1.5 Cross-Sectional Shape

For the fibre reinforced composite filament, the cross-sectional shape of the filament will be an important material property that must be considered. The process for producing the composite filament must be able to consistently produce the filament with the same cross-sectional shape. The basis of most AM technologies is based on adding and bonding layers upon layers on top of one another to create three-dimensional objects. Any inconsistencies in the cross-sectional shape could result in the bonding between layers, interlayer bonding, to be insufficient and will cause the layers to separate from one another. Any area where the interlayer bonds are insufficient will be an area of weakness within an object and can cause the object to fail under load. Therefore, any inconsistencies in the cross-sectional shape of the material used to make the layers will result in inconsistencies in the final part.

3.2 Flowchart Key Processes

The flowchart shown in Figure 3-1 illustrates the sequence of key processes, identified by research conducted in the literature review, that would be required to produce a composite filament composing of a thermoset resin and long/continuous fibre reinforcement. Additionally, these key processes would allow for the ability to control some of the material properties of the composite filament stated previously.

The overall design for this flowchart was to create a linear system of processes that would take the base materials and create the composite filament with the desired properties. Each process would interact with the base materials to further the process of creating the composite filament. The section below will explain some of the key considerations and difficulties for each of the key processes in the flowchart. Additionally, this section will also provide some insight into the responsibilities and desired outcomes for each process as well as detail how the processes interacts with one another to create the composite filament.

3.2.1 Carbon Fibre Yarn Management

The first key process in the flowchart is responsible for controlling carbon fibre yarn as it is passed through the various other key processes for creating the composite filament. The carbon fibre yarn is typically wound onto a spool and this spool of carbon fibre yarn will act as the source of carbon fibre yarn for the composite filament. As the carbon fibre yarn comprises of thousands of individual carbon fibres bundled together, it is important to ensure that these

individual carbon fibres remain together throughout the various processes as the individual fibres can be prone to separating. If the individual carbon fibres do separate from the main bundle, these stray fibres could get caught on various parts, damage some electrical components or cause damage to the fibres within the composite filament.

One of the main aspects of this process is determine how the carbon fibre yarn is passed through the various processes to create the composite filament. The carbon fibre yarn needs to pass through the various process so that the long/continuous fibre reinforcement within the composite filament is not damaged and that the composite filament has the desired properties specified in the previous section. The main area of concern with the handling of the carbon fibre yarn is the period before the carbon fibre yarn is combined with the thermoset resin into the composite filament. The period before the carbon fibre yarn is protected by the thermoset resin is when the carbon fibre yarn is most likely to be damaged.

3.2.2 Thermoset Resin Management

The second key process in the flowchart is responsible for controlling the thermoset resin utilised to produce the composite filament. The main area of consideration for this process is to control the thermoset resin up until the resin and the carbon fibre yarn combine to create the thermoset resin. The process of controlling the resin must be designed in such a way that the process imparts the desired properties into the produce composite filament, including a high, fibre volume fraction and a lack of impurities and/or air pockets.

The first area of concern for controlling the thermoset resin has to do with ensuring that the resin does not cure before encountering the carbon fibre yarn. If the resin has partially begun to cure, this could inhibit the resin from being able to coat each of the individual fibres within the carbon fibre yarn, could result in sections of the composite filament having little to no resin and could potentially damage either the composite filament or the components of the process. Therefore, depending on the method for curing the thermoset resin, the stimulus for initiating the curing process must not be introduced to the thermoset resin before the resin encounters the carbon fibre yarn. For a UV curable resin, this would include not subjecting the resin to any source of UV-light before the resin has combined with the carbon fibre yarn to create the composite filament.

A secondary area of concern is to reduce the chances of introducing air pockets and impurities into the thermoset resin as this could introduce air pockets and impurities into the composite

filament. Introducing air pockets or impurities into the composite filament can weaken the composite filament and could result in the composite filament failing prematurely. Therefore, this process must be designed to introduce the least amount of impurities and air pockets as possible. This includes preparing the thermoset resin in a way that ensures that air pockets and impurities are not introduced into the thermoset resin before being used to make the composite filament.

3.2.3 Integrating the Fibre Reinforcement with the Thermoset Resin

The next key process from the flowchart is the process of combining the carbon fibre yarn and a thermoset resin into the composite filament. This is the most important process as this process is responsible for ensuring that each of the individual fibres within the carbon fibre yarn are coated with the thermoset resin and combines the thermoset resin and the carbon fibre yarn to create the composite filament with the desired properties.

One of the key areas of consideration for this process is to ensure that the correct amount of thermoset resin is applied to the carbon fibre yarn to fully impregnate the carbon fibre yarn within the resin. If there is not enough resin to fully impregnate the carbon fibre yarn within the resin, this will create a weakness in the composite filament. Ideally, this process will provide more resin than necessary to coat all the individual fibres to ensure that there is enough resin within the composite filament. Additionally, the process must be able to ensure that the resin is able to penetrate all areas within the carbon fibre yarn. Otherwise, this could result in sections of the composite filament being devoid of resin and will be areas of weakness. A possible solution to this problem would be to apply a pressure to force the thermoset resin into the bundle of carbon fibre yarn to ensure that the resin is able to penetrate all areas of the carbon fibre yarn.

3.2.4 Removal of Excess Resin from the Composite Filament

Following the process of combining the thermoset resin and the carbon fibre yarn into the composite filament, the next process involves removing the excess resin from the composite filament. This process is responsible for controlling the fibre volume fraction of the composite filament by removing the excess resin before the composite filament becomes cured.

For this process, the process needs to ensure that most of the excess resin is removed from the composite filament. If most of the excess resin is not removed from the composite filament,

this will create areas within the composite filament that are devoid of the carbon fibre reinforcement. This will result in areas within the composite filament that are significantly weaker. These areas will be the first to fracture under stress and could result in the fracture propagating throughout the composite filament.

Additionally, this process needs to make sure that the process does not remove too much of the excess resin. If too much resin is removed, this could result in some of the carbon fibre on the extremities of the composite filament being exposed and unprotected by the thermoset resin. This again will create areas that will be prone to fracturing and causing the composite filament to fail. Therefore, a balance needs to be created to remove enough resin to reduce the areas within the composite filament without fibre reinforcement without exposing the fibre reinforcement to outside influences.

3.2.5 Controlling the Cross-Sectional Shape of the Composite Filament

Following the process of removing the excess resin from the composite filament, the subsequent process is to control the cross-sectional shape of the composite filament before the filament is cured. Ideally, this process will be able to create the composite filament that has a consistent shape, size and number of carbon fibres throughout the entire composite filament. Ensuring that the composite filament has these characteristics will help ensure that the process of utilising the composite filament will have relatively consistent mechanical properties with reduced chance of deficiencies.

3.2.6 Controlling the Curing of the Thermoset Resin

The next process in the flowchart is responsible for controlling the curing of the thermoset within the composite filament after the thermoset resin and carbon fibre yarn have been combined and the excess resin has been removed. This process is heavily dependent on the method utilised for curing the resin. Ideally, this process will cure the thermoset resin enough to allow the composite filament to be handled towards the next process without the composite filament becoming damaged or becoming rigid. If the composite filament was to become rigid, the composite filament will not be flexible enough to be utilised for AM applications. AM applications are used to make parts with complex cross-sections Therefore, a material that is rigid without the ability to become flexible will not be able to make the complex cross-sections. Additionally, AM applications require the bonding of multiple layers of materials to create parts. If the composite filament is rigid, the composite filament would require a bonding agent

to bond multiple layers of the filament together. Finding the optimal amount of curing for the thermoset resin will be an important factor in making the composite filament useful.

The method for curing the thermoset resin will heavily impact this process. For a two-part resin, the combination of the two materials triggers the curing process which can be quickened by increasing the temperature and slowed by reducing the temperature. However, controlling the curing of the thermoset resin using this curing method could be quite difficult. Additionally, this curing method will require the two materials to be mixed together before being combined with the carbon fibre yarn. Having the two materials mixed together before making the filament, can introduce the risk of the thermoset resin possibly, curing prematurely within the various processes and possibly damaging the filament and/or various components. This curing method would require temperature control of various processes to accelerate and decelerate the curing of the resin to provide adequate control of the resin within the composite filament and within the various processes.

Another option for the curing method is to utilise a UV-curable resin for the composite filament. A UV-curable resin utilises UV-light to trigger the curing process. By controlling when the UV-light contacts the thermoset resin and ensuring that no external sources of UV-light reach the resin, this will allow for the curing of the resin to be controlled and reduce the risk of resin curing in the various processes. Additionally, UV light can be utilised to partially cure the external surface of the composite filament while the internal is not cured. This could allow for the filament to be able to be handled whilst the filament will still be flexible. Once the filament has been used, the filament can then be subjected to further UV-light to cure the filament completely.

3.2.7 Application or Storage of the Composite Filament

The final process in the flowchart is responsible for the process of utilising the composite filament for AM applications. There are two options for utilising this filament in AM applications. The first option is for the composite filament to be fed directly onto an AM application. This option would optimal as it would reduce the risk of the thermoset resin within the composite filament curing overtime and becoming unusable. The problem with this option is that this requires that an AM application has been designed and is ready to utilise the composite filament as it is being produced. Currently, the device to utilise this material has not been constructed.

The second option for this process is to store the composite filament to be used later by an AM application. This will allow for the composite filament to be made in bulk and used later but does increase the risk of the thermoset resin curing in the period between when the filament was made and when it will be used. Additionally, the composite filament could be used for a variety of applications instead of being fixed to one application. While there is no AM application ready to utilise the filament, storing the filament for later is the best option. Once the AM application to utilise the composite filament has been designed and constructed, the composite filament would feed directly into the AM application.

4. Composite Filament Production Development

Following the identification of the key processes required to produce a composite filament comprising of long/continuous fibre reinforcement and a thermoset resin and the identification of several key material properties for the filament, a series of prototypes were designed and developed. These prototypes were designed based on the structure and processes set out by the flowchart. Each prototype was developed to achieve a specific outcome to develop the design for the final prototype. Several iterations of prototypes were developed to analyse the performance of various designs to determine the optimal designs for producing the composite filament. After analysing each of the various designs, the best performing designs would be chosen and utilised in the development of subsequent prototypes.

The predominant factor in determining the optimal design for a specific process was based on the material properties of the composite filament directly after the process. Additionally, each process was analysed based on additional factors that could be used to improve upon the design. The additional factors that designs were analysed against include the following:

- Ease of use
- Ease of setup
- Consistency
- Reliability

Each prototype was modelled using SolidWorks to create computer aided design (CAD) models of the various components within each prototype to show how the different components would interact with one another. Additionally, SolidWorks was utilised to generate the required files and technical drawings needed to manufacture the various components within each prototype.

4.1 Prototype 1

The first prototype for producing the composite filament was developed as a platform for testing different designs for the processes starting from managing the base materials until just before the curing process is required. The reason for this was to develop a set of processes to ensure that the composite filament had the required material properties prior to being cured. Additionally, this would allow for various designs to be tested to determine which designs would produce the composite filament with the desired properties.

4.1.1 Prototype 1 – Overview

The design used for the first prototype was based on pulling the carbon fibre yarn through a linear series of processes designed to create the composite filament without damaging the carbon fibre yarn. This prototype divided the individual process required to make the composite filament into stations. These stations were designed to be connected but with the ability to remove a station and replace the station with a new design. This prototype design allowed for different designs for each process and different combination of designs to be tested and analysed to determine the best performing design for each process.

The basis of the design for Prototype 1, illustrated in Figure 4-1, is based around pulling the carbon fibre yarn through a series of processes to create the composite filament. By pulling instead of pushing the carbon fibre yarn, this requires the carbon fibre yarn to be pulled through each of the processes prior to the composite filament being made and will result in a section of the carbon fibre yarn being without a thermoset resin matrix each time the prototype is setup. One of the additional benefits to pulling the carbon fibre yarn through the different processes is that it can reduce the chance of individual fibres separating from the carbon fibre yarn. The other additional benefit of pulling the carbon fibre yarn instead of pushing the carbon fibre yarn through the various processes is that the consistency of the distribution of the carbon fibre yarn within the composite filament. If the carbon fibre yarn is pulled at a consistent rate and is under the same amount of tension, this will reduce the chances of inconsistencies in the internal structure of the carbon fibre yarn within the composite filament.

The basic overview of the sequence processes for preparing the composite filament using Prototype 1 begins by first combining the carbon fibre yarn and the thermoset resin at a junction point. The subsequent composite filament created from this junction point is then passed through a combination of pressure rollers and shaping dies that are designed to remove the excess resin and dictate the cross-sectional shape of the filament before the curing process is initiated.

The process for controlling the flow of resin for Prototype 1 involves storing a premixed solution of thermoset resin within a syringe that is connected to the junction, via a tube, where the carbon fibre yarn and thermoset resin will meet. The plunger for the syringe can be used to force the thermoset resin into contact with the carbon fibre yarn and the process of producing the composite filament begins. For this prototype, the process of controlling the flow of the

thermoset resin will be a manual process to display whether this concept will work fundamentally before being refined. Ideally, this process would be automated to provide a constant pressure and volume of the thermoset when it reaches the carbon fibre yarn to help with producing a composite filament with consistent properties.

For this prototype, one of the key areas that will be addressed is the lack of automation. As several designs were tested for this prototype, providing automation for each design would take extra time and effort and would be addressed in subsequent prototypes. Ideally, each of the processes for producing the composite filament would be automated to increase the consistency of the processes.

One of the processes that has not been automated for this prototype is the process of pulling the carbon fibre yarn through each process. This process will be done by hand as it will be quicker than implementing an automated solution for all designs. This process and several others will be automated in subsequent prototypes, but automation of these processes was not deemed important for the first prototype.

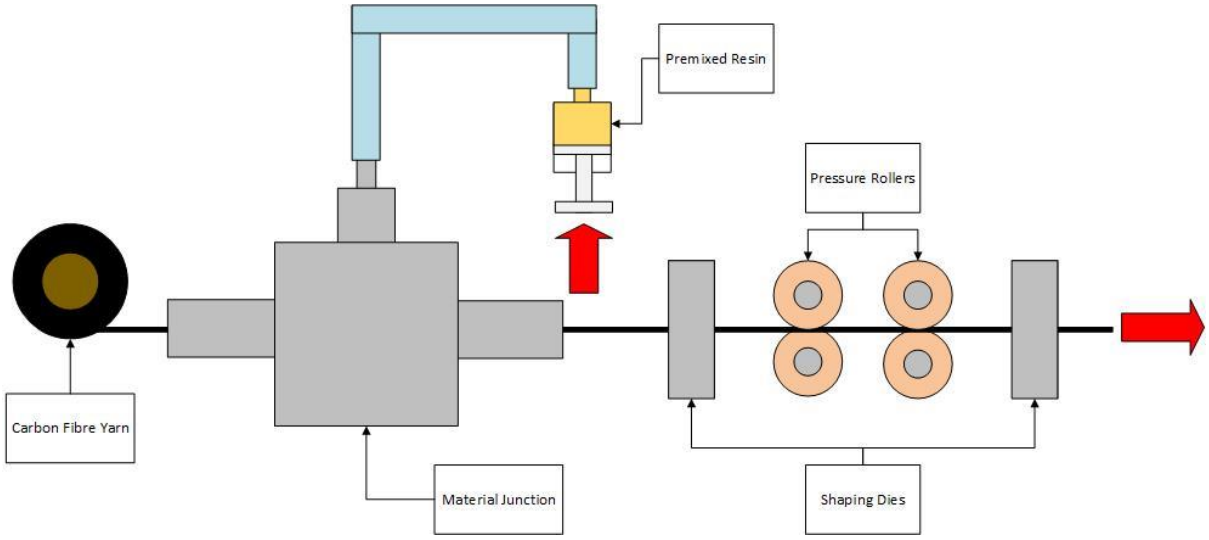

Figure 4-1 - Diagram of the Processes for Prototype 1.

4.1.2 Prototype 1 – Materials

For the first prototype, the base materials used for producing the composite filament comprised of carbon fibre yarn as the reinforcement phase and two types of two-part thermoset resins for the matrix phase. The first type of resin used in the first prototype was two-part polyester resin. This resin was chosen due to the resin having a low viscosity and that photoinitiators could be added to the polyester resin to make the resin UV-curable. The technical data sheet for this polyester resin can be found in Appendix A.

The second type of two-part thermoset resin was an epoxy resin. The technical data for the two-part epoxy resin is shown in Appendix B. It was important to utilise an epoxy resin for this research as epoxy resins are the most commonly used type of resin used in the production of carbon fibre composite parts. One area of concern with using epoxy resins over polyester resins is that epoxy resins typically have a higher viscosity. These differences in the viscosities would allow for analysis to be done on the effect that viscosity would have on carbon fibre composite filament made using the first prototype. Table 4-1 shows some of the key information for both the polyester and epoxy thermoset resins.

4.1.3 Prototype 1 – Stations

The first prototype for producing a composite filament is made up of a series of stations. These stations contain at least one of the processes as stated earlier. The stations that make up the first prototype are as follows:

- Carbon Fibre Spool Management
- Impregnation Process
- Filament Post-Processing

4.1.3.1 Station 1 – Carbon Fibre Spool Management

The first station for making the composite filament using Prototype 1 is responsible for controlling the feed and supply of carbon fibre yarn into the various components in the remaining stations. The responsibilities for Station 1 include controlling the method of passing the carbon fibre yarn through the various stations and ensuring that the carbon fibre yarn is not damaged when entering the other stations. The supply of carbon fibre yarn for Prototype 1 to use to create the composite filament, shown in Figure 4-2, is a spool of carbon fibre yarn. This

spool of carbon fibre yarn has the carbon fire yarn wound onto a hollow cardboard cylinder. The dimensions for the spool of carbon fibre yarn are shown in Figure 4-3.

The design for Station 1 is designed to accommodate the spool of carbon fibre yarn and safely transport the carbon fibre yarn to the subsequent stations. The design for this station, illustrated by the SolidWorks CAD model shown in Figure 4-4, involves positioning the spool of carbon fibre yarn between two parallel walls. These parallel walls are designed to be made using laser cut 3mm MDF sheets. Each wall has identical cut-outs that are designed to allow the ends of the spool of carbon fibre yarn to be placed within the cut-outs and allow the spool to rotate freely. The parallel walls are locked in place by four spacers that run between each wall. The length of these spacers is shorter longer than the total length of the spool of carbon fibre yarn so that the spool does not fall into the gap between the two walls.

The spacers used for Station 1, illustrated by the technical drawing shown in Figure 4-5, are made using four aluminium rods that have had the ends turned down to a smaller diameter and have been threaded. The threaded ends of the rods are then inserted through the holes that are cut into both walls. The change in diameter for the rods is used to set the distance between the two walls and ensure that the gap does not get smaller. A nut is then threaded onto the ends of each of the rods to stop the spacers from falling in the gap between the walls and locks the walls onto the ends of the spacers. The combination of the change in diameter in the rods and the nuts threaded onto the ends of the rods locks the walls into position and allows the carbon fibre spool to be positioned between the walls.

	Polyester Resin	**Epoxy Resin**
Part A (Base Material)	Polyplex Clear Ortho Casting Resin	ADR270 Epoxy Resin
Part B (Hardener/Catalyst)	Norox MEKP 9 Catalyst	ADH 25 Hardener
Viscosity (cP)	300 – 450	975
Pot Life (minutes)	15 – 20 (at 25℃)	20 (at 20℃)

Table 4-1 - Properties of Resins used for Prototype 1.

Figure 4-2 - Spool of Carbon Fibre Yarn.

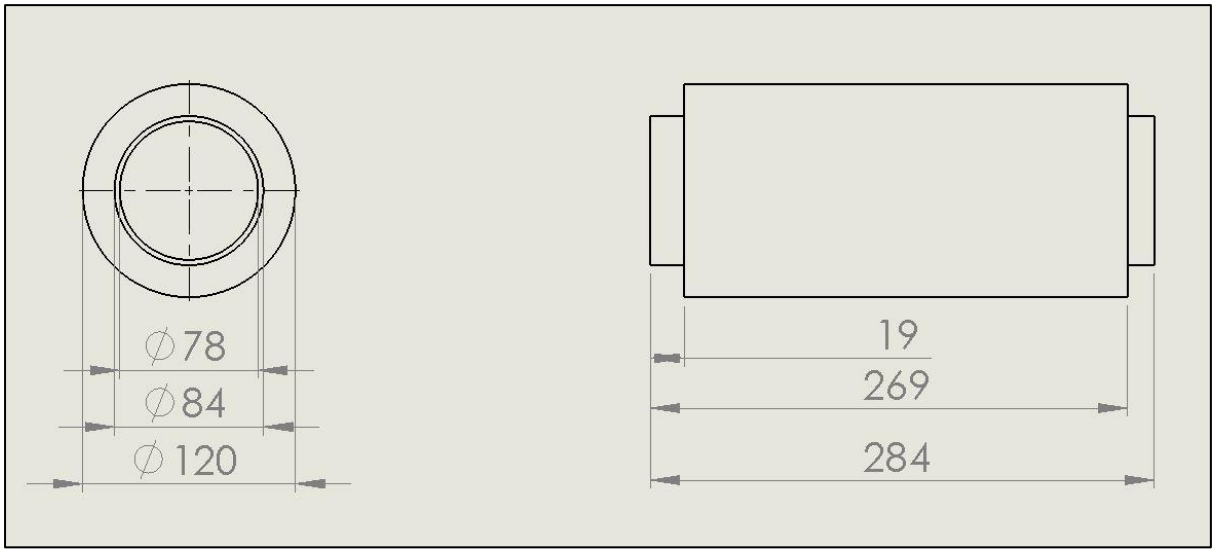

Figure 4-3 - Dimensions of the Spool of Carbon Fibre Yarn (mm).

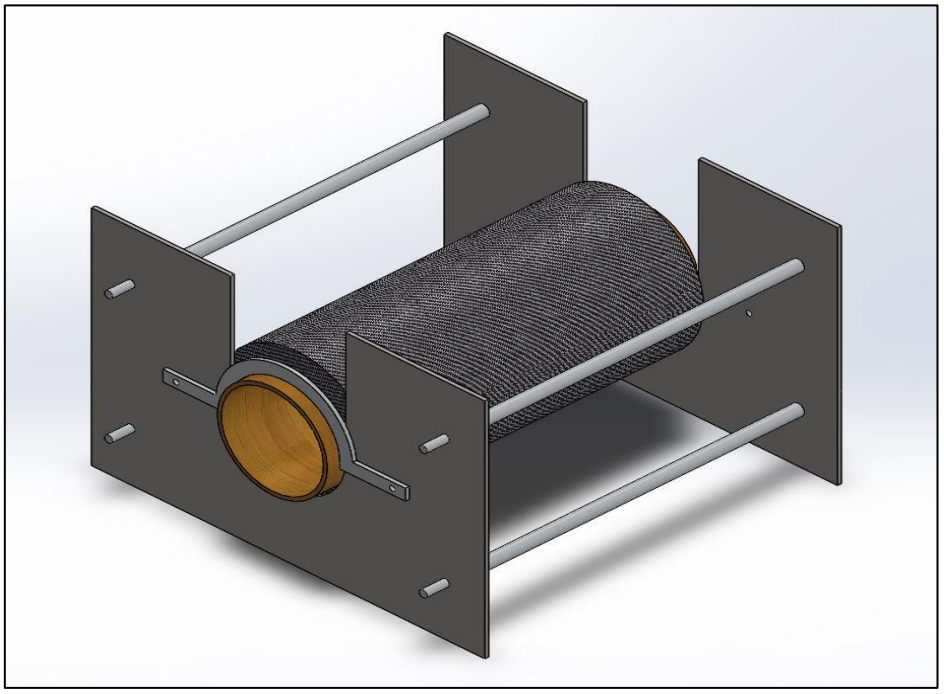

Figure 4-4 - CAD model of Station 1 for Prototype 1.

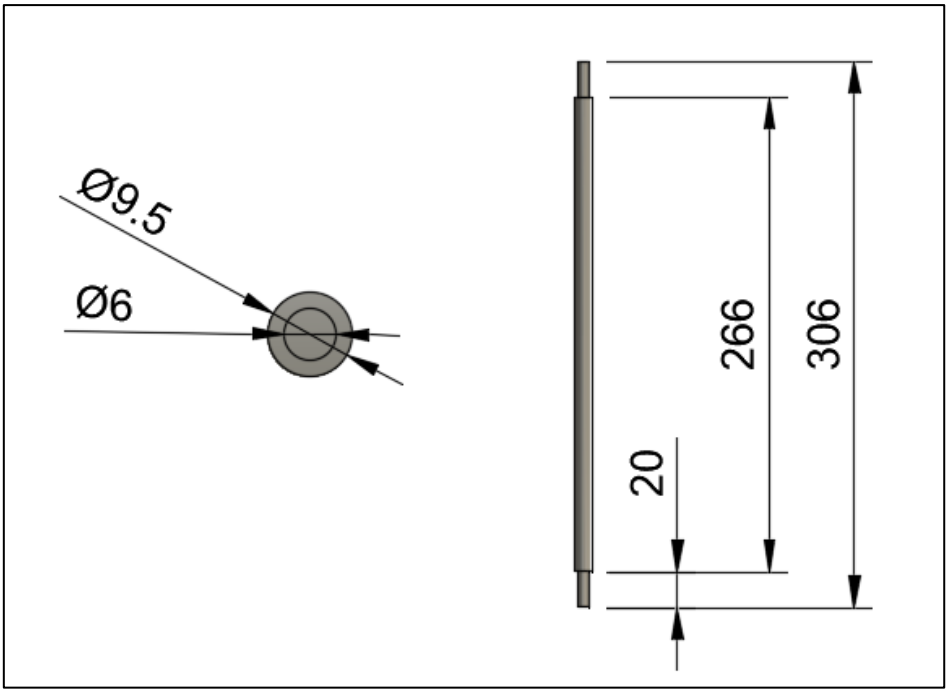

Figure 4-5 - Technical Drawing for the Spacers in Station 1 (mm).

A possible problem with this design is the possibility of the carbon fibre yarn getting trapped between the walls and the spool. The probability of the carbon fibre yarn getting trapped is increased if the spool lifts while the carbon fibre yarn is being pulled through the other stations. If the spool lifts, this could result in the carbon fibre yarn getting trapped between the spool and the MDF walls. Therefore, a locking mechanism has been introduced into the design to ensure that the spool cannot lift off the walls without the locking mechanism being removed. The locking mechanism involves two small cut-outs that can be locked onto either of the walls. These cut-outs follow the diameter of the hollow cardboard cylinder and can be positioned on the top half of the hollow cardboard cylinder to stop the spool from lifting. The cut-outs used for the locking mechanism are also made of 3mm MDF that has been laser cut.

4.1.3.2 Station 2 – Impregnation Process

The second station for the first prototype is responsible for impregnating the carbon fibre yarn into the thermoset resin to create the composite filament. This station is situated directly after Station 1 and receives the carbon fibre yarn from the carbon fibre spool. This station is required to provide a junction for the carbon fibre yarn and the thermoset resin to combine and create the composite filament. Ideally, this station will impart some of the desired material properties for the composite filament including a high fibre volume fraction, providing sufficient bonding between the carbon fibre yarn and the thermoset resin and introducing little to no air pockets or impurities into the composite filament.

For Station 2, several designs were developed for impregnating the carbon fibre yarn into the thermoset resin for the carbon fibre composite filament. Some of these designs for Station 2 were based on a design that utilises no moving parts [64]. The chosen design for this station is based on creating a platform for testing multiple parameters to find an optimal combination while still being able to reliably create the composite filament with the desired material properties.

4.1.3.2.1 Design 1 – T-Junction

The design used for Station 2 is a design based around utilising a T-junction to allow the carbon fibre yarn to combine with the thermoset resin to create the composite filament. The T-junction is designed around using four separate aluminium parts that combine to create the T-junction. This design allows for each of the four parts to have various iterations to determine an optimal combination. The T-junction works by having the carbon fibre yarn running through the

through hole and the thermoset resin coming into the T-junction through the perpendicular hole. By having the carbon fibre yarn running through the through hole, this allows the carbon fibre yarn to continuously be pulled through the T-junction without being damaged. Additionally, with the thermoset resin coming through the perpendicular hole in the T-junction, this can provide a consistent source of thermoset resin for the carbon fibre yarn to be pulled through and create the composite filament.

The most important part of the T-junction utilised in Station 2 is the junction point where the carbon fibre yarn and thermoset resin combine. The junction point for Station 2 is based on utilising a 30mm x 30mm x 30mm milled aluminium block that has various holes situated on different surfaces of the block that allow the carbon fibre yarn and thermoset resin to come into contact. Additionally, this block is designed to be the mounting point for the remaining parts to allow the T-junction to be altered. Figure 4-6 shows a CAD model of the cross-section for the milled aluminium block.

The block for the T-junction is created by drilling a 4mm diameter through hole at the centre of opposing surfaces and the drilling a 4mm diameter hole at the centre of a perpendicular until the perpendicular hole reaches the through hole. Once all these 4mm holes have been drilled, the 4mm holes are enlarged for the first 5mm from the outer surface of the block. A M8 x 1.0 thread is then cut into each of the enlarged holes to provide a method for attaching the remaining parts. This can allow various combinations of parts with different parameters to be attached to the block. Finally, four mounting holes are positioned at the corners of a surface that is perpendicular to the surfaces with the original three holes.

The remaining three parts for the T-junction are a series of aluminium connectors that are designed to control the input and output of materials within the T-junction. These connectors are aluminium rods that have various diameters and have a through hole in the centre of each rod for materials to pass through. These connectors have threaded ends that allow the connectors to be attached to the threaded holes in the aluminium block. Figure 4-7 is a CAD model that illustrates the aluminium block with each of the connectors connected to the block.

Connector 1 is connected to one end of the through hole on the aluminium block and is responsible for receiving the carbon fibre yarn from Station 1. The connector has a total length of 25mm and has a 4mm diameter through hole for the carbon fibre yarn to pass through. Additionally, one end of Connector 1 is threaded so Connector 1 can connect to the aluminium

block to create the T-junction. The through hole has a tapered edge, on the unthreaded end of the connector, that assists with feeding the carbon fibre yarn through the T-junction and reduces the chances of the carbon fibre yarn being damaged by passing over the edge of the through hole.

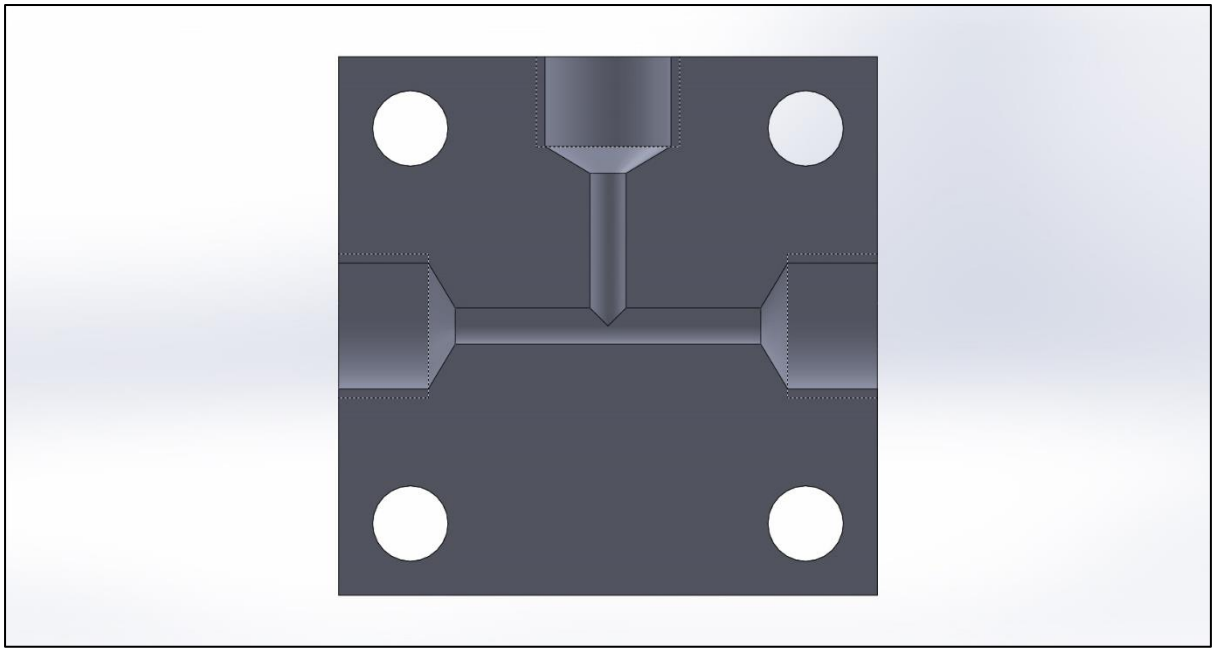

Figure 4-6 - Cross-section View of the Aluminium Block in Station 2.

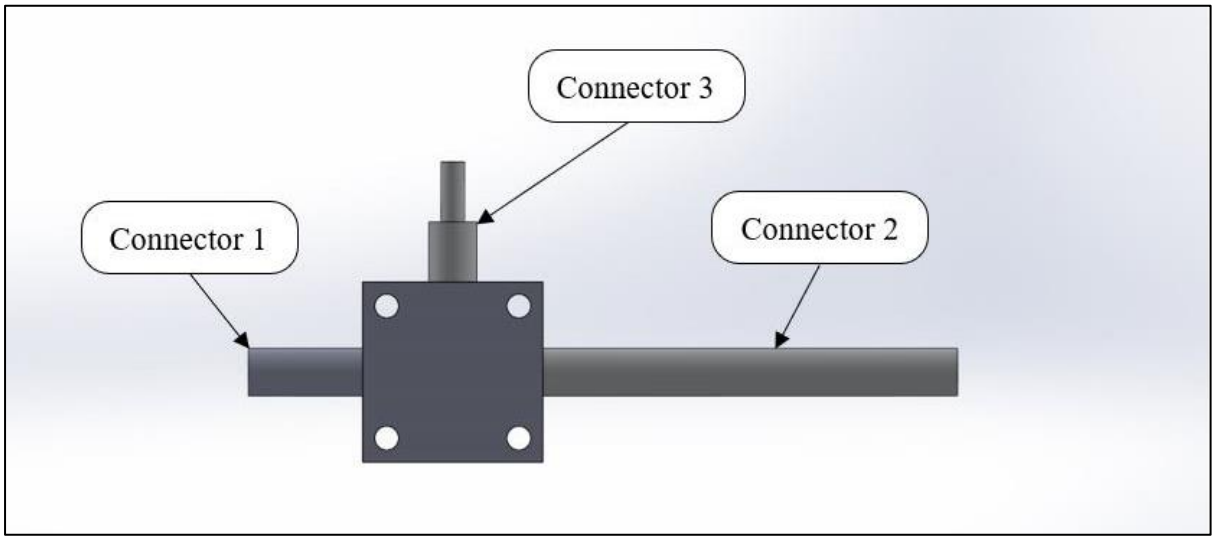

Figure 4-7 - CAD model of the Connectors attached to the Aluminium Block.

Connector 2 is connected to the other end of the through hole in the aluminium block and is responsible for guiding the composite filament to the next station and for dictating the period that the carbon fibre yarn and thermoset are in contact. Connector 2 has a total length of 80mm with a 4mm diameter through hole for the composite filament to pass through. Similar to Connector 1, Connector 2 also has one of the ends of the through hole tapered and has a threaded end to connect to the aluminium block.

Connector 3 is the final part of the T-junction and connects to the perpendicular hole in the aluminium block. Connecter 3 is responsible for guiding the thermoset resin into contact with the carbon fibre yarn. Connector 3 is 25mm in length and has a 2mm through hole for the thermoset resin to pass through. One end of Connector 3 has a 10mm section with a 4mm outer diameter that allows the attachment of a tube that is connected to the source of thermoset resin. Similar to the other connectors, Connector 3 has a threaded end that allows the connector to connect to the aluminium block.

For Station 2, the T-junction is situated between two 3mm MDF walls using the four mounting holes on the aluminium block. These walls are designed to position the T-junction to receive the carbon fibre yarn from Station 1 without damaging the carbon fibre yam. Connector 2 is positioned upwards to allow easy access for a tube to be connected to the T-junction. Figure 4-8 shows a CAD model with Station 1 and Station 2 connected.

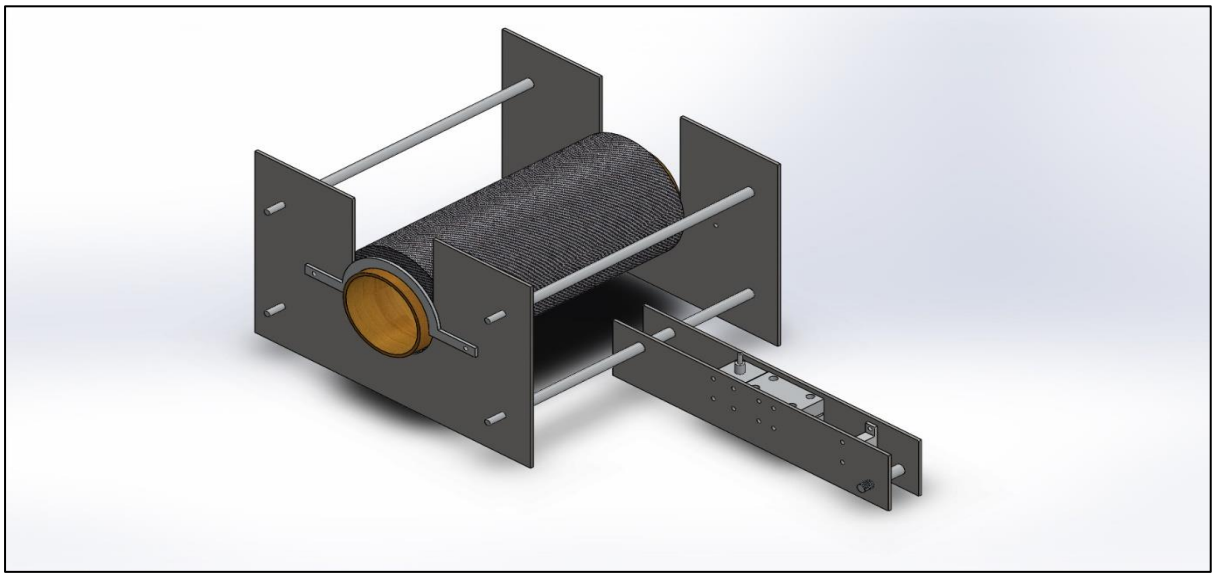

Figure 4-8 - CAD model of Station 1 and Station 2 connected.

4.1.3.3 Station 3 – Filament Post-Processing

Station 3 is the final station for Prototype 1 and is responsible for removing the excess resin from the composite filament created in Station 2 and for dictating the cross-sectional shape of the composite filament. Although Prototype 1 does not have a curing process, this station will set some of the key characteristics of the composite filament before being subjected to the curing process.

The design for this station involves pulling the composite filament through a combination of pressure rollers and shaping dies to remove the excess resin from the filament and to set the final cross-sectional shape of the filament. An important aspect for this design was the ability to have different combinations of the pressure rollers and shaping dies to ascertain the optimal combination. Therefore, the design for this station allows for the order of shaping dies and pressure rollers to altered.

The overall design for this station is to have the pressure rollers and shaping dies positioned between two parallel 3mm MDF walls. The walls have an assortment of mounting holes that allow for a maximum total number of components of four to be mounted onto the walls at one time. This maximum number of components include different combinations of components but can also comprise solely of either shaping dies or pressure rollers. Figure 4-9 shows the top view of a CAD model of a combination of shaping dies and pressure rollers for Station 3.

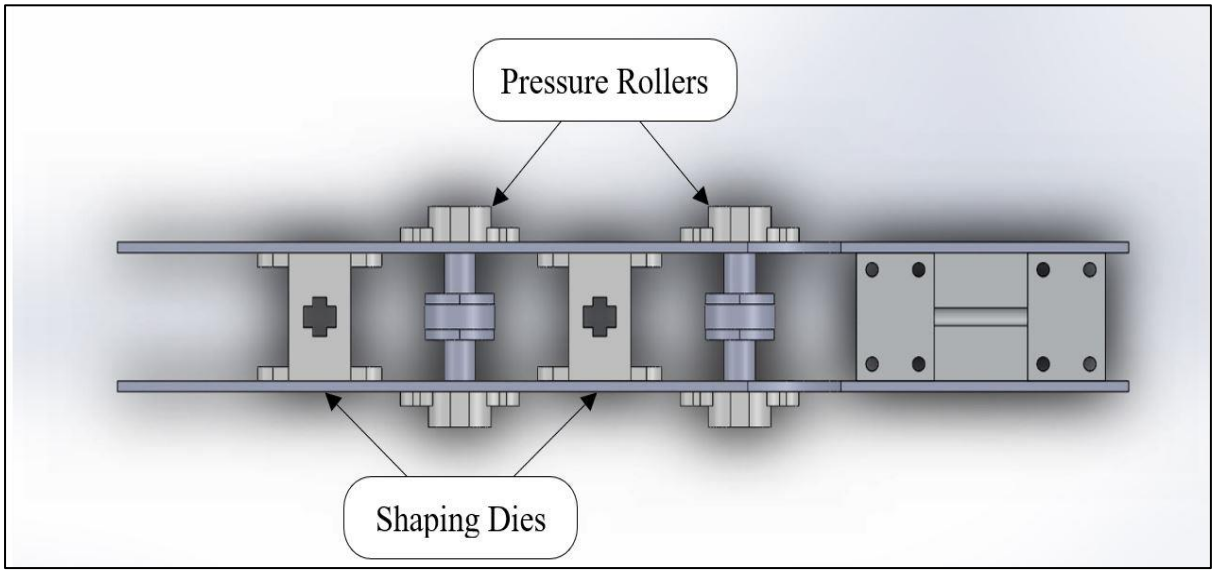

Figure 4-9 - CAD Model of Station 3 for Prototype 1.

4.1.3.3.1 Shaping Dies

The principal design for the shaping dies is for the composite filament to be pulled through a hole with a smaller cross-section than the cross-section of the composite filament to remove the excess resin. Additionally, with the composite filament passing through a smaller cross-section, the shape of the hole will also dictate the cross-sectional shape of the composite filament after the filament has passed through the shaping dies.

There are several problems with utilising the shaping dies for removing the excess resin. One of the possible problems with utilising the shaping dies is that the carbon fibre yarn within the composite filament could become damaged when passing through the shaping die. A second possible problem is that the thermoset resin could build-up and possibly block the shaping die after continual use.

The design for the shaping dies is based on creating a mechanism that allows shaping dies with different size holes to be tested to find the optimal hole size for the shaping die. The design consists of a mounting bracket that allows for a single shaping die to be locked into place and then utilised. The shaping dies are made of aluminium plate with a singular hole in the centre for the composite filament to pass through. Based on testing, the optimal shaping die was with a 2mm diameter circular hole.

4.1.3.3.2 Pressure Rollers

The principal design for the pressure rollers is to pass the composite filament through a gap between two rollers that is smaller than cross-section of the composite filament. Having the composite filament pass through a small gap will remove the excess resin from the composite filament and give the composite filament a rectangular cross-sectional shape. Similar to the shaping dies, possible problems with the pressure rollers is that the process of removing the excess resin could damage the carbon fibre yarn within the composite filament. Additionally, the pressure rollers could possibly seize up or the gap between the pressure rollers could become blocked with the build-up of resin that is removed from the composite filament.

The design for the pressure rollers involves utilising a 1mm gap between two pressure rollers to pass the composite filament through. The pressure rollers utilised in this design are nylon rollers, made using a ball bearing with a nylon coating on the outer diameter of the ball bearing, that are positioned on top of one another. Each pressure roller has a steel shaft running through

the ball bearing to allow the pressure roller to rotate. The ends of the shafts are locked in place with additional ball bearings that are fixed within ball bearing mounts. Spacers are placed on the ends of each of shafts to ensure the composite filament is pulled between the two pressure rollers.

4.1.4 Prototype 1 – Final Design

The final design for Prototype 1 comprises of the combination of the stations stated previously to create the processes for producing a composite filament using a thermoset resin and long/continuous fibre reinforcement. Figure 4-10 illustrate the CAD model developed for Prototype 1, including all stations. From the CAD model, Prototype 1 was built and utilised to produce the composite filament using a two-part thermoset resin and carbon fibre yarn. Figure 4-11, Figure 4-12, Figure 4-13 and Figure 4-14 show Prototype 1 after all the parts were created and assembled.

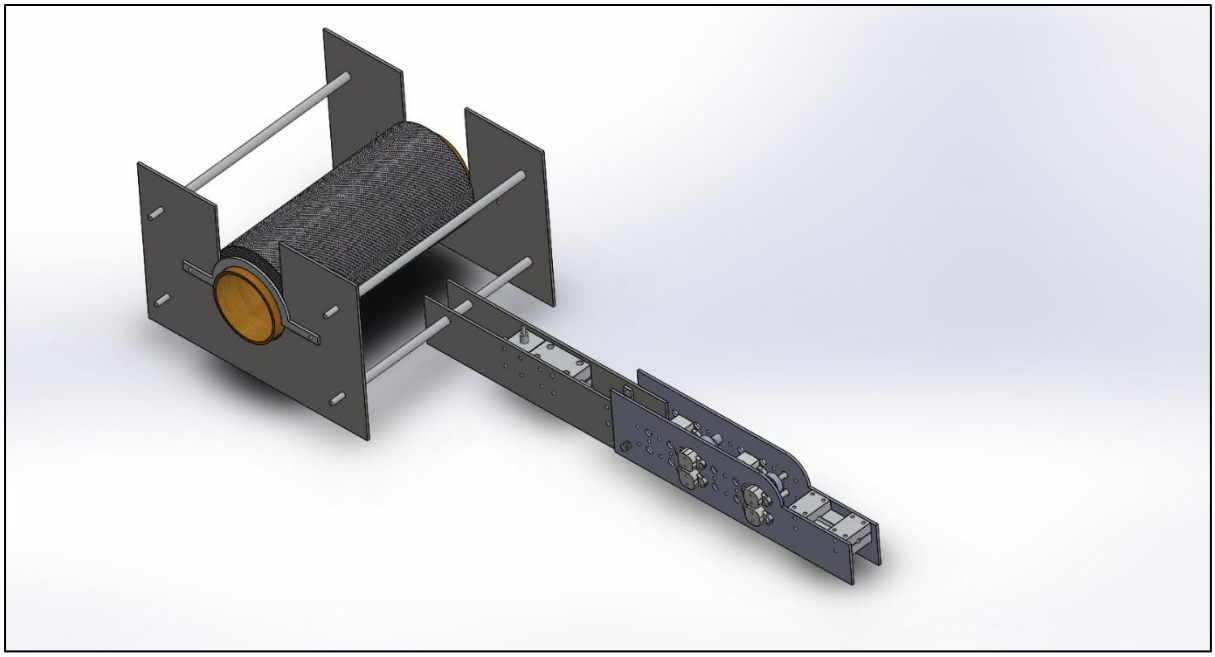

Figure 4-10 - CAD model of Prototype 1 with all Stations connected.

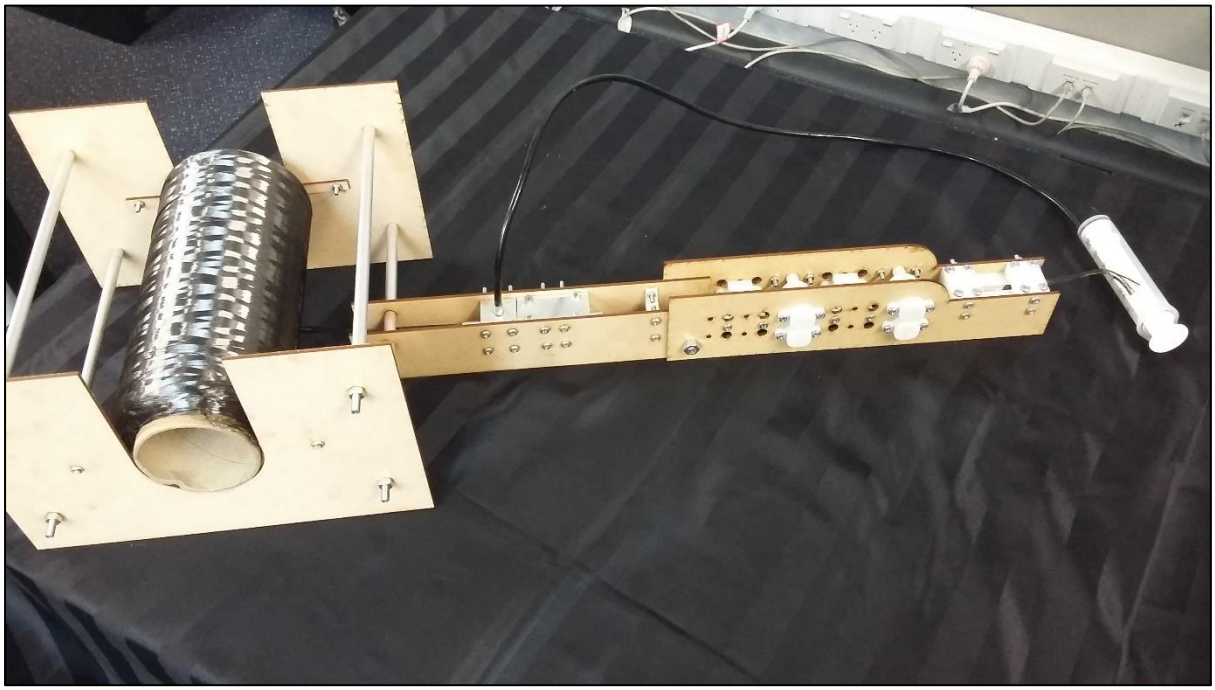

Figure 4-11 - Image 1 of Prototype 1.

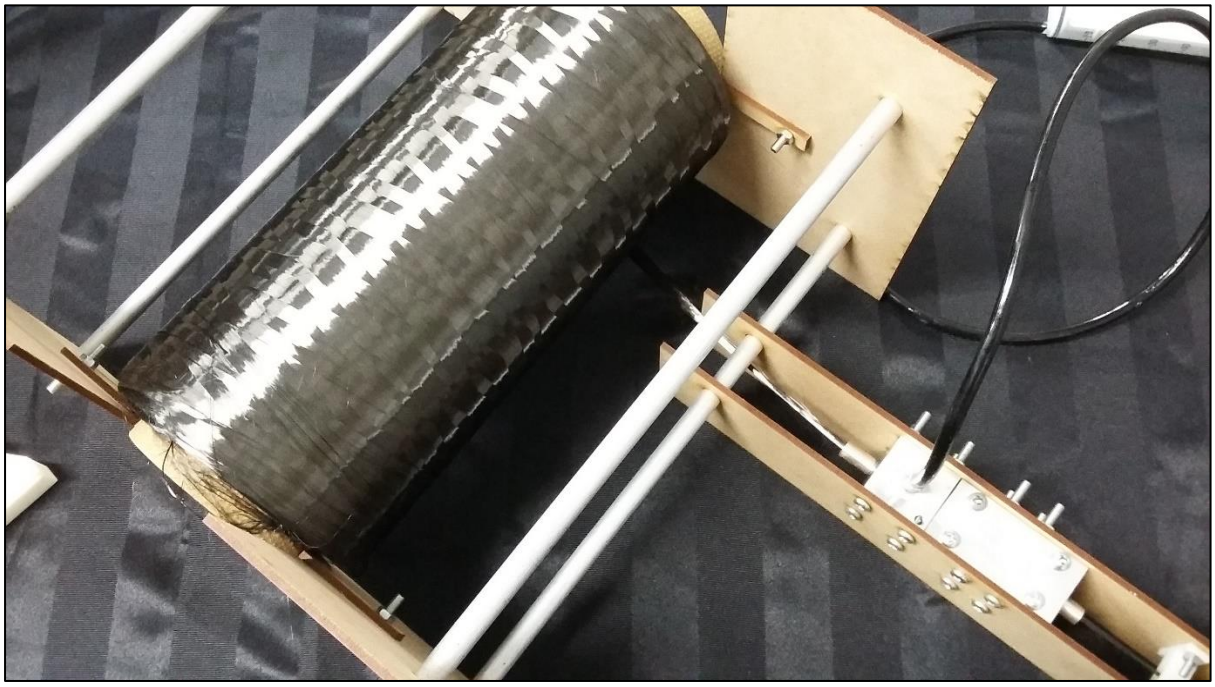

Figure 4-12 - Image 2 of Prototype 1.

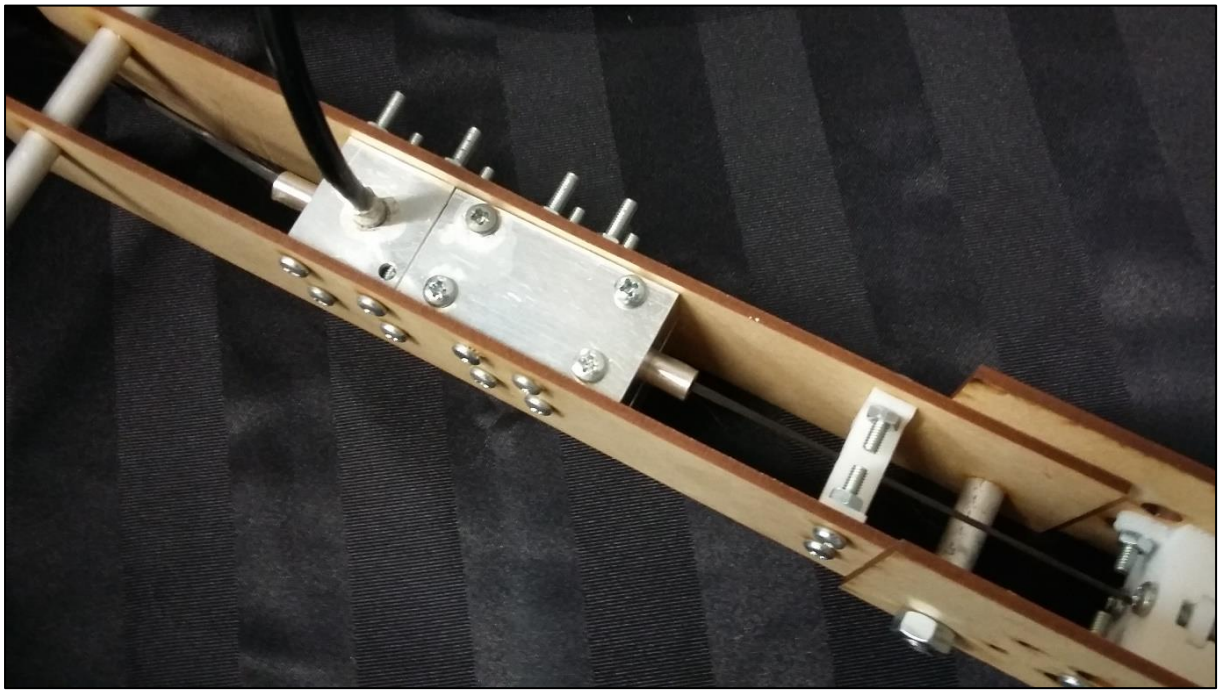

Figure 4-13 - Image 3 of Prototype 1.

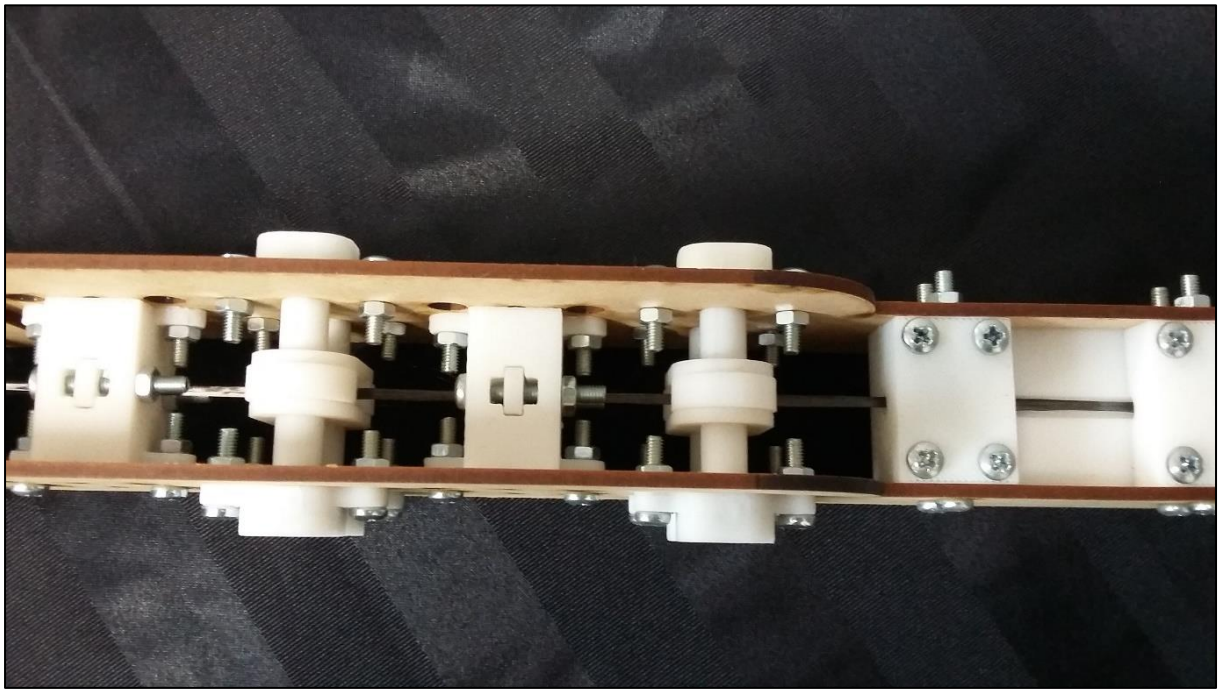

Figure 4-14 - Image 4 of Prototype 1.

4.1.5 Prototype 1 – Testing

Prototype 1 was used to produce a composite filament using a thermoset resin and long/continuous fibre reinforcement. The process of creating the composite filament can be split into three procedures: setup, production and cleaning. Each of the procedures are explained and can be analysed in terms of how each procedure can be improved to create the composite filament with desired material properties. The analysis of these procedures will be utilised for the development of the next prototype.

4.1.5.1 Prototype 1 – Setup Procedure

The setup procedure for Prototype 1 is based around preparing the base materials for each of the stations. The steps for the setting up the carbon fibre yarn and thermoset resin for Prototype 1 are as follows:

1. Wear the correct personal protective equipment (gloves, respirator, lab coat, etc).
2. Place the carbon fibre yarn spool within Station 1 with the end of the carbon fibre yarn underneath the spool.
3. Feed the carbon fibre yarn through aluminium block and connectors in Station 2.
4. Feed the carbon fibre yarn through the shaping dies and pressure rollers.
5. Measure the quantities of both parts of the thermoset resin in separate containers to achieve the desired ratio.
6. Pour both parts of the thermoset resin into a single container and mix thoroughly for approximately five minutes, without adding air to the mixture.
7. Pour the mixed resin solution into the syringe.

One of the key considerations with this setup process is the time before the thermoset cures. The curing process for the thermoset resin begins as soon as the two parts are mixed together. Therefore, the testing procedure must commence straight after the setup procedure to reduce the chances of the thermoset resin curing within each of the stations.

4.1.5.2 Prototype 1 – Production Procedure

The production procedure for Prototype 1 is focussed on creating specimens of the composite filament. These specimens are used to identify whether the designs for the processes used in Prototype 1 can create a carbon fibre composite filament with the desired material properties. The procedure for creating these specimens using Prototype 1 is as follows:

1. Push the plunger in the syringe until the mixed resin solution is seen coming out of the connectors in the aluminium block.
2. Pull the carbon fibre yarn until the composite filament (carbon fibre yarn coated in the thermoset resin) has passed through Station 3.
3. Cut the carbon fibre yarn that has passed through Station 3 but is not coated in the thermoset resin.
4. Pull approximately a 100mm lengths of the filament through Station 3.
5. Cut the composite filament at approximately 100mm lengths for specimens.
6. Repeat step 4 and step 5 for approximately eight minutes.
7. Place the carbon fibre composite filament specimens on a flat surface to cure. Ensure that specimens are not touching each other and are on a flat surface.
8. Allow time for the carbon fibre composite filament specimens to cure completely.

Depending on the speed of the operator, this production procedure can achieve roughly eighteen carbon fibre composite filament specimens and allow enough time for the cleaning procedure. It is important to leave enough time for the cleaning procedure. Otherwise, resin will cure within the stations and cause damage to parts or will require parts to be replaced.

4.1.5.3 Prototype 1 – Cleaning Procedure

The cleaning procedure for Prototype 1 is for removing the thermoset resin from the different stations before the thermoset resin has cured. If this procedure is not completed before the thermoset resin cures, this can result in different parts within stations getting damaged or having to be replaced. The steps for the cleaning procedure for Prototype 1 are as follows:

1. Cut the carbon fibre yarn before Station 2.
2. Pull the remaining composite filament through all stations and dispose of the composite filament.
3. Pour acetone into the syringe and into a separate container.

4. Pushdown on the plunger to force the acetone into the aluminium block.
5. Remove the all the aluminium parts from all the stations that contacted the thermoset resin and submerge the parts in the acetone within the container.
6. Stir the acetone until all traces of resin have been removed from the parts.
7. Dispose of the acetone appropriately.

The use of acetone is effective in removing both the polyester and epoxy resins if the resins have not cured completely. Holes that have been blocked by cured resin can be drilled out and cured resin can be removed from flat surfaces by either sanding down or filing the resin. For parts that have resin that cannot be removed, these parts will have to be replaced.

4.1.6 Prototype 1 – Analysis

Analysing the performance of Prototype 1 can be split into two key areas. The first area is the quality of carbon fibre composite filament specimens that Prototype 1 can produce. The second area that can be analysed is the functionality of setting up, using and cleaning the prototype. These two areas are the most important aspects of the prototype and need to be analysed to assist in the development of the next prototype.

4.1.6.1 Composite Filament Specimens

The first aspect for analysing the performance of Prototype 1 is the ability to produce the composite filament. Additionally, the performance of the designs utilised in each of the stations can be analysed by the material properties exhibited in the composite filament specimens. Analysing the overall performance of Prototype 1 and the performance of the different stations is important in improving the designs utilised in Prototype 2. It is important to remember that the development of Prototype 1 was to identify the designs of the processes required to get the composite filament up to the stage of the curing process and not the entire process. Additionally, Prototype 1 has several processes that are not autonomous and some of the problems could possibly be solved through automating the processes.

One area of concern for analysing the specimens made using Prototype 1 is the environment that the specimens were produced. The specimens were produced while Prototype 1 was situated in a spray booth to eliminate the fumes generated by the thermoset resin. As the spray both is utilised for various applications, producing the composite specimens within the spray booth will impart impurities into the thermoset resin.

Based on the specimens shown in Figure 4-15, Prototype 1 can produce the composite filament with a thermoset resin and long/continuous fibre reinforcement. These specimens were made using non-autonomous designs for each of the processes and this shows in the inconsistencies in the cross-section of the specimens. Although Prototype 1 can produce the composite filament, there are a number of problems that will need to be addressed in future prototypes.

The first problem with the specimens created by Prototype 1 is the inconsistencies in the fibre volume fraction across specimens. Different sections of the specimens have differing amounts of resin coating the carbon fibre yarn, thus resulting in a different fibre volume fraction across specimens. The main reason behind this is the inconsistencies in the flow of resin into the material junction which results in either too much or too little resin coating the carbon fibre yarn. Additionally, this can partly be attributed to the pooling of resin when the specimens are cured on a flat surface and due to the resin being removed from the composite filament while being pulled through Prototype 1.

The second problem with the specimens created using Prototype 1 is to do with the introduction of air pockets and impurities into the composite filament. Air pockets are entering the thermoset resin either before or during the process of combining the resin with the carbon fibre yarn which results in the composite filament specimens having air pockets. Figure 4-16 exhibits some of the air pockets found in the composite filament specimens using an optical- microscope to analyse the outer surface of the specimens.

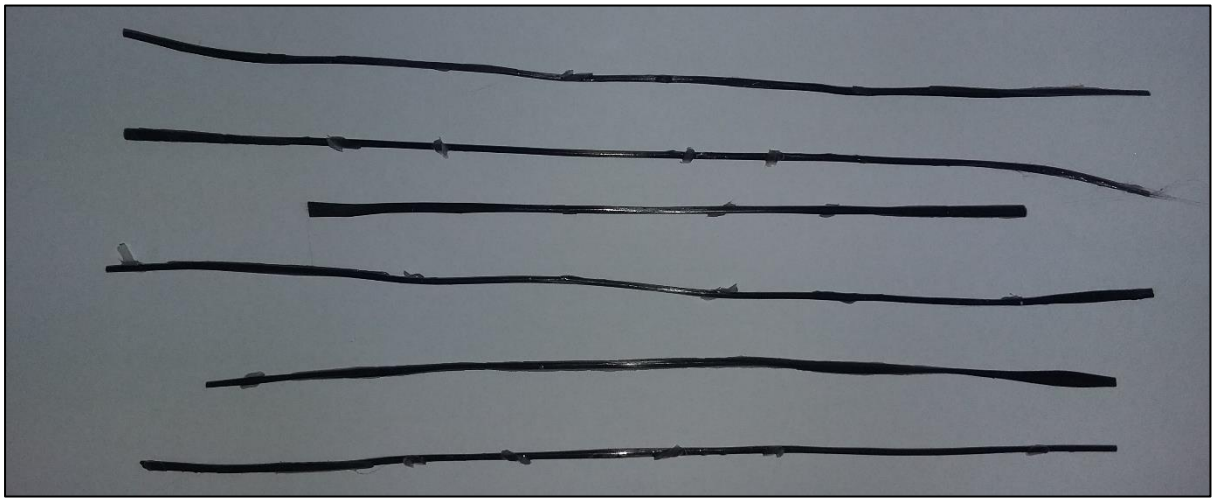

Figure 4-15 - Specimens Produced from Prototype 1.

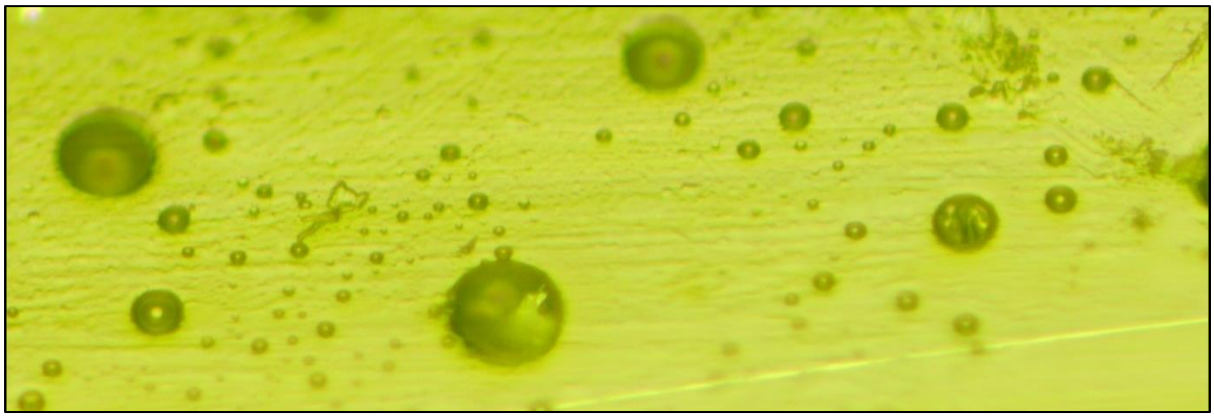

Figure 4-16 - Air Pockets within Prototype 1 Specimens.

4.1.6.2 Functionality

The second area for analysing the performance of Prototype 1 is the ease of which the prototype can go through the procedures mention in the previous section. This analysis includes analysing the ease of which the procedures can be executed, the ease of utilising the materials, the ease of creating the specimens of the composite filament and the ease of removing the resin after the specimens have been made.

4.1.6.2.1 Setup Procedure

In terms of functionality, the setup procedure has a few problems that needed to be addressed in future prototypes. The major problem with the setup procedure is feeding the carbon fibre yarn through Station 2 and Station 3. Feeding the carbon fibre yarn through the small holes in T-junction in Station 2 and the shaping dies and pressure rollers in Station 3 cause the carbon fibre yarn to fray and become very difficult to push through the holes. Devising a method for easing the feeding of the carbon fibre yarn through these holes without increasing the size of the holes will ease functionality without sacrificing the quality of specimens.

A secondary problem with the functionality of the setup procedure is the introduction of air pockets and possible impurities into the thermoset resin. Currently, the solution is mixed in a container by hand and this process could be adding air pockets into the thermoset resin. Additionally, the spray booth that the prototype is stored in when specimens are being made is introducing impurities into the thermoset resin. These air pockets and impurities will cause inconsistencies in the carbon fibre composite filament and needs to be addressed in future prototypes.

4.1.6.2.2 Production Procedure

In terms of functionality for the production procedure, there are two main issues that need to be addressed. The first issue is the lack of control over several of the key processes responsible for dictating the material properties for the composite filament, such as fibre volume fraction. The key processes that lack control are for controlling the flow of resin into the material junction and the speed that the carbon fibre yarn is fed into the material junction. Currently, these materials are controlled by hand, which decreases the consistency of material properties in the filament. Automating these processes will reduce the inconsistencies in the composite filament and will need to be implemented in future prototypes to solve these issues.

The second issue with the functionality of the production procedure is to do with the difficulty with pulling the carbon fibre yarn once it was coated in the resin. Currently, the composite filament is being pulled by hand with gloves and the resin makes it difficult to grip. This results in the filament being gripped tighter and the cross-sectional shape becoming rectangular rather than circular in areas that the filament has been gripped by hand. The issue of reducing the difficulty of pulling the composite filament through the various stations will need to be solved in subsequent prototypes.

4.1.6.2.3 Cleaning Procedure

The issue in terms of functionality for the cleaning procedure has to do with the speed at which the parts from different stations can be removed and cleaned in acetone. As this prototype utilises a two-part thermoset resin, the curing process starts once the two parts are mixed until the resin is cured completely. This means there is a fixed window to clean the parts before the parts can be clogged with resin. Increasing the ease of removing the parts from stations will reduce the chances of parts getting clogged in cured resin and should be addressed in future prototypes. Otherwise, acetone has proved suitable in removing the uncured resin from the aluminium components.

4.1.7 Prototype 1 – Conclusion

Prototype 1 was developed to develop designs for the processes required to create a composite filament using a thermoset resin and long/continuous fibre reinforcement up to the point before the resin would be cured. Overall, Prototype 1 has been able to create the composite filament with some of the desired material properties but there are definitive problems with the

specimens that are being produced and the functionality of Prototype 1 that need to be addressed in the next prototype. Subsequent prototypes will take the information garnered from Prototype 1 and improve the quality of specimens being produced and improve the functionality for producing the composite filament.

4.2 Prototype 2

Prototype 2 is the second prototype developed to produce a composite filament using long/continuous fibre reinforcement and a thermoset resin. As with Prototype 1, Prototype 2 has been developed based on identified processes required to produce the composite filament but has addressed some of the problems that became evident while producing composite filament specimens using Prototype 1. Sections of Prototype 1 have been altered or redesigned for Prototype 2 to improve the quality of specimens compared to specimens made using Prototype 1 and to improve the functionality for Prototype 2.

The aim of Prototype 2 is to determine some factors that improve the impregnation of the thermoset resin with the carbon fibre yarn and improve the fibre volume fraction. This is done by creating a range of composite filament specimens that have been made with alterations to the impregnation process. These specimens can then be analysed to determine certain factors for improving the desired composite filament material properties.

4.2.1 Prototype 2 - Overview

The design of Prototype 2 utilises some of the same processes that were used in Prototype 1 but with some alterations to the design of these processes. As with Prototype 1, Prototype 2 will have carbon fibre yarn pulled through a series of processes designed to create the composite filament with certain material properties. Prototype 2 will also utilise the same thermoset resins and carbon fibre yarn for creating specimens and these base materials will be controlled by hand. Additionally, Prototype 2 will only consist of the processes from the original flowchart up to just before the curing process.

4.2.2 Prototype 2 - Alterations

Despite the similarities between Prototype 1 and Prototype 2, Prototype 2 has undergone several alterations and the redesigning of sections to improve the properties of the produced composite filament. The alterations made to Prototype 2 are as follows:

- Vertical Impregnation Process
- Optimising Station 3 (Filament Post-Processing)
- Reduction in Prototype Footprint

4.2.2.1 Vertical Impregnation Process

The main alteration made to Prototype 2 from Prototype 1 is the change from a horizontal impregnation process to a vertical impregnation process. This entails positioning the spool of carbon fibre yarn above the impregnation process and pulling the carbon fibre yarn downwards through the impregnation process. The reasons behind making the alteration to the impregnation process is twofold. The first reason for making this alteration is to do with ensuring that the carbon fibre yarn is fully impregnated within the thermoset resin. Previous specimens made using Prototype 1 had inconsistent amounts of thermoset resin coating the carbon fibre. By making the impregnation process vertical, excess resin will flow out of the impregnation process and down the carbon fibre filament. As the resin flows down the filament, some of the resin will remain and coat the carbon fibre yarn that has not received enough resin. This alteration will help to ensure that the carbon fibre yarn is sufficiently coated in resin and therefore, increase the consistency in the material properties of the carbon fibre composite filament.

The second reason for altering the horizontal impregnation process to a vertical impregnation process for Prototype 2 is to reduce the chances of resin solidifying within the impregnation process. The horizontal impregnation process in Prototype 1 would result in a significant amount of the thermoset resin remaining and curing within aluminium block and connectors. This would require the cured resin to be removed after each set of specimens were made. The vertical impregnation process will allow the thermoset resin to flow out of the impregnation process and reduce the risk or at least reduce the amount of the thermoset resin curing within the impregnation process. This improvement in functionality will increase the number of specimens that can be made before the impregnation process will have to be cleared of resin.

4.2.2.2 Optimising Station 3 (Filament Post-Processing)

One of the other main alterations made to Prototype 2, that is not evident in Prototype 1, is the optimisation of the combination of pressure rollers and shaping dies for creating the composite filament. The optimal combination of pressure rollers and shaping dies is to have a shaping die at the start and end of the station with pressure rollers in between the shaping dies. Making specimens using Prototype 1 showed that the first component used for removing the excess resin will remove the most resin from the filament and is most likely to have a build-up in resin. As the shaping dies have fewer moving parts then the pressure rollers, the shaping dies are less likely to be damaged due to a build-up of resin and will be more suitable.

After the initial shaping die, Station 3 utilises a set of pressure rollers. The pressure rollers are useful for forcing the resin into the centre of the carbon fibre yarn by first flattening the filament and forcing the resin into the carbon fibre yarn. It is important that there is not too much resin coating the carbon fibre yarn when the filament is passed through the pressure roller as the excess resin will adhere to the pressure rollers and the build-up of resin will eventually cause the pressure rollers to stop rotating or stop the carbon fibre yarn from being able to pass through the pressure rollers.

The final component for Station 3 is a shaping die. The last component is responsible for dictating the cross-sectional shape of the carbon fibre composite filament before the filament is cured. As the chosen cross-sectional shape is circular, a shaping die with a circular hole for the filament to pass through will force the filament into a circular shape.

4.2.2.3 Reduction is Prototype Footprint

The other main alteration that was made to Prototype 2 is the reduction in the prototype footprint compared to Prototype 1. Prototype 2 has undergone significant reduction in the prototype footprint compared to Prototype 1. The design of Prototype 1 was to have separate stations that are connected to create a method for producing a carbon fibre composite filament. Prototype 1's design created a large and long prototype that was difficult to manoeuvre and required the filament and its base material to move more distance than required to achieve the desired task. Prototype 2 has removed the separate stations and combined them into a single station comprising of parts from the different stations in Prototype 1.

Other methods for reducing the footprint of Prototype 2 has been the introduction of the vertical impregnation process and removing the large spool of carbon fibre yarn and replacing it with a smaller spool. The implementation of the vertical impregnation process has reduced the horizontal floor space by utilising vertical floor space and thus decreasing the footprint of Prototype 2. The utilisation of a smaller spool of carbon fibre yarn has reduced the footprint required by reducing the size of the components needed to manage the spool. These changes combine to reduce the footprint of Prototype 2 to take the total dimensions for the footprint of Prototype 1 of approximately 825mm x 272mm x 200mm (Length x Width x Height) down to the footprint dimensions for Prototype 2 of approximately 250mm x 111mm x 300mm.

4.2.3 Prototype 2 – Stations

Although the design of Prototype 2 does not utilise separate stations that combine to create the means for producing the composite filament, like Prototype 1, Prototype 2 can still be split up into the stations depending on the purpose of components. Prototype 2 utilises the same processes utilised in Prototype 1, but alterations have been made to stations to improve the functionality and performance of all stations. The stations that make up Prototype 2 are listed below:

- Carbon Fibre Spool Management
- Impregnation Process
- Filament Post-Processing

Prototype 2 is designed to position each of the stations between a single set of walls. These walls are made from clear acrylic, instead of the MDF walls used in Prototype 1. Clear acrylic will assist with observing the performance of the different stations. Additionally, acrylic will not absorb the resin that the walls will contact during the process of creating the composite filament.

4.2.3.1 Station 1 – Carbon Fibre Spool Management

The first station for Prototype 2 is responsible for managing the spool of carbon fibre yarn and to ensure that the carbon fibre yarn does not become damaged when being passed onto subsequent stations. The change to using a smaller spool from a large spool for the source of the carbon fibre yarn has reduced the overall footprint of Prototype 2 but has required a new

design for Station 1. Figure 4-17 shows the new smaller spool of carbon fibre yarn that will be used for Prototype 2.

The new design for Station 1, shown in Figure 4-18, for controlling the smaller spool of carbon fibre yarn utilises a 3D printed insert, a magnet and a steel pin. The insert is designed be mounted onto a wall and to hold the spool in position while the carbon fibre yarn is used to make the composite filament. One end of the insert has a shaft that is inserted into the hole in the carbon fibre yarn spool. The shaft end of the insert has a hollow section for the steel pin to pass through and will stop the spool from falling off the insert but not stop the spool from rotating. The other end of the insert has a cavity for a magnet that will attract the steel pin and ensure that the pin does not fall out of the insert and subsequently, the spool from falling off the insert.

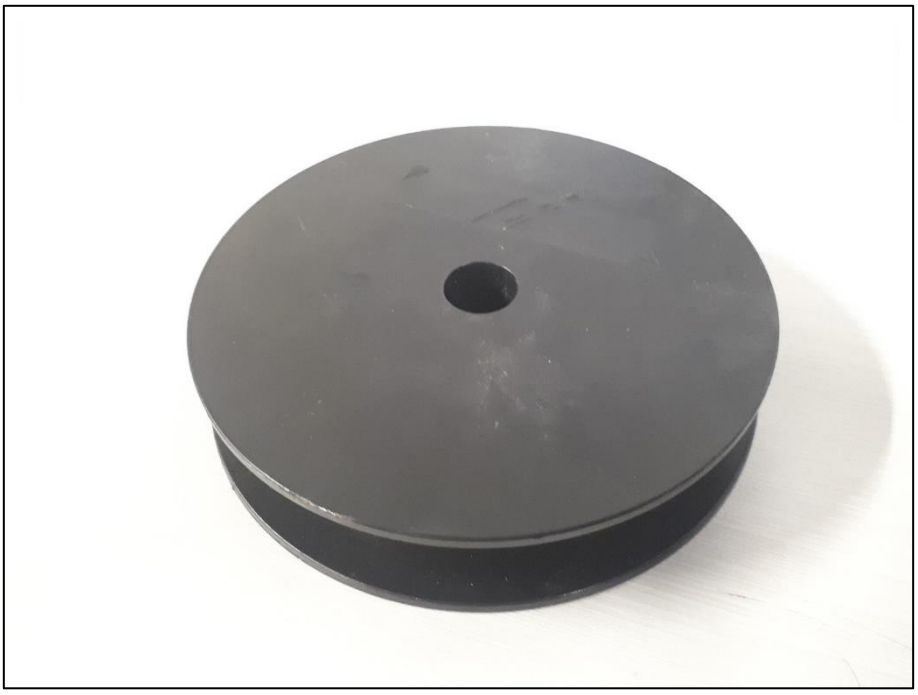

Figure 4-17 - Smaller Spool used in Prototype 2.

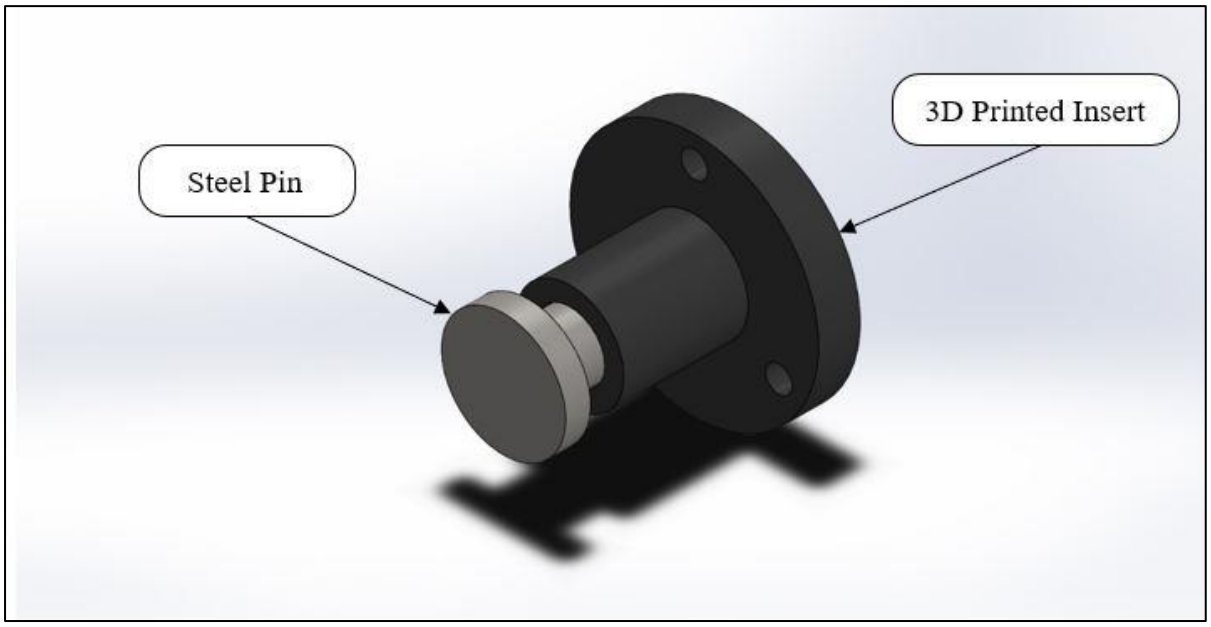

Figure 4-18 - CAD model of the Locking Mechanism for Station 1 of Prototype 2.

4.2.3.2 Station 2 – Impregnation Process

The design of Station 2 for Prototype 2 utilises similar components that were utilised in Prototype 2 and is responsible for combining the carbon fibre yarn and the thermoset resin into the composite filament. This station is important in dictating certain properties of the composite filament, including the fibre volume fraction. The main change for this station, compared to the station in Prototype 1, is the decision to make the impregnation process vertical. The vertical impregnation process utilises the same T-junction used in Prototype 1 but rotates the aluminium junction 90 degrees. This rotation results in the through hole, for the carbon fibre yarn to pass through, in the T-junction to be vertical and for the perpendicular hole, for the resin to enter the T-junction, to be horizontal. This change hopes to improve the consistency of the coating of resin onto the carbon fibre yarn.

There have also been some smaller alterations to Prototype 2 that are designed to improve the properties of the composite filament. One of the minor changes is that the inner diameter of the connectors for the T-junction have been decreased from 4mm to 2mm. The 2mm diameter for the connectors is close to the minimum diameter size that easily allows the carbon fibre yarn to pass through the connectors. The smaller diameter for the connectors is designed to reduce the amount of resin escaping the T-junction and ensure that the resin leaving the T-junction will mostly be in contact with the carbon fibre yarn. This will hopefully reduce the wastage of the thermoset resin and assist with ensuring that the carbon fibre yarn is fully coated in resin.

Another change to this station for Prototype 2 is the change in the through hole diameter for the aluminium block. In Prototype 1, the aluminium block has a through hole diameter of 4mm, but Prototype 2 will utilise a range of aluminium blocks with different through hole diameters. Five aluminium blocks, each with a different through hole diameter, have been made and will all be used to make the composite filament with the new connectors. Specimens will be made using the five aluminium blocks and the cross-section for these specimens will be analysed to determine some of the material properties of the specimens. This will determine what effect the through hole diameter has on the properties of the composite filament. The range of through hole diameters for the aluminium blocks are 2mm, 3mm, 4mm, 5mm and 6mm. Figure 4-19 shows all the aluminium blocks that will be used for creating specimens.

Regarding the inflow of the thermoset resin into the T-junction, a syringe will used to store the thermoset resin and the plunger will be used to force the thermoset resin through a tube into the T-junction. 3D printed mounts are used to mount the syringe vertically on one of the acrylic walls. Figure 4-20 shows the layout for Station 2, including the syringe being connected to the T-junction.

Figure 4-19 - Aluminium Blocks made for Prototype 2.

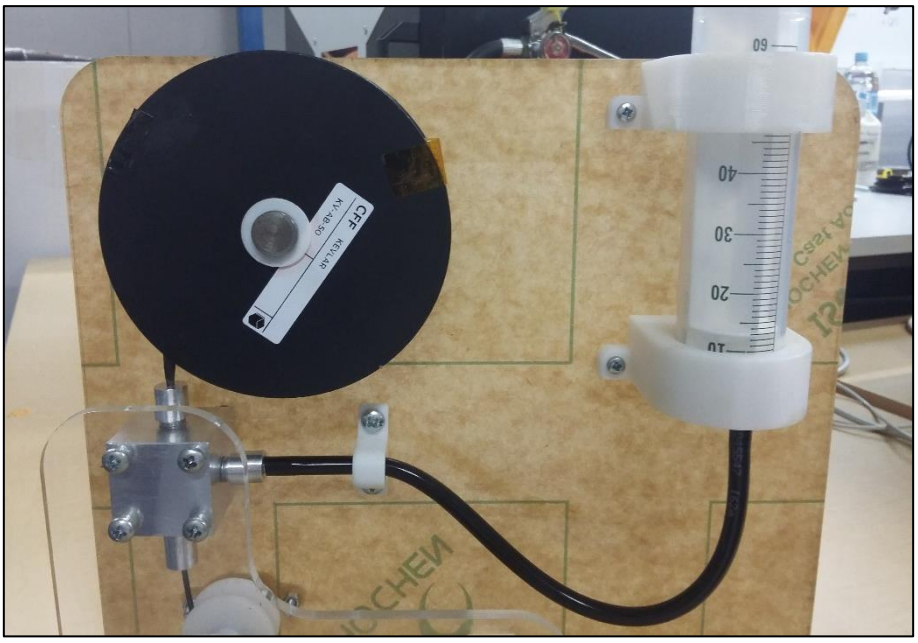

Figure 4-20 - Station 2 Layout for Prototype 2.

4.2.3.3 Station 3 – Filament Post-Processing

Station 3 for Prototype 2 is responsible for controlling the fibre volume fraction of the composite filament by removing the excess resin from the filament and for dictating the cross-sectional shape of the filament before the filament is cured. The design for Station 3 uses a design that is similar to the design used in Prototype 1 but utilises the combination of pressure rollers and shaping dies that perform optimally and that results in a circular cross-sectional shape. The combination utilised in this prototype starts with an initial shaping die to remove most of the excess resin followed by a set of pressure rollers to force the thermoset resin into all areas of the carbon fibre yarn and then a final shaping die to set the cross-sectional shape of the composite filament. Figure 4-21 illustrates the design used for Station 3.

With the implementation of the vertical impregnation process for Station 2 this has resulted in a few alterations for Station 3. One of the changes to the design for Station 3 is that the position of Station 3 to Station 2 is offset. The reason behind this change is that the vertical impregnation process will result in some of the excess resin removed from the composite filament falling directly below the T-Junction in Station 2. If the components for Station 3 are situated directly below Station 2, this will result in resin gathering on the components and possibly curing on the components. Having the cured resin on components, especially those with moving parts, can result in components not performing or becoming damaged. Therefore, a single nylon roller

is positioned below the T-junction in Station 2 to redirect the composite filament towards the offset Station 3. This roller allows for the redirection of the composite filament without putting too much stress on the fibre reinforcement.

After the single roller is used to redirect the composite filament from Station 2 to Station 3, the composite filament is redirected 45-degrees to the first shaping die. Having the die at a 45-degree angle reduces the possibility of the build-up of resin within the shaping die by allowing the resin to flow out of the bottom of the shaping die. Reducing the possibility of resin building up in the initial shaping dies is important as the initial die is responsible for removing most of the resin from the composite filament.

Following the initial shaping die, the composite filament continues the same orientation from the shaping die until it meets a set of pressure rollers. These pressure rollers have a 1mm gap between the rollers, are the same design as the pressure rollers used in Prototype 1 and are used to redirect the filament a further 45 degrees to a horizontal orientation. After the pressure rollers, the composite filament then passes through the final shaping die to force the composite filament into a circular cross-sectional shape.

Another small change to Station 3 is the design of the shaping dies. The shaping dies for Station 3 have been redesigned to improve the functionality of feeding the carbon fibre yarn through the shaping dies and for being cleaned after being used. The shaping dies used in Prototype 2 are made of aluminium rods that have a 1.5mm diameter countersunk through hole for the composite filament to pass through. The countersunk through hole assists with feeding the initial carbon fibre yarn through the shaping die and reduces the stress placed upon the carbon fibre yarn. The shaping dies are 10mm in length and are press-fit into 3D printed mounts to lock them in place. After being used, the shaping dies can easily be removed and placed in acetone to remove any residual resin.

A small change that was made to the design of the pressure rollers is the ability to move the top pressure roller. A small cut out has been made into both acrylic walls that allow for the top pressure roller to be moved. The ability to move the top pressure roller makes the process of feeding the carbon fibre yarn through the gap in the pressure rollers easier and reduces the chances of the carbon fibre yarn being damaged during this process. Once the carbon fibre yarn has been fed through the gap between the two pressure rollers, the top pressure roller can be moved back into place and locked in position.

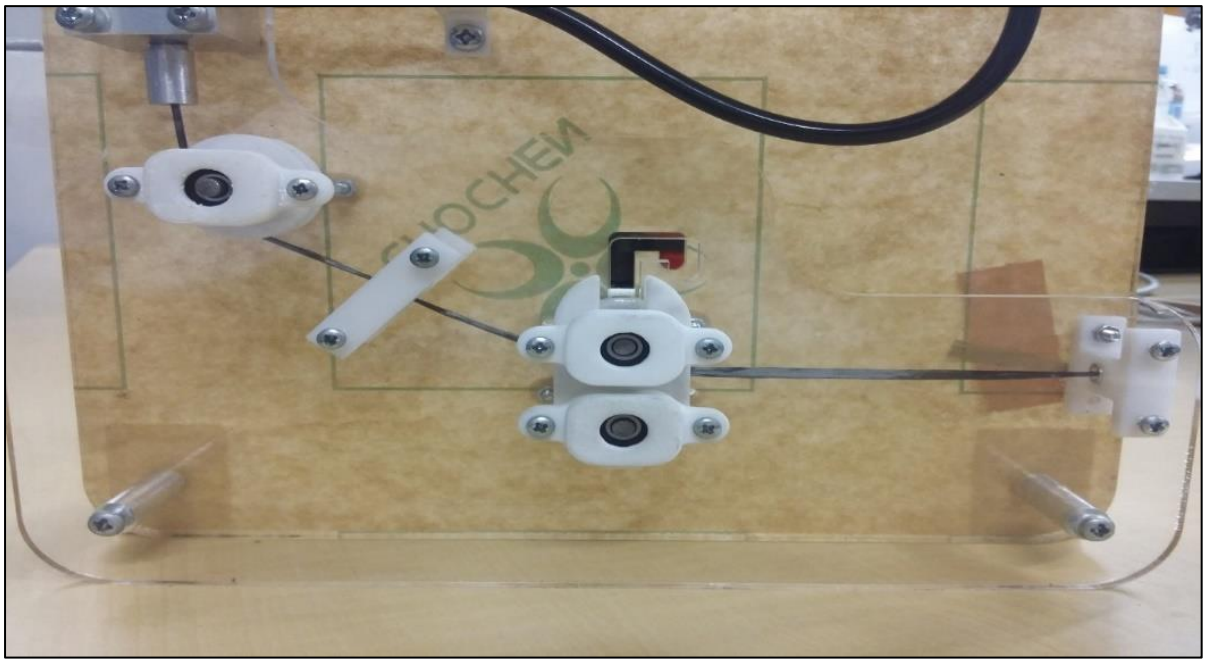

Figure 4-21: Station 3 Layout for Prototype 2.

4.2.4 Prototype 2 – Experimental

One of the main purposes of developing Prototype 2 is to determine the effect that altering the diameter of the through hole for the aluminium blocks has on the quality of the material properties for the composite filament. Therefore, a minimum of ten specimens were made using each of the five aluminium blocks using the same connectors. A secondary set of ten specimens made using the aluminium block with the 2mm diameter to be used for testing a few methods of preparing the specimens for analysis. It is important to note that these specimens were all made within a spray booth, which will impart impurities into the composite filament

All the specimens made using Prototype 2 were made using the same setup and testing procedure used in Prototype 1. Specimens were prepared and cut to roughly 100mm lengths using scissors and left to cure for over twelve hours. Unlike specimens made using Prototype 1, specimens for Prototype 2 were made and left to cure using a platform, shown in Figure 4-22, instead of being left to cure on a flat surface. The curing platform is designed to for the composite specimens to be draped on top of the platform with the ends of the specimens hanging freely over the sides. The platform would allow both ends of the specimens to be utilised for testing, provided that the ends of the specimens did not contact each other or the platform. The platform solves the problem of the thermoset resin pooling when place on a flat surface. Once all specimens had cured completely, the specimens were removed from the

platform and stored within labelled zip lock bags to correctly identify each set of specimens and reduce the chances of contamination.

For determining some of the properties of the composite filament made using Prototype 2, specimens would be subjected to a cross-sectional analysis using a scanning electron microscope (SEM). The SEM used for analysing the cross-section of the specimens is the Hitachi Tabletop Microscope TM3030 PLUS. Specimens were prepared for SEM analysis by fracturing the specimens into approximately 10mm length specimens and exposing the cross-section of the specimens for analysis. Once the specimens were fractured, the specimens were inserted into a custom-made stainless-steel 3D printed specimen stand. This specimen stand, shown in Figure 4-23, contains a five by five array of tapered holes for the specimens to be inserted into for analysis. This allowed for 25 specimens to be analysed at one time without having to remove each specimen from the SEM. The tapered holes in the specimen stand allow specimens to stand vertically regardless of the differences in diameter of the specimens.

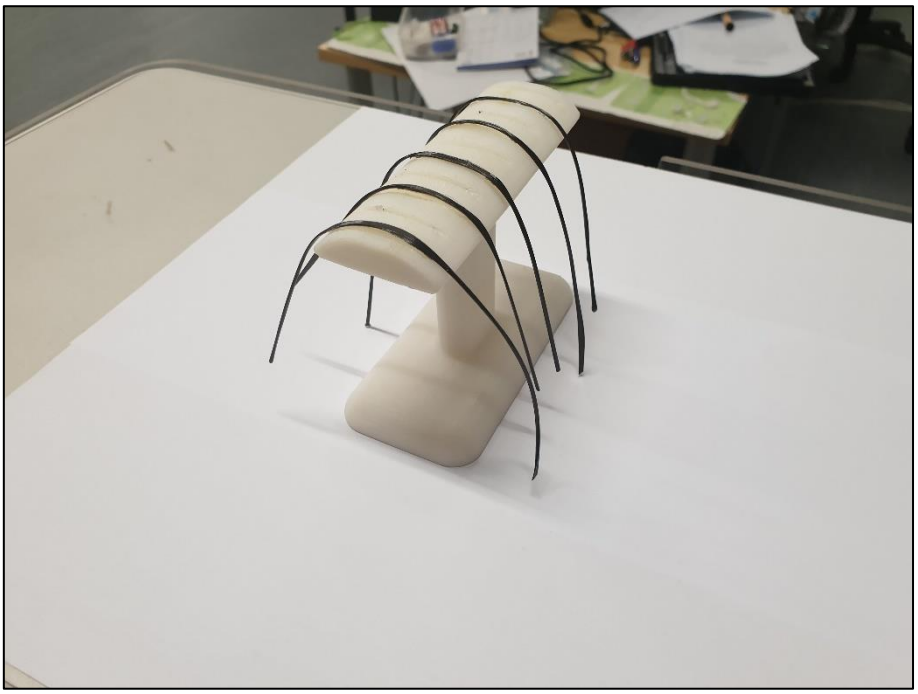

Figure 4-22 - Platform used to make Specimens for Prototype 2.

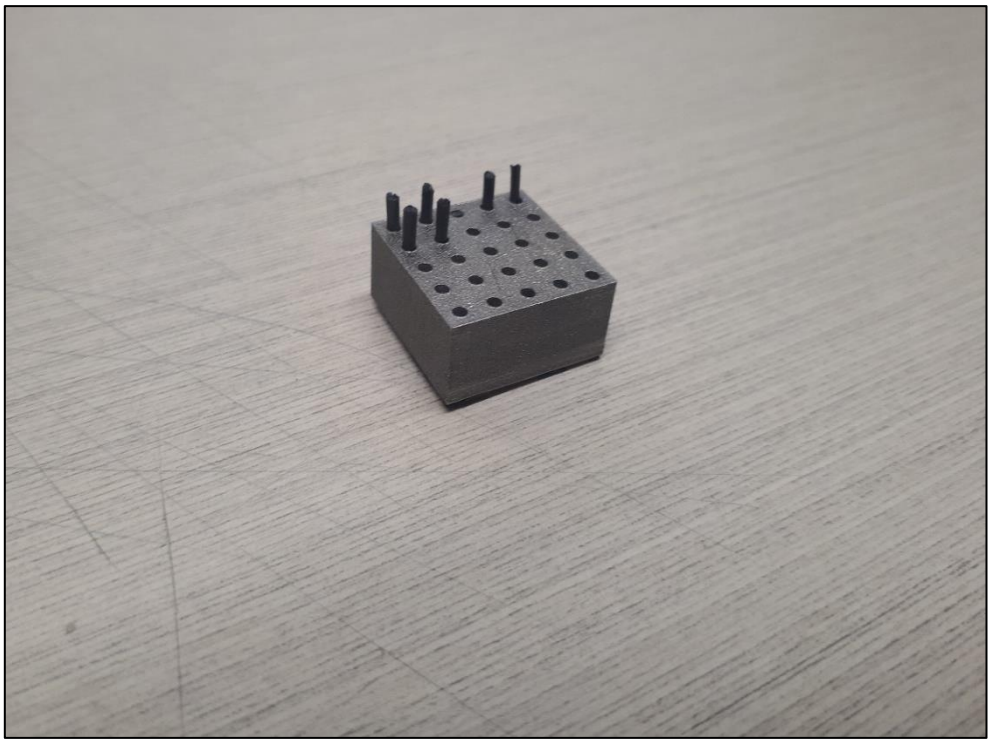

Figure 4-23 - 3D Printed Specimen Stand.

There were two methods that were utilised to fracture the composite filament specimens for cross-sectional analysis using the SEM. Both methods will be used to prepare specimens for the SEM and will be analysed to determine which method performs better by analysing the cross-sectional surface of the specimens made using the aluminium block with the 2mm diameter through hole. The method that produces the more suitable specimens for analysis will be used to fracture the remaining specimens for each of the different through hole diameters for the aluminium blocks.

The first method for fracturing the composite filament specimens involved clamping the specimens in place and utilising a scalpel to cut through the specimens to create approximately 10mm length specimens. For this method the specimens made using Prototype 2 were inserted into a different 3D printed stainless steel specimen stand, shown in Figure 4-24, to hold them in place and then the scalpel was used to cut through the specimens. This method was chosen instead of using cutting tools, such as a wire cutter, as these will create a cross-sectional surface that is crimped. The crimped surface will inhibit any cross-sectional analysis and provide little information regarding the internal structure of the specimens.

The second method for fracturing the specimens involved subjecting the specimens to liquid nitrogen for a set period, removing the specimens from the liquid nitrogen and snapping the specimens as quickly as possible before the specimens had time to heat up. Specimens were submerged in liquid nitrogen for a period of ten minutes and were quickly removed and inserted into the second stand before the specimen could heat up. Figure 4-25 shows a sample being inserted into the specimen stand before being snapped. If the process of inserting a specimen took too long, the specimen was placed back into the liquid nitrogen for an additional five minutes. This method was chosen as a possible improvement over using the scalpel due to this method fracturing the specimen in one clean break. Using the scalpel to cut through the specimens could result in the cross-sectional surface becoming damaged or marred due to the multiple number of strokes required to cut through the specimens.

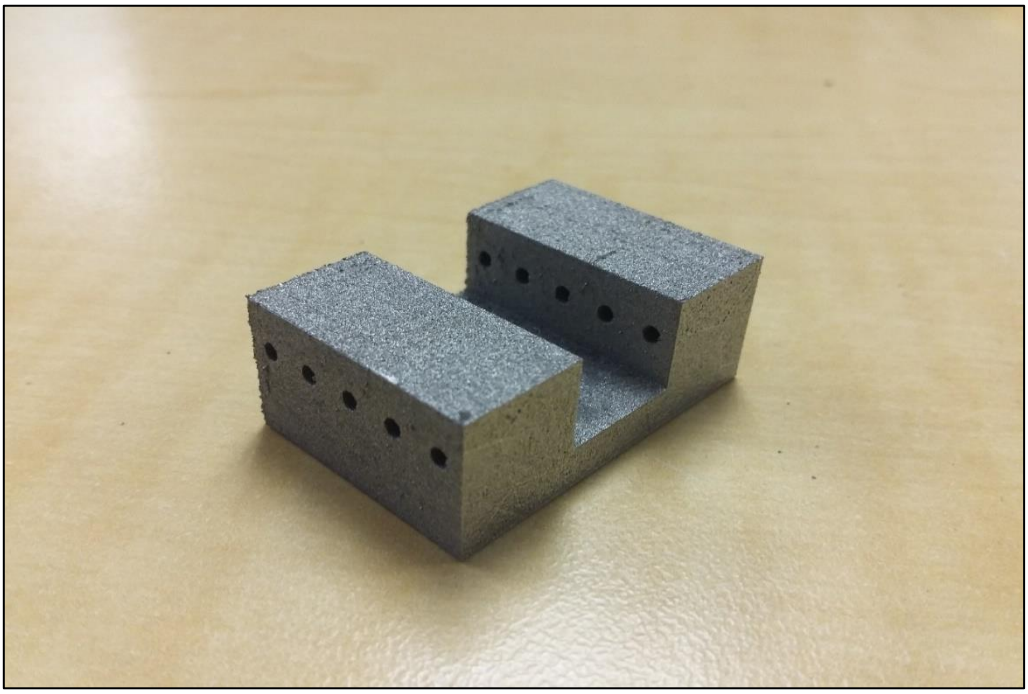

Figure 4-24 - The Second 3D printed Specimen Stand.

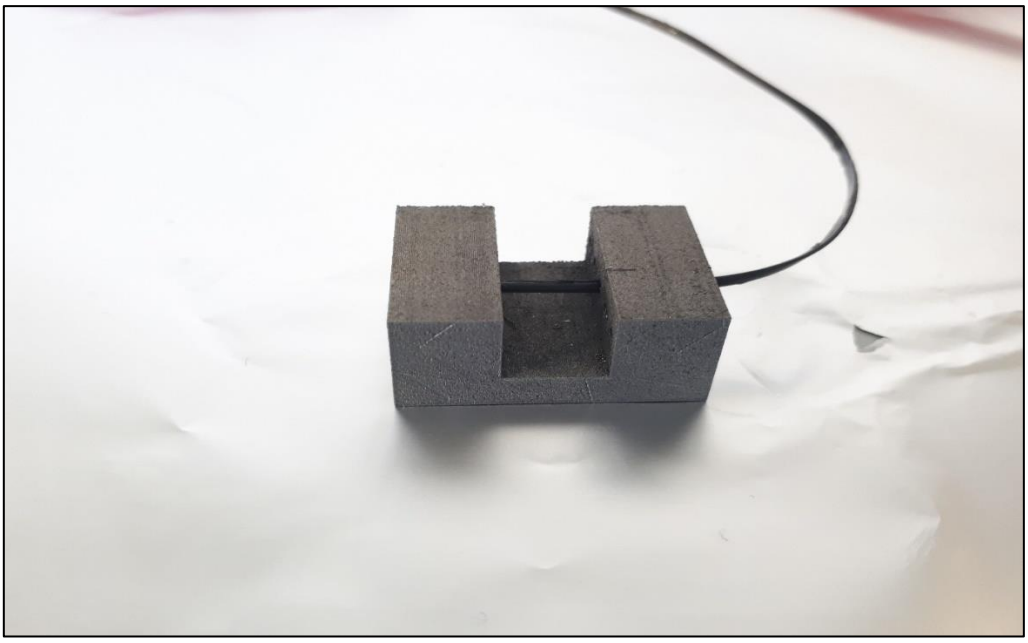

Figure 4-25 - A Composite Filament Specimen Inserted into the Second Specimen Stand.

4.2.5 **Prototype 2 – Results & Discussion**

The results for the SEM analysis of the composite specimens can be split into two key sets of results. The first set of results are for identifying the best performing method for fracturing the specimens. The second set of results will be analysing the cross-sectional surface of the specimens made using the five different aluminium blocks, which have been fractured using the best performing fracture method. This will determine the effect the size of the through hole diameter has on the properties of the specimens.

A secondary area of analysis for Prototype 2 is the effect on functionality of using the prototype. Several of the stations have been redesigned or have had components added and need to be analysed. The analysis of these stations will assist with the development of Prototype 3 or the overall process for producing the composite filament.

4.2.5.1 Fracture Method Analysis

The first set of results from the cross-sectional analysis of specimens made using Prototype 2 is to determine the method that is better suited for fracturing the composite filament specimens for the SEM. The cross-section of specimens made using each method will be analysed based on the quality of specimens generated using each fracture method to determine how the remining set of specimens will be fractured for analysis. A focus on analysing the performance

will be the ease of which the SEM will be able to distinguish the different phases of the materials used to create the composite filament.

After analysing the cross-sections of specimens made using both fracture methods, the fracture method utilising the liquid nitrogen was deemed to provide specimens that were better suited for cross-sectional analysis. The liquid nitrogen fracture method was able to distinguish between the two phases of the composite filament better than that of specimens prepared using a scalpel fracture method.

4.2.5.1.1 Scalpel Method Specimen Analysis

Analysis of the cross-sections of specimens that were prepared using the scalpel fracture method shows that there are problems with using this method for fracturing specimens. Figure 4-26 shows an example of the cross-sectional analysis of a specimen prepared using the scalpel fracture method using the SEM. The image does not clearly distinguish between the reinforcement phase, the carbon fibre yarn, and the matrix phase, the thermoset resin, for the composite filament.

There are a couple of positives when analysing the cross-section of the composite filament specimens created using the scalpel fracture method. One of the positives is that the thermoset resin has penetrated to all areas of the composite filament. If the resin was not reaching all areas within the composite filament, this would be an area of weakness and would require the process of combining the carbon fibre yarn and thermoset resin to be redesigned. An additional positive for analysing the cross-section of the scalpel fracture method specimens is that the specimen is clearly circular in shape which shows that the last shaping die in Station 3 is functioning properly.

4.2.5.1.2 Liquid Nitrogen Method Specimen Analysis

Analysis of the cross-section of specimens prepared using the liquid nitrogen fracture method are better suited for SEM analysis as the different phases for the composite filament specimens are easily distinguishable compared to specimens made using the scalpel fracture method. Figure 4-27 shows an image of the cross-section for a specimen made using the liquid nitrogen fracture method. The image clearly shows the location of carbon fibres within the composite filament specimen and shows that the thermoset resin is reaching all areas within the composite filament.

Further analysis of the image of the cross-section of multiple specimens shows several promising material properties for the composite filament specimens. One of the most important material properties for the composite filament is the fibre volume fraction. Analysing the cross-section of specimens shows that the carbon fibre yarn is situated throughout all areas within the composite filament but there is still a protective layer around the outer circumference of the composite filament. These findings suggest that the fibre volume fraction for the composite filament is fairly suitable but further analysis is required before this can be confirmed.

There are a few concerns with the analysis of cross-section for specimens prepared using the liquid nitrogen fracture method. Foremost amongst those concerns are the cracks that appear in the cross-section of specimens subjected to liquid nitrogen but are not apparent in the cross-section of specimens prepared using a scalpel. Whether these cracks were within the composite filament prior to being subjected to the liquid nitrogen fracture method or were created during the liquid nitrogen fracture method is unclear. Nevertheless, these cracks can provide some insight into the bonding of the carbon fibre yarn and thermoset resin, as shown in Figure 4-28.

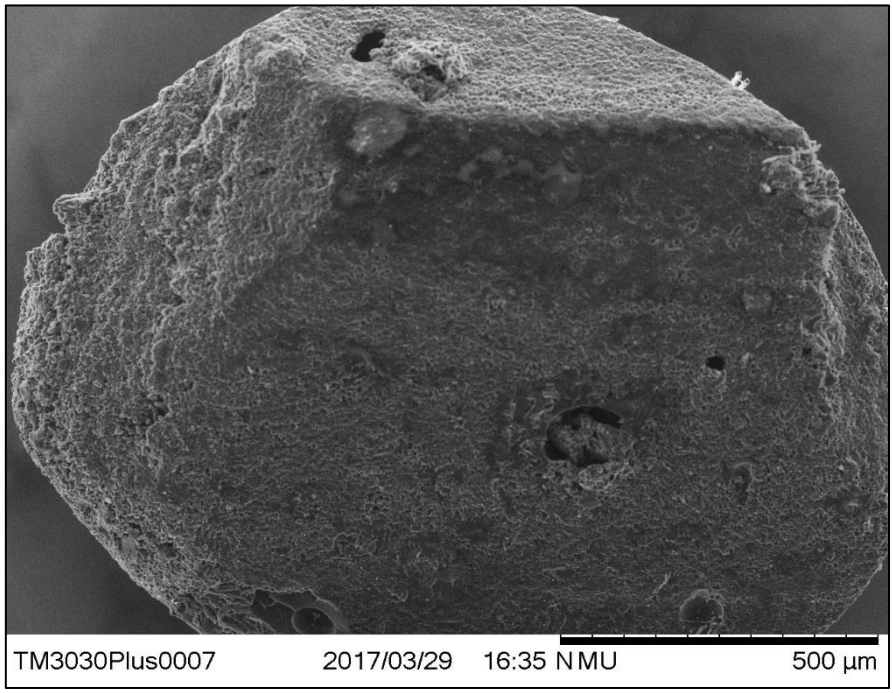

Figure 4-26 - SEM Analysis of the Cross-section for a Composite Filament Specimen.

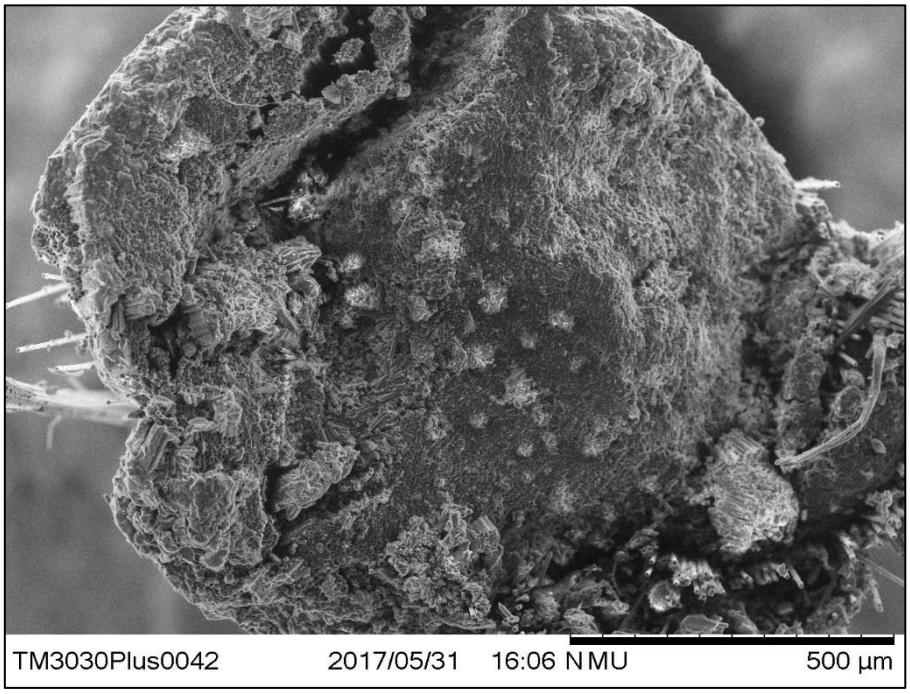

Figure 4-27 - SEM Cross-section Analysis of a Specimen Broken using Liquid Nitrogen.

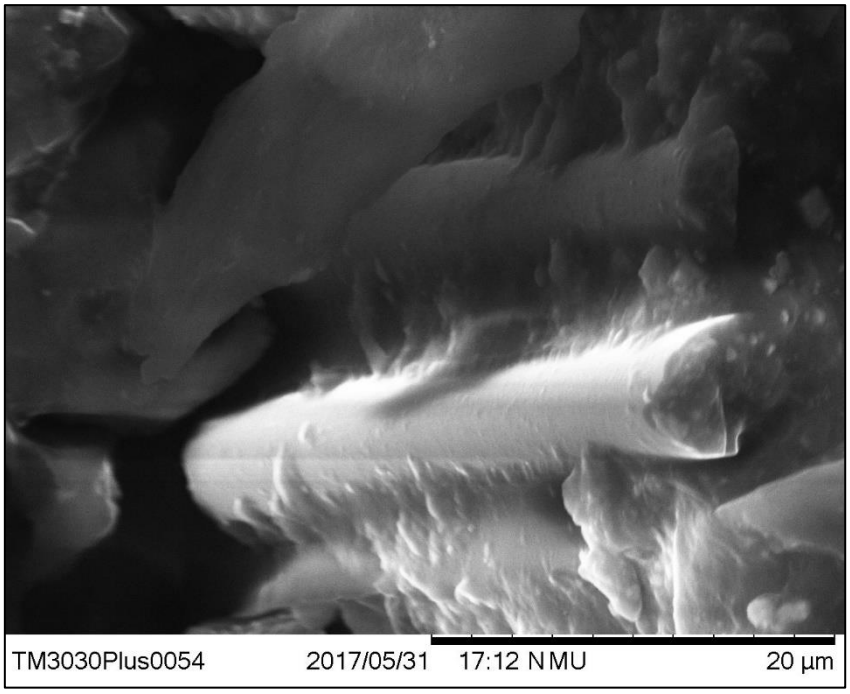

Figure 4-28 - SEM Analysis of the Interfacial Bonding for a Composite Filament Specimen.

4.2.5.2 Through Hole Diameter Analysis

One of the aims of Prototype 2 was to analyse the effect that altering the through hole diameter for the T-junction would have on the material properties of the composite filament specimens. The cross-sections of specimens made using different through hole diameters for the T-junction were subjected to SEM analysis to determine this effect. A minimum of ten specimens, for each through hole diameter were subjected to the liquid nitrogen fracture method and were analysed using the same stainless-steel stand.

The results from the SEM analysis of the cross-sections of specimens made using different through hole diameters for the T-junction are quite clear. Specimens predominantly exhibited similar characteristics regardless of the through hole diameter. All specimens exhibited the circular cross-sectional shape, that the thermoset resin was reaching all areas within the composite filament and that the carbon fibre yarn was evident in most areas within the composite filament. Figure 4-29 and Figure 4-30 are examples of the cross-sections of specimens made using different through hole diameters.

Analysing the cross-sections for the specimens made using the different through hole diameters provides some conclusions that can be utilised for the development of the next prototype for producing the composite filament. There appears been little to no difference between the specimens prepared using the different through hole diameters. The analysis of the cross-sections showed that all through hole diameters were able to produce specimens that had cross-sections that were not devoid of the thermoset resin. Additionally, the through hole diameters were able to fully encapsulate the carbon fibre yarn and bond onto the carbon fibres. Therefore, the current impregnation process can produce the composite filament with some of the desired properties, but steps can be taken to increase the consistency of the impregnation process.

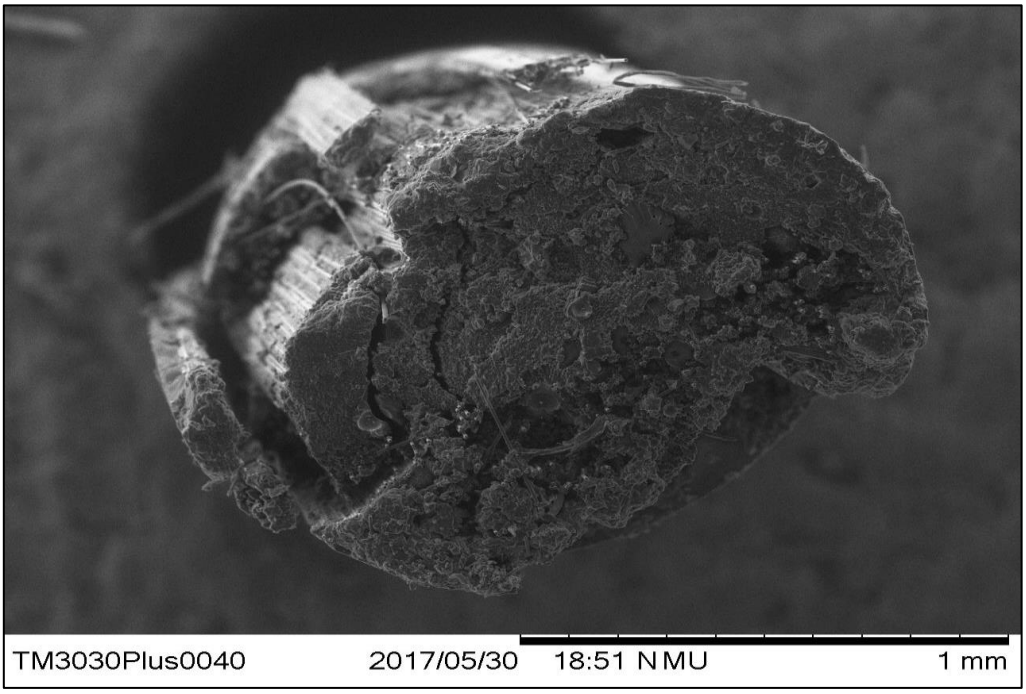

Figure 4-29 - SEM Analysis of a Composite Filament Specimen made using a 2mm Diameter Through Hole.

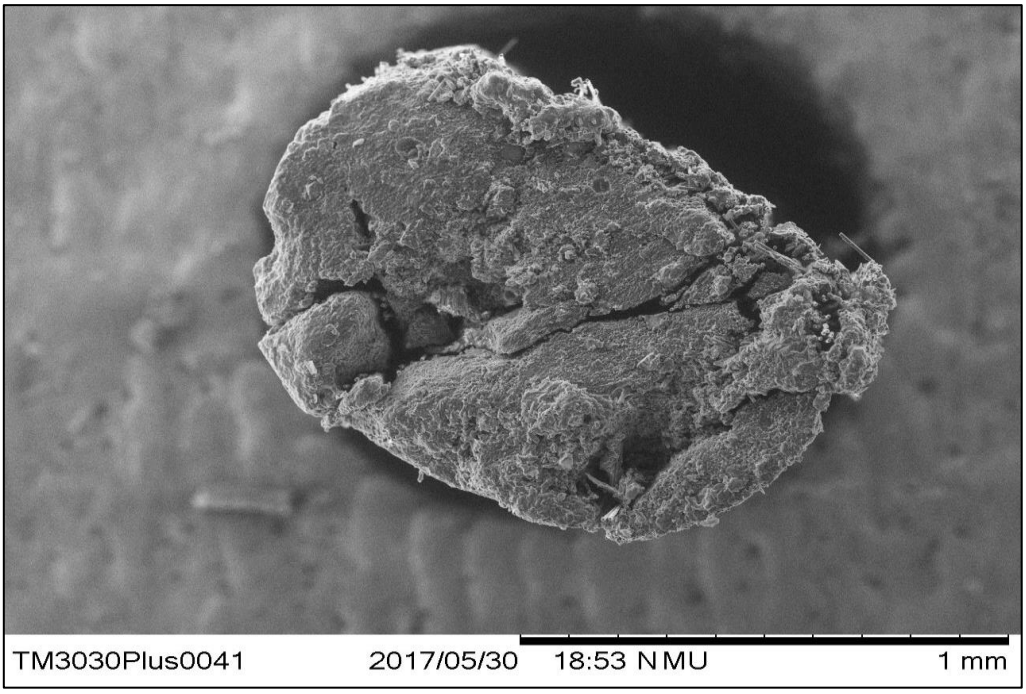

Figure 4-30 - SEM Analysis of a Composite Filament Specimen made using a 3mm Diameter Through Hole.

4.2.5.3 Functionality

Analysing the functionality of Prototype 2 is useful in determining the changes needed for the development of Prototype 3. The functionality of Prototype 2 can be determined by analysing some of the problems with the setup, production and cleaning procedures when producing the composite filament using Prototype 2. Additionally, analysing the effect of the alterations made to the designs for processes in Prototype 2 can aid in the development of Prototype 3.

4.2.5.3.1 Setup Procedure

The setup procedure for Prototype 2 involves preparing and storing the thermoset resin and feeding the carbon fibre yarn through the T-junction, shaping dies and pressure rollers. One of the main difficulties with Prototype 1 was feeding the carbon fibre yarn through the T-junction, shaping dies and the pressure rollers. The problem of feeding the carbon fibre yarn through the pressure rollers was made easier by redesigning the pressure rollers so that the top roller could be raised to allow the carbon fibre yarn to be feed through the gap in the rollers. A solution for assisting with feeding the carbon fibre yarn through the T-junction and the shaping dies has not yet been found.

Some of the other alterations to Prototype 2 that made conducting the setup procedure easier was the reduction in the overall footprint of Prototype 2 and utilising a small spool for the carbon fibre yarn spool. With Prototype 2 being so much smaller than Prototype 1 and having a smaller spool of carbon fibre yarn, handling and feeding the carbon fibre yarn through the smaller holes and gaps in the T-junction, shaping dies and pressure rollers was easier.

There are still some problems with the setup procedure for Prototype 2. Foremost amongst these problems is the introduction of impurities and air pockets into the composite filament. As with Prototype 1, Prototype 2 produced specimens while in a spray booth for health and safety reasons. Producing specimens within these conditions imparts the impurities into the thermoset resin and thusly, the composite filament. The air pockets are introduced into the thermoset resin while mixing the thermoset resin and the catalyst together. Removing these air pockets prior to being introduced into the composite filament will need to be addressed for Prototype 3.

4.2.5.3.2 Production Procedure

The procedure for producing the composite filament using Prototype 2 is the same production procedure as Prototype 1 but the alterations made to some of the designs has improved some aspects of this procedure. One of the main improvements has been the vertical impregnation process. The vertical impregnation process has resulted in the excess resin leaving the T-junction traveling down the carbon fibre yarn and ensures that the carbon fibre yarn is enclosed within the thermoset resin. Therefore, the vertical impregnation process has increased the consistency of the cross-section for the composite filament specimens.

Some of the small improvements to Prototype 2 are the mounting of the syringe, the combination of the shaping dies and pressure rollers and the smaller carbon fibre spool. These small improvements have improved controlling the inflow of the thermoset resin, the feed speed of the carbon fibre yarn and the material properties of the composite filament.

The main problem with the production procedure for Prototype 2 is the lack of automation. The lack of automation makes controlling the feed speed of the carbon fibre yarn and the inflow of the thermoset resin difficult and can introduce variance into the material properties of the composite filament. Automating the inflow of the thermoset resin and the feed speed of the carbon fibre yarn will need to be integrated into the design for Prototype 3.

4.2.5.3.3 Cleaning Procedure

The cleaning procedure for Prototype 2 has been improved with the implementation of the changes in the design of the different processes. The vertical impregnation process has reduced the build-up of resin within the T-junction and has made removing the build-up of resin easier. Additionally, with Station 3 being offset from being directly below the T-junction in Station 2, this has limited the amount of excess resin passing from the T-junction to the pressure rollers and shaping dies.

One of the minor alterations that have assisted with easing the cleaning procedure for Prototype 2 includes redesigning the shaping dies to be made from aluminium rods. Submerging the aluminium shaping dies in acetone easily removes the build-up of resin.

4.2.6 Prototype 2 – Conclusion

Prototype 2 was developed to improve upon the designs utilised by Prototype 1 to produce the composite filament before being subjected to the curing process. The main areas of improvement for Prototype 2 were an improvement in terms of the quality and consistency of the composite filament being produced and improving the functionality of using the prototype to create the composite filament.

One of the aspects of improving the designs for Prototype 2 was to analyse the effect that altering the through hole diameter for the T-junction would have on the quality of the composite filament being produced. By creating various specimens using the different through hole diameters and analysing the cross-sections, the performance of Prototype 2 and the different through hole diameters could be analysed. The findings from this analysis suggest that there is little to no effect on certain material properties of the composite filaments by altering the through hole diameter. The findings do suggest that the current set of designs for Prototype 2 can produce the composite filament with some of the desired material properties.

Overall, Prototype 2 has improved the quality of the composite filament specimens generated and the functionality for producing the composite filament specimens. The main concern with Prototype 2 is the lack of automated control over the handling of the base materials and the effect this has on the quality and consistency of the composite filament. Additionally, Prototype 2 does not handle the curing process for solidifying the composite filament and this needs to be developed in future prototypes. Prototype 3 will be developed to allow for automated control over the base materials and develop the curing process for the composite filament.

4.3 Prototype 3

Prototype 3 is the final prototype for designing a manufacturing process capable of producing a composite filament that comprises of long/continuous reinforcement and a thermoset resin and that is a suitable for AM applications. Prototype 3 is designed to utilise the best components from Prototype 1 and Prototype 2 and introduces a control system to automate several of the processes that were previous controlled by hand. The main aims of this prototype are to develop an autonomous platform that can produce a composite filament and for the prototype to allow for certain parameters to be altered during the production of the filament to help determine the optimal parameters.

4.3.1 Prototype 3 Key Alterations

The development of Prototype 3 included several of the best performing processes utilised in previous prototypes, but most of the design used for Prototype 3 utilises new processes that are focussed on providing an autonomous solution for producing the composite filament. These new processes are based on the utilisation of a control system designed to provide better control over certain aspects of the processes and producing a composite filament that has more consistent properties compared to the composite filament produced using previous prototypes.

The key alterations made to Prototype 3 that are not apparent in previous prototypes include, but are not limited to, the following:

- Implementation of a control system.
- Utilisation of a UV-curable resin.
- Control of the flow of resin and the feed of carbon fibre yarn.

Each of the key alterations made to Prototype 3 are designed to improve upon the performance shown in previous prototypes and thusly, has had a significant effect in the overall design of Prototype 3. Each key alteration made to Prototype 3 will be discussed in detail to explain the reasoning behind each of the alterations and the effect each alteration had on the design of Prototype 3.

4.3.1.1 Implementation of a Control System

The most important new alteration that was made to Prototype 3 is the implementation of a control system. The control system has been implemented into Prototype 3 to improve the consistency of the processes for producing the composite filament. Previous prototypes had some processes that were controlled by hand, which had a negative effect on the quality of the filament produced and the consistency of the material properties for the composite filament.

Improvements in the consistency of the process in the production of the carbon fibre composite filament and the material properties of the filament is achieved by utilising a control system to control the key processes that dictate the material properties of the filament. The key processes that have been designed to improve the consistency of Prototype 3 include: controlling the flow of the thermoset resin, controlling the feed of carbon fibre yarn throughout the prototype and controlling the curing of the thermoset resin within the filament.

An additional benefit of implementing a control system into Prototype 3 is the ability to alter certain parameters responsible for determining the material properties of the composite filament. This ability to alter certain parameters allows for testing to be conducted on filament specimens made using different combinations of parameters to help determine the optimal combination of parameters that provide a filament that exhibits consistent material properties. Additionally, the effect that changes in the different parameters have on the material properties can be analysed.

4.3.1.2 Utilisation of a UV-Curable Resin

One of the key alterations made to Prototype 3 is the utilisation of a UV-curable resin for the matrix phase of the composite filament. Previous prototypes utilised a two-part epoxy or polyester thermoset resin that was designed to cure completely after a period. Previous prototypes exhibited little control over when the resin cured and the method for stopping the resin from curing completely was to store the resin at low temperatures. This lack of control over the curing of the resin introduced the risk of the thermoset resin curing midway through the production of the composite filament and possibly having the resin used for the matrix phase of the composite filament being too rigid to be useful for AM applications.

The main reasoning behind changing from a two-part thermoset resin to a UV-curable resin is that the UV-curable resin provided a better method for controlling when the resin is cured and how much the resin is cured. By controlling the source of UV-light that contacts the UV-curable resin, the risk of the UV-curable resin curing midway through the production process can be reduced. Additionally, being able to control the source of UV-light also allows for control over the duration that the resin is exposed to UV-light and will allow for testing to be conducted on the optimal duration that the resin is exposed to the UV-light to produce a composite filament suitable for AM applications.

The change from using the two-part thermoset resin for Prototype 1 and Prototype 2, to using a UV-curable resin for Prototype 3 did have a significant effect on the overall design of Prototype 3. As the resin used for the matrix phase of the composite filament could be cured using UV-light, it is important that no external sources of UV-light are able to contact the resin. Failure to ensure that the resin is not exposed to external sources of UV-light increases the risk of the resin curing midway through the processes and could either damage parts of Prototype 3 or cause the filament's material properties being unsuitable for AM applications. Therefore, Prototype 3 has been designed as a single enclosed unit to ensure that the resin is not exposed to external sources of UV-light. Additionally, the source of UV-light used in Prototype 3 has been designed to be enclosed to a specific area within the enclosed unit to ensure that the UV-light does not accidently contact the resin outside of the predetermined area for the curing process.

One of the additional benefits of Prototype 3 being designed as a single enclosed unit is that this will limit the possibility of external impurities contacting the thermoset resin and residing within the composite filament. The problem of impurities being found within the composite filament has been apparent in the previous two prototypes and this single enclosed unit design will aid in removing this problem.

4.3.1.3 Control of the Flow of Resin and the Feed of Carbon Fibre

The final alteration made to Prototype 3 is the inclusion of methods to control the flow of the thermoset resin and the feed speed of the carbon fibre yarn into the process of making the composite filament. Previous prototypes controlled the flow of thermoset resin and the feed speed of the carbon fibre yarn manually and this introduced inconsistencies within the material properties of the composite filament.

The ability to control the base materials combining to create the composite filament has had a significant impact on the design for controlling the thermoset resin for Prototype 3. Previous designs for controlling the flow of thermoset resin were based on manually controlling a syringe to force the thermoset resin into contact with the carbon fibre yarn. The new design for controlling the thermoset resin must involve a method to automatically control when the thermoset resin can flow as well as control the speed and pressure that the resin contacts the carbon fibre yarn.

The development of a method to control the speed at which the carbon fibre yarn is passed through the required processes to create the composite filament had an impact on the design of Prototype 3. The previous design for controlling the speed of the carbon fibre yarn was to pull the carbon fibre yarn manually through the required processes. This design resulted in inconsistent material properties for the composite filament. The new design for controlling the carbon fibre yarn must be able to consistently control when the carbon fibre yarn is pulled through the processes and the speed that the carbon fibre yarn is pulled through the processes.

4.3.2 Prototype 3 Overview

Prototype 3 is designed to be an autonomous process that allows for the control of certain parameters during the production of the composite filament for use in AM applications. The alterations made to Prototype 3 has introduced processes that were not evident in previous prototypes but introduces a method for controlling the processes that have a direct effect on the material properties of the filament. Figure 4-31 shows a CAD model, made using SolidWorks, for Prototype 3.

Prototype 3 has been designed to incorporate a range of processes and combines them to create an autonomous process for creating a composite filament. All the processes will be discussed in detail below to explain the design process for each process and how each process functions. The processes incorporated for Prototype 3 are as follows:

- Frame.
- Carbon Fibre Spool Management.
- Resin Flow Control.
- Impregnation Process.
- Curing Process.
- Control System.

The layout for Prototype 3, shown using a diagram in Figure 4-32, is based on creating a linear set of processes within the confines of the frame to create a single enclosed unit. The diagram shows that the only section that is outside the confines of the frame is the ‘Resin Flow Control’ section. The reason behind having this section outside the frame is that this design allows for the flow of the resin to be adjusted at any time. If the other sections were situated on the outside of the frame, this would result in the problem, shown in previous prototypes, of impurities being apparent in the composite filament.

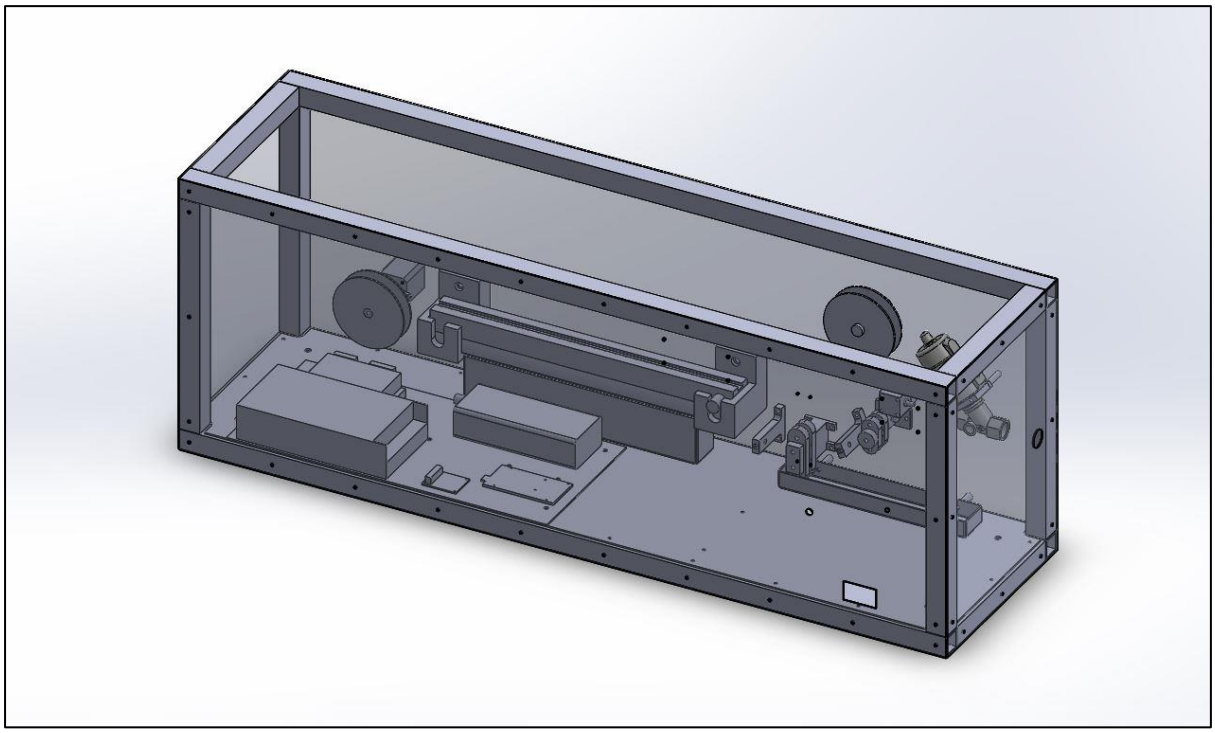

Figure 4-31 - CAD Model of Prototype 3.

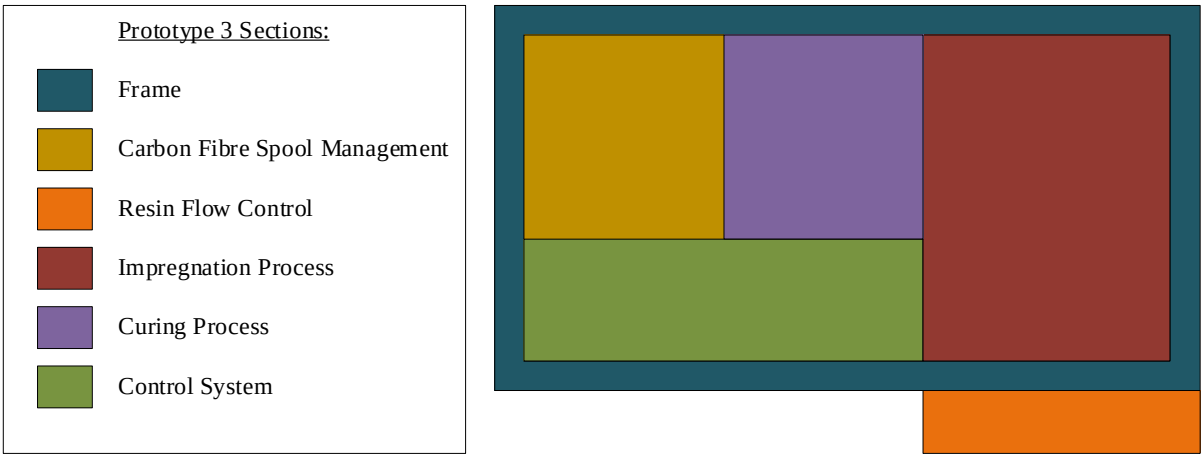

Figure 4-32 - A Diagram of the Sections in Prototype 3.

4.3.2.1 Frame

Prototype 3 is designed as a single an enclosed unit designed to utilise a UV-curable resin and carbon fibre yarn to produce a composite filament. A key component for creating this enclosed unit for Prototype 3 is the design of the frame. The frame is designed for two purposes. The first purpose is for creating the enclosed space to ensure that UV-light from external sources does not reach the UV-curable resin used for the matrix phase of the filament. The second purpose is to create a sturdy frame upon which the components used for key processes can be mounted securely.

The design for the frame for Prototype 3 is based on creating a suitably sized enclosed space to house the different components for the different sections, provide a means for mounting each of the components securely and ensure that no external sources of UV-light can reach within the enclosed space. The design for Prototype 3, shown using a CAD model in Figure 4-33, comprises of various lengths of aluminium square tube that are welded together to create a box shaped structure. The overall dimensions for this structure are 1100mm x 300mm x 400mm (length x width x height) and consist of a total length of 7200mm of the aluminium square tube. The breakdown of the lengths of aluminium square tube are shown in Table 4-2 and the dimensions for the aluminium square tube are shown in Figure 4-34.

The frame for Prototype 3 is designed for holes to be positioned periodically along the length of each section of aluminium square tube. These holes are situated on the surfaces of the square tube that will be facing the outer surface of the frame and are designed to allow sheets of material to be mounted onto the outer surfaces of the frame. Mounting these sheets of material will stop the possibility of external sources of UV-light from reaching the confines within the frame and will also provide a method for mounting the different components in place.

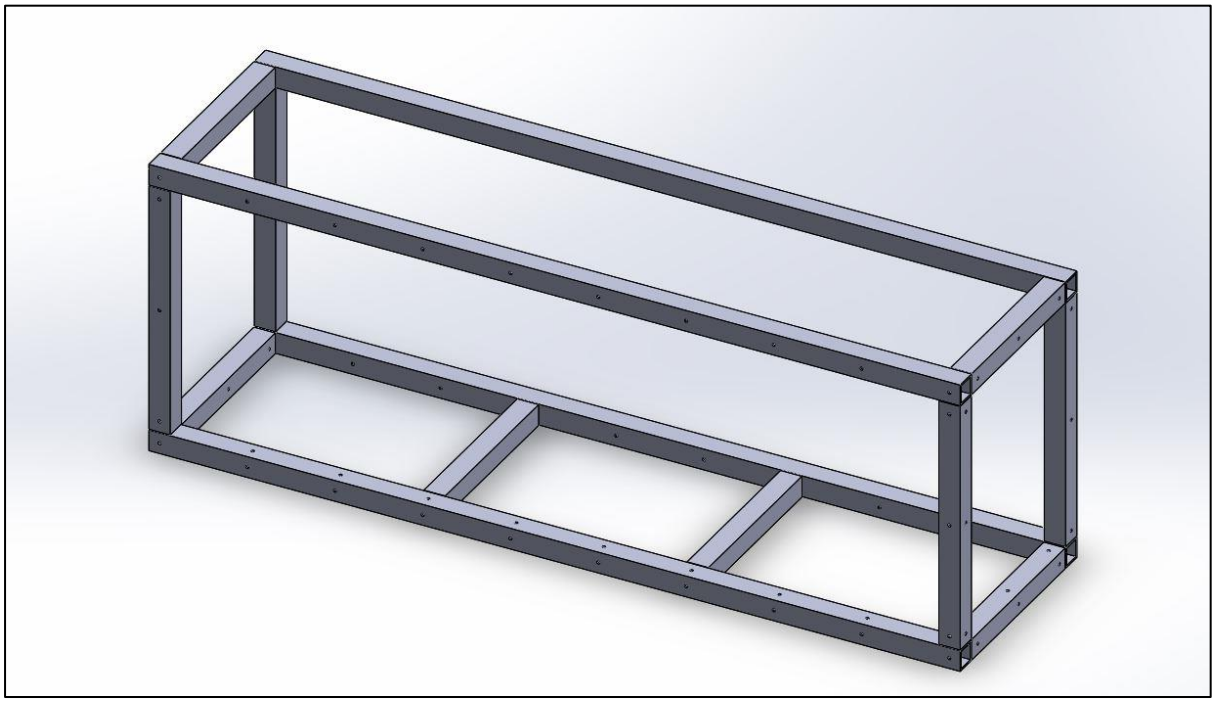

Figure 4-33 - CAD Model of the Frame for Prototype 3.

Square Tube Length (mm)	Quantity	Total Length (mm)
240	6	1440
340	4	1360
1100	4	4400

Table 4-2 - Quantities and Lengths of Aluminium Extrusions for the Frame in Prototype 3.

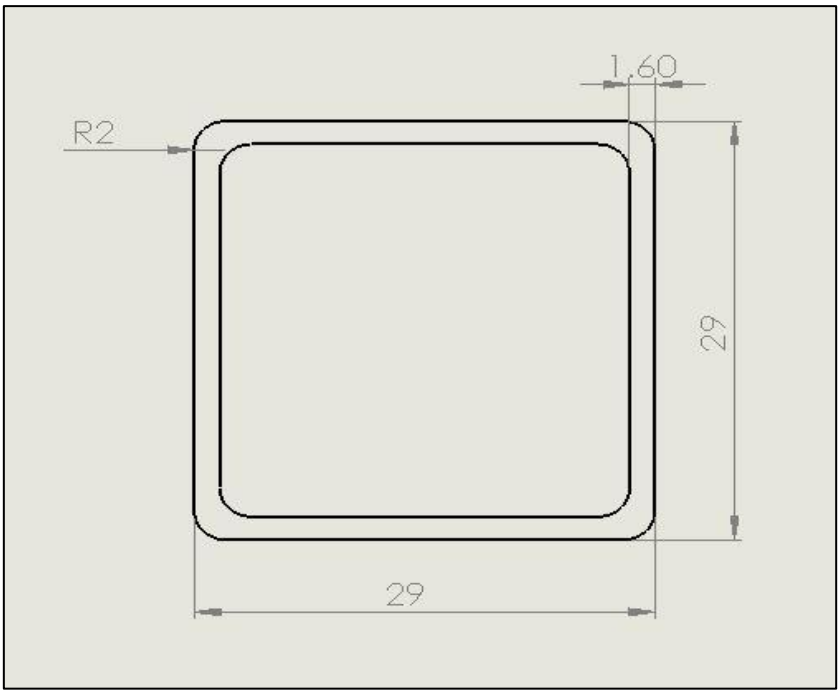

Figure 4-34 - Dimensions of the Cross-section for the Aluminium Extrusion used in the Frame.

The sheets of material that were mounted onto the frame were made using 2mm thick aluminium sheet. Different size and shaped cut-outs of the aluminium sheets would be waterjet cut with the desired dimensions and would then be mounted onto the outer surfaces of the frame. These cut-outs would have a set of holes that would be used for components to be mounted onto the cut-outs and a secondary set of holes that would be used to mount the cut-outs onto the frame. The secondary set of holes would follow the outer edges of the cut-outs and would line up with the holes made into the lengths of aluminium square tube. These secondary set of holes would be used to rivet the cut-outs onto the outer surfaces of the frame and create an enclosed unit. Figure 4-35 shows a CAD model of one of the cut-outs.

The reasons behind choosing 2mm aluminium sheet to be mounted onto the frame to create the enclosed unit were that the material is a lightweight material that will stop UV-light from leaving or entering the enclosed unit and the material would be sturdy enough to be mounted onto the frame and for components to be mounted onto the cut-outs without the cut-outs deforming. An additional benefit for using aluminium is that thermoset resin can be easily removed from the aluminium with the use of alcohols, like acetone.

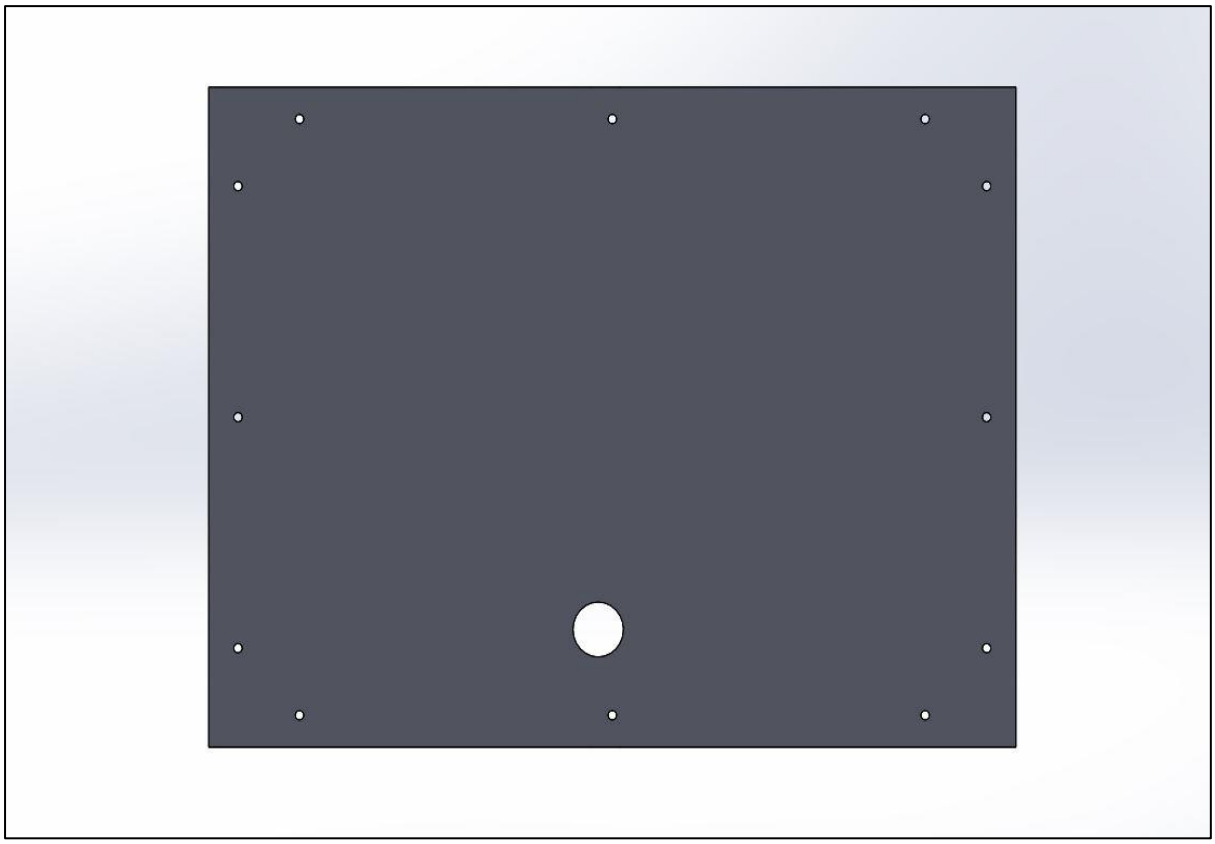

Figure 4-35 - CAD Model of a Cut-out for Prototype 3.

Prototype 3 is designed to be a single enclosed unit but there needs to be access to components within the frame to make alterations. A lid is used to create the enclosed unit and can be removed to allow alterations to be made. This lid is made from clear 3mm polycarbonate sheet and is waterjet cut into shape. This lid is not locked in place but sits on top of the square tube to create the enclosed unit A clear polycarbonate sheet is used as it will stop UV light from entering Prototype 3 and allow the components to be visible from outside the prototype. Table 4-3 gives the details for each of the aluminium and polycarbonate cut-outs.

Overall, Prototype 3 utilises fourteen sections of aluminium square tube, six 2mm aluminium cut-outs and a single polycarbonate cut-out to make Prototype 3 an enclosed unit. Figure 4-36 shows the base frame, the frame without the cut-outs, with all the sections of square tube welded together. Figure 4-37 shows the frame with all the cut-outs attached onto the square tube.

Part Name	Material	Dimensions (Length x Width)
Base Plate	Aluminium	1100mm x 300mm
Base Mounting Plate	Aluminium	1090mm x 290mm
Wall 1	Aluminium	300mm x 400mm
Wall 2	Aluminium	1100mm x 400mm
Wall 3	Aluminium	1100mm x 400mm
Wall 4	Aluminium	300mm x 400mm
Top Plate	Polycarbonate	1090mm x 390mm

Table 4-3 - Table of Cut-outs used in Prototype 3.

Figure 4-36 - Frame used in Prototype 3.

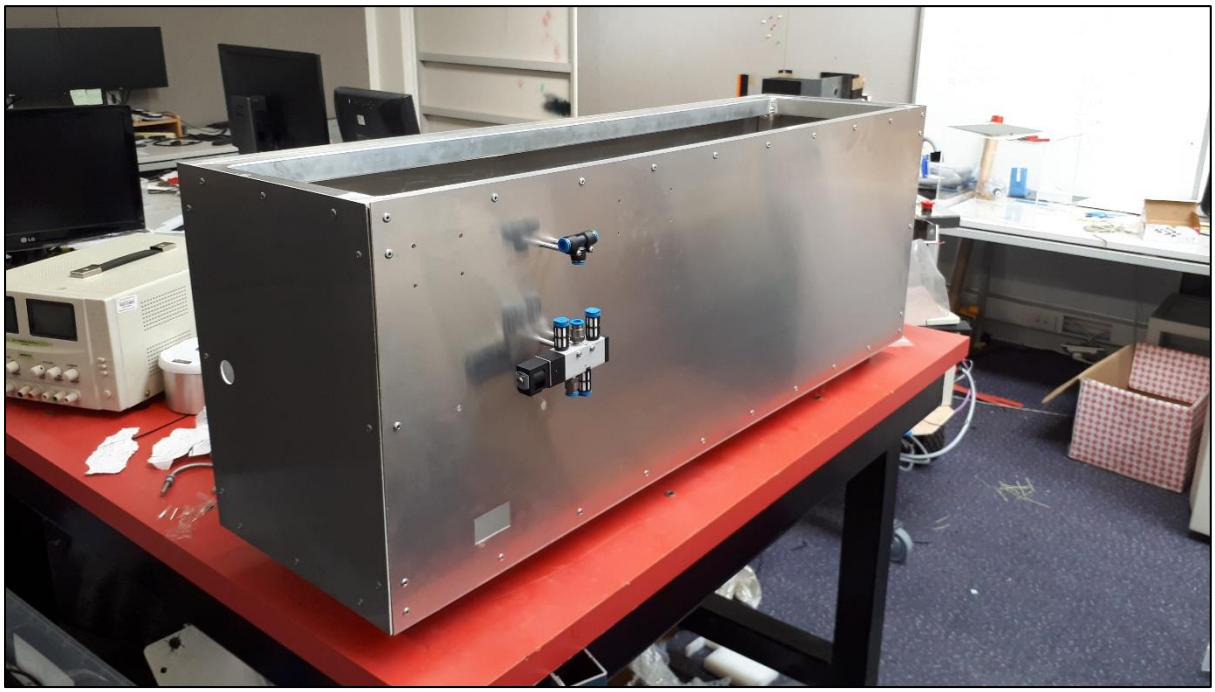

Figure 4-37 - The Frame for Prototype 3 with the Cut-outs Attached.

4.3.2.2 Carbon Fibre Spool Management

For Prototype 3, the carbon fibre spool management process is responsible for controlling the feed of carbon fibre yarn into the other processes to produce the composite filament. Control of the feed of carbon fibre yarn into the subsequent processes includes developing a loading mechanism for the source of the carbon fibre yarn, a method for transporting the carbon fibre yarn through the various processes and a system for controlling the speed at which the carbon fibre yarn is fed into the various processes.

The design for controlling the carbon fibre yarn is based on a similar design as used in previous prototypes but a control system is added. Previous prototypes controlled the carbon fibre yarn by having the carbon fibre yarn on a spool and to manually pull the carbon fibre yarn through the required processes to create the composite filament. The design used in Prototype 3 uses the same spool of carbon fibre yarn as used in Prototype 2 but the method for pulling the carbon fibre yarn through the various processes is by attaching the carbon fibre yarn to a secondary spool that is connected to a stepper motor. The stepper motor is used to rotate the secondary spool and the carbon fibre yarn is pulled through the various processes as the stepper motor rotates. The stepper motor allows for control and consistency over the speed at which the carbon fibre yarn is pulled through the various processes.

An important addition to the carbon fibre spool management process is the ability to count the number of rotations that the secondary spool has made at one time. The ability to count the number of revolutions made by the secondary spool is important as the ability gives the option to set a predetermined amount of revolutions during the process of creating the composite filament. Additionally, the ability to count the number of revolutions also allows for the customisation of various pre-production and post-production procedures that involve rotating the secondary spool a set amount of revolutions. Figure 4-38 is a diagram of the mechanism used to control the secondary spool.

The method for counting the number of revolutions made by the secondary spool involves attaching a cam to the shaft of the stepper motor and a limit switch. The cam will rotate when the shaft of the stepper motor rotates, and the cam will trigger the limit switch each time the limit switch is triggered. The triggering of the limit switch will be used to count the number of revolutions. Additionally, the limit switch can also be used to get the cam in the correct position before the process of making the composite filament begins. A debouncing program has been applied to the limit switch to ensure that no single triggering of the limit switch is read as the limit switch being triggered multiple times. Figure 4-39 and Figure 4-40 show different angles of the setup for controlling the feed of carbon fibre yarn.

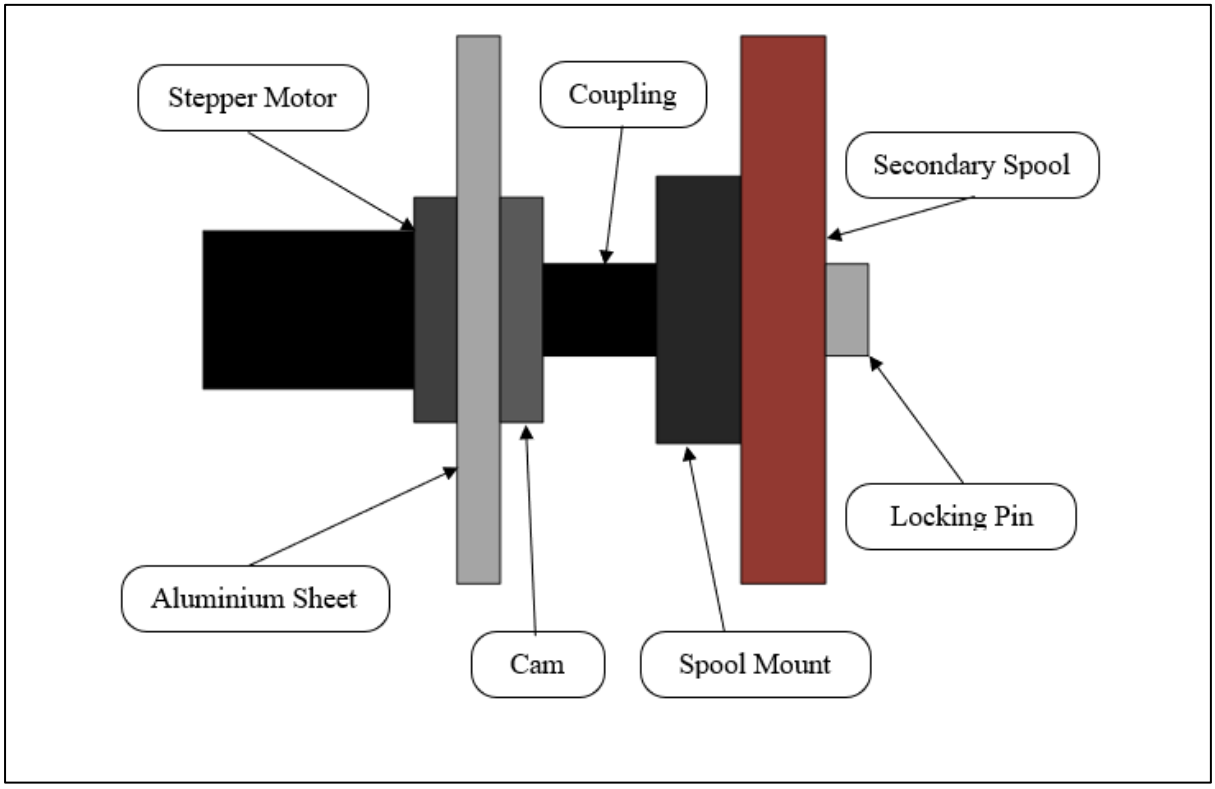

Figure 4-38 - Diagram of the Setup for Controlling the Secondary Spool.

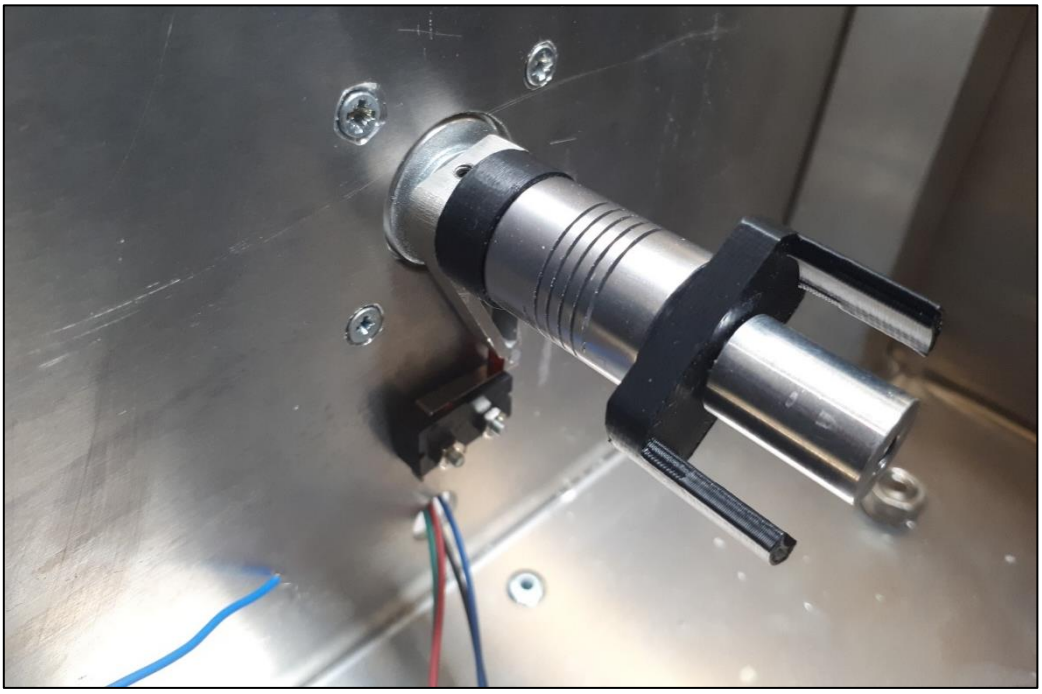

Figure 4-39 - The Setup used to Control the Feed of Carbon Fibre Yarn without the Spool.

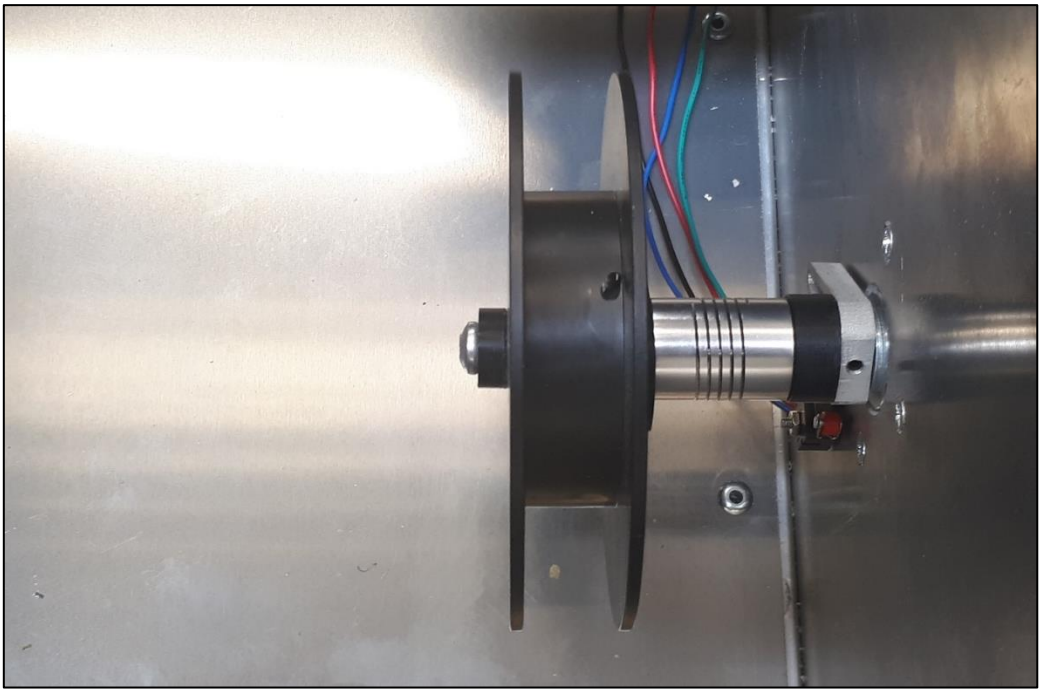

Figure 4-40 - The Setup used to Control the Feed of Carbon Fibre Yarn with the Spool.

4.3.2.3 Resin Flow Control

The resin flow control section of Prototype 3 is responsible for controlling the flow of resin during the production of the composite filament. These responsibilities include controlling when the resin contacts the carbon fibre yarn, controlling the amount of resin that contacts the carbon fibre yarn and providing storage for the resin prior to being used. This process has a significant impact on the quality of the composite filament produced from Prototype 3 and impacts several of the material properties of the composite filament.

One of the major alterations made to Prototype 3, compared to previous prototypes, is the implementation of a control system to automate some of the manual processes, including the process for controlling the thermoset resin. The new design for controlling the thermoset resin is an automated process that utilises compressed air and pneumatic components to control the flow of the thermoset resin. The new design provides a more consistent flow of thermoset resin that contacts the carbon fibre yarn and provides a method for adjusting the pressure that the thermoset resin contacts the carbon fibre yarn. Figure 4-41 illustrates a basic pneumatic circuit of all the pneumatic components used for this section and Table 4-4 shows a list of the pneumatic components used in the pneumatic circuit.

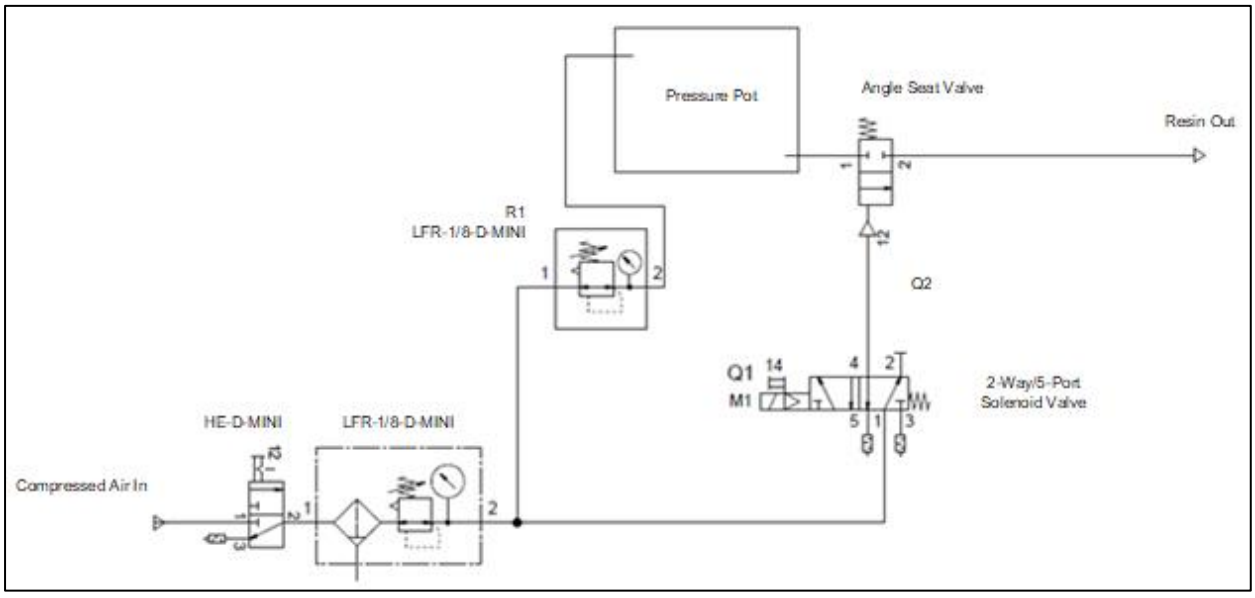

Figure 4-41 - The Pneumatic Circuit used for Prototype 3.

Pneumatic Component	Code
On/Off Valve	HE-D-MINI
Filter/Regulator	LFR-1/8-D-MINI
Regulator	LR-1/8-D-MINI
2-Way/5-Port Solenoid Valve	VUVS-LK20-M52-AD-G18-1C1-S
Angle Seat	VZXF-LM22C-M-B-G12-120-H
Pressure Pot	N/A

Table 4-4 - The Pneumatic Components used in Prototype 3.

The pneumatic circuit is based around the utilisation of a pressure pot for storing the UV-curable resin and for providing a means to pressurise the resin before allowing the resin to contact the carbon fibre yarn. The basis of this design is to build up the pressure within the pressure pot until the desired pressure is reached and to then allow the resin to contact the carbon fibre yarn. A valve is used to close off the pressure pot to allow the pressure within the pressure pot to build and the valve is opened to allow the resin to flow out of the pressure pot.

The pneumatic circuit begins with a ON/OFF valve and an air filter/regulator. The ON/OFF valve serves as a kill switch for the entire pneumatic circuit as it will stop the flow of compressed air into subsequent components and it will drain the compressed air already in the circuit. The filter/regulator is positioned after the ON/OFF valve and is used to determine the pressure entering the pneumatic circuit and will filter the air of hazardous material that will damage the longevity of the components.

After the filter/regulator, the circuit branches off into two separate branches using a T-junction. The first branch is towards the pressure pot and is responsible for building up the pressure within the pressure pot. A secondary regulator is positioned between the start of the first branch and the pressure pot. This regulator allows for adjustments to be made for the pressure of the

compressed air entering the pressure pot. The range of pressure for this secondary regulator is limited based on the pressure that the compressed air that passes through the filter/regulator. This secondary regulator has a direct effect on the pressure of the resin contacting the carbon fibre yarn and will be used to ensure that the resin penetrates all areas within the carbon fibre yarn.

The second branch within the pneumatic circuit is used to control the flow of resin within the pressure pot. The first pneumatic component along the second branch is a 2-way/5-port solenoid valve. The solenoid valve has two positions depending on whether the solenoid is active or not. This solenoid valve is utilised so that air can flow to open the valve that lets the resin flow when the solenoid is active. Otherwise, the resin is not allowed to flow from the pressure pot when the solenoid valve is not active. An additional feature of this solenoid valve is that the compressed air after the solenoid valve is drained when the solenoid valve is not active.

After the solenoid valve there is an angle seat valve. Angle seat valves are a type of valve that can be used for controlling the flow of liquids including viscous materials, such as oils or resins. The angle seat valve is positioned to receive the resin from the pressure pot and is opened and closed based on the flow of compressed air from the solenoid valve. This angle seat valve is designed to be open and allow resin to flow when the solenoid valve is active and allows the compressed air to pass through to the angle seat valve. Subsequent to the angle seat valve is the start of the impregnation process where the carbon fibre yarn and the UV-curable resin combine to create the composite filament.

The pneumatic circuit for Prototype 3 could only be utilised efficiently due to the change from a two-part resin, for previous prototypes, to a UV-curable resin. A two-part resin would be too prone to cure within each of the components and would require the components to be replaced. The UV-curable resin can be stored within the components for vastly longer periods with less risk of the resin curing within the components. Figure 4-42 and Figure 4-43 shows the components used for the pneumatic circuit prior to being attached to the frame.

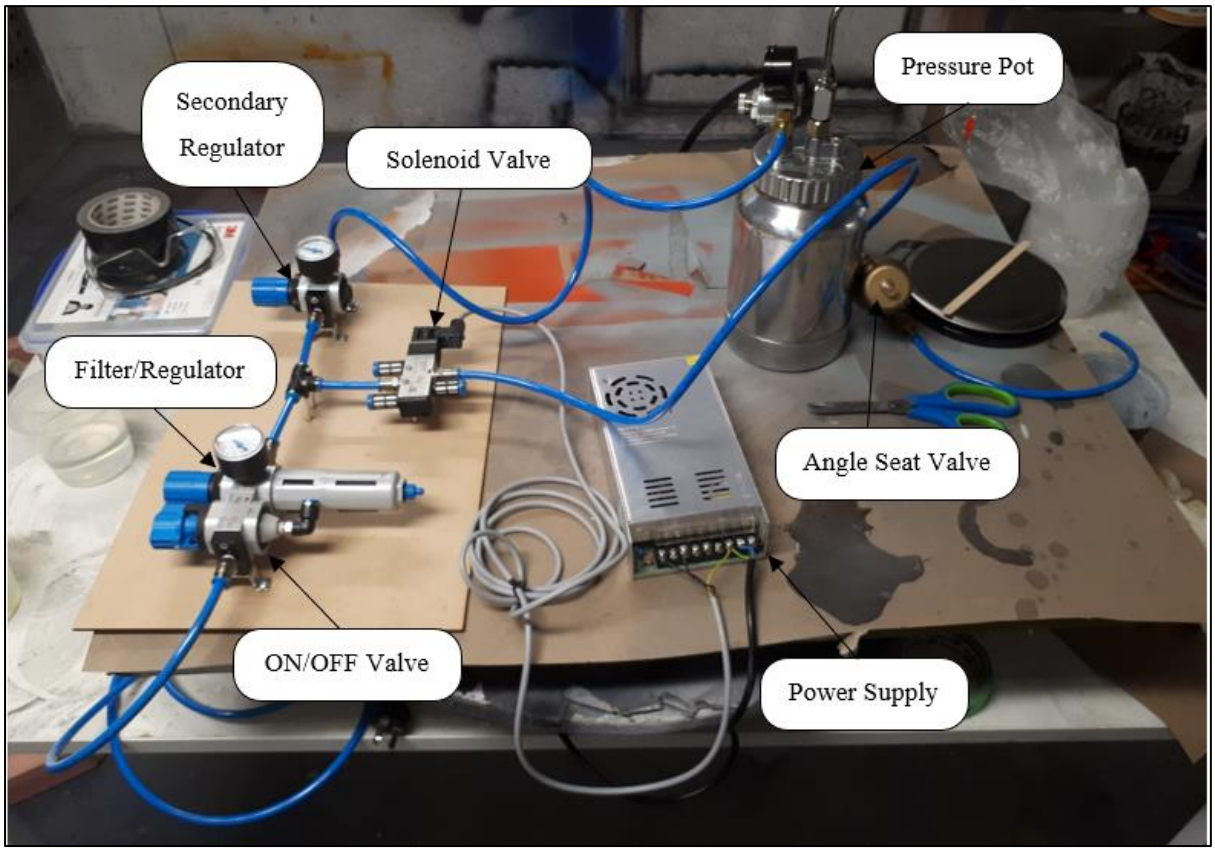

Figure 4-42 - The Connected Pneumatic Circuit utilised in Prototype 3.

Figure 4-43 - The Angle Seat Valve used in Prototype 3.

As shown in the layout diagram for Prototype 3, the components for the pneumatic circuit are positioned outside of the frame. The components were positioned on the outside of the frame as this would allow adjustments to be made without having to go inside the enclosed unit. The only component from the pneumatic circuit that is within the frame is the angle seat valve. The reason for this is that there will be less of a pressure drop in the resin from the pressure pot if the angle seat valve is close to the impregnation process. Figure 4-44 and Figure 4-45 show the pneumatic circuit connected to the frame.

Figure 4-44 - The Pneumatic Circuit Mounted onto the Frame for Prototype 3.

Figure 4-45 - The Angle Seat Valve mounted in Prototype 3.

4.3.2.4 Impregnation Process

The impregnation process is responsible for receiving the carbon fibre yarn and the UV-curable resin and combine the two materials into the composite filament. The impregnation process used in Prototype 3 uses the same vertical impregnation process that was used in Prototype 2 and includes the pressure rollers and shaping dies. Alterations have been made to both the shaping dies and the pressure rollers so they can be incorporated onto one of the walls of the frame and so that each component is easier to be removed and replaced. Figure 4-46 and Figure 4-47 show the impregnation process utilised for Prototype 3.

One of the major alterations to the impregnation process is the addition of an aluminium tray situated beneath the impregnation process. As Prototype 3 is an enclosed unit, the build-up of excess resin within Prototype 3 will gradually increase as more and more of the composite filament is produced. Therefore, a method for collecting the excess resin that is removed from the composite filament must be collected and disposed of properly prior to curing. The aluminium tray is made of waterjet cut 2mm aluminium sheet which has been bent and welded together to create a tray to collect the excess resin. This tray can be connected onto the same wall as the rest of the impregnation process and will be positioned directly below the impregnation process.

Figure 4-46 - The Impregnation Process used in Prototype 3.

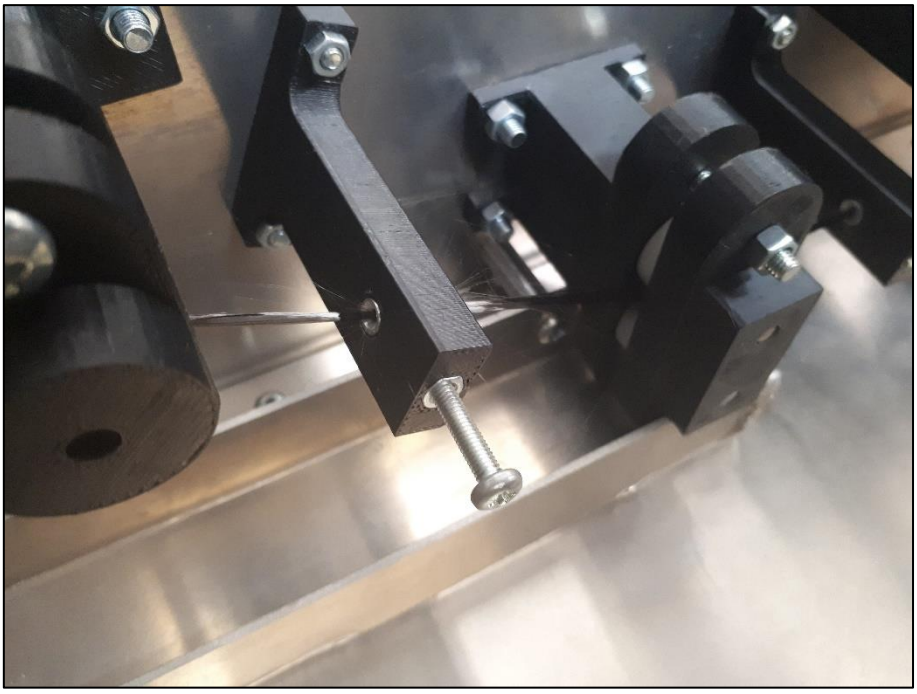

Figure 4-47 - A Closeup of the Pressure Rollers and Shaping Dies used in Prototype 3.

4.3.2.5 Curing Process

The curing process for Prototype 3 is a new addition to producing the composite filament and was only implemented with the addition of using a UV-curable resin. The curing process is responsible for controlling the duration that the composite filament is subjected to UV-light and ensuring that the UV-light does not contact the UV-curable resin prior or after the curing process. The curing process is the last process before the secondary spool is used to collect the composite filament.

The design for curing process involves passing the composite filament, from the impregnation process, through a series of UV light emitting diodes (LEDs). The source of UV-light is a UV lamp that comprises of a single line of eight UV LEDs. This UV lamp will be positioned above the composite filament and will be used to cure the UV-curable resin. The UV lamp will be controlled via a relay to determine when the UV lamp is on or off. The UV lamp will be locked in place using 3D printed mounts that will connect directly to one of the aluminium walls used for the frame.

One of the other components is an aluminium tray similar to the tray used in the impregnation process. This aluminium tray has been made using waterjet cut 2mm aluminium sheet that has been bent and welded together to create the tray. This tray will be positioned directly below the UV-lamp to stop any UV-light from the UV lamp reaching the UV-curable resin outside of the curing process. The tray will have holes that allow the composite filament to move through the tray, underneath the UV-lamp and onto the secondary spool. The aluminium tray is secured directly below the UV lamp by attaching the tray to one of the walls of aluminium used for the frame. Figure 4-48 shows the composite filament passing through the aluminium tray and Figure 4-49 shows the UV lamp positioned directly above the aluminium tray.

One of the key factors for this process will be in determining how long the composite filament will be exposed to UV-light. The period that the composite filament is exposed to the UV-light will be an important parameter to experiment with to ensure that the composite filament is not cured too much and solidifies.

Figure 4-48 - The Carbon Fibre Yarn passing through the Aluminium Tray.

Figure 4-49 - The Carbon Fibre Yarn passing underneath the UV Light and onto the Secondary Spool.

4.3.2.6 Control System

The control system used for Prototype 3 can be split into two major sections. The first major section is the electronic components used to control various process within the prototype. The second major section for the control system is the programming utilised to automate and control the electronic components used in several processes. These two sections combine to provide one of the main differences between Prototype 3 and previous prototypes; the automation of several processes.

4.3.2.6.1 Electronics

The electronics for Prototype 3 utilise a range of electronic components used in conjunction with a microcontroller to provide the automated processes for producing the composite filament. The microcontroller utilised for Prototype 3 is an Arduino Mega as it is suitable for prototyping. Table 4-5 shows the details of all the electronic parts utilised in Prototype 3 and Figure 4-50 shows a diagram of how each of the electronic components are connected.

Part Name	Quantity
Arduino Mega	1
UV Light	1
Stepper Motor	1
Stepper Motor Driver	1
24V Power Supply	1
12V Power Supply	1
2-Relay Module	1

Table 4-5 - The Electronic Components used in Prototype 3.

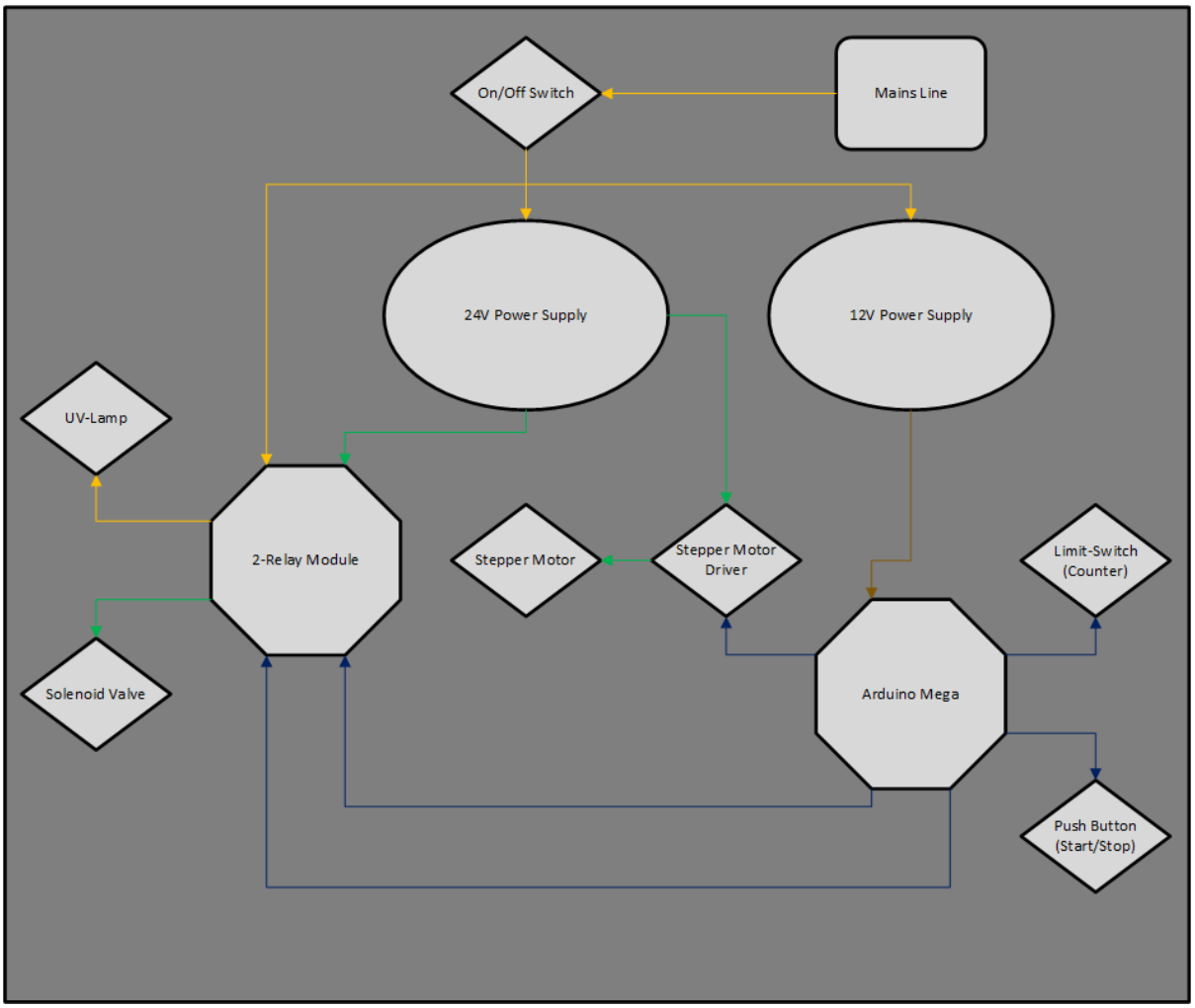

Figure 4-50 - A Diagram Showing how the Electronic Components are Connected for Prototype 3.

A shield was developed for the Arduino Mega to allow for the connections between the ports on the Arduino Mega and the peripheral electronic components to be connected using screw terminals. The shield for the Arduino Mega was designed using the Autodesk Eagle software. The design schematic for the shield developed for the Arduino Mega used in Prototype 3 is shown in Figure 4-51 and Figure 4-52 shows the shield attached to the Arduino Mega with the screw terminals soldered on.

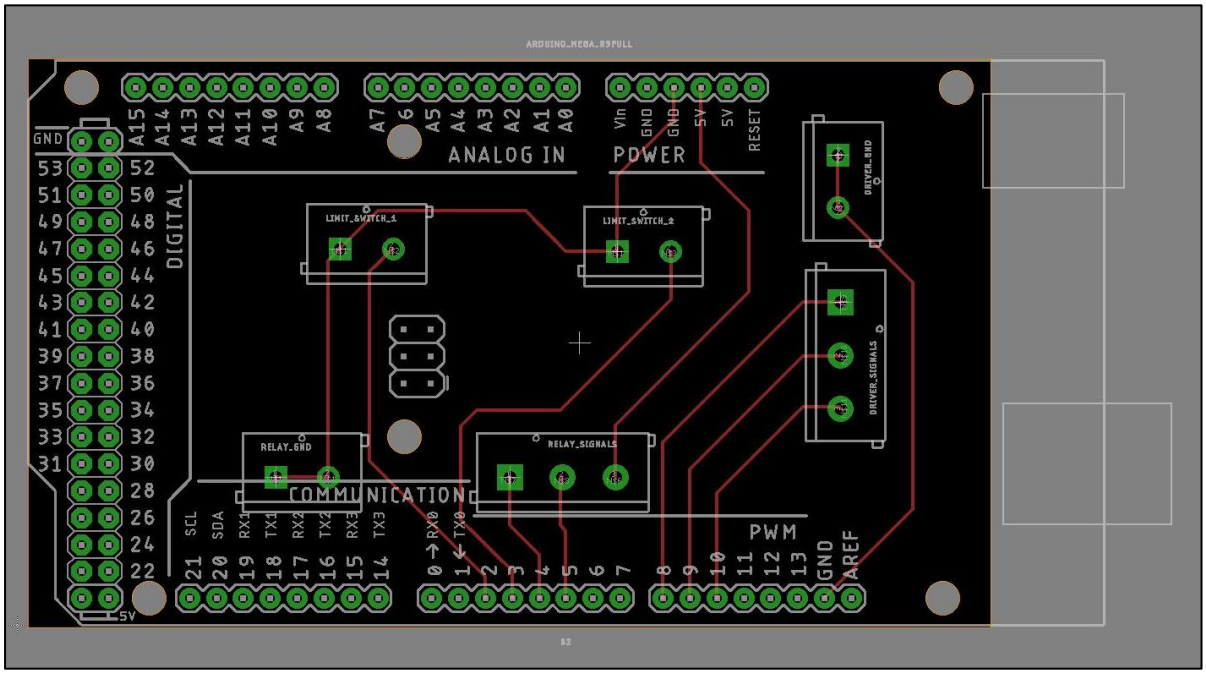

Figure 4-51 - The Design Schematic for the Arduino Mega used in Prototype 3.

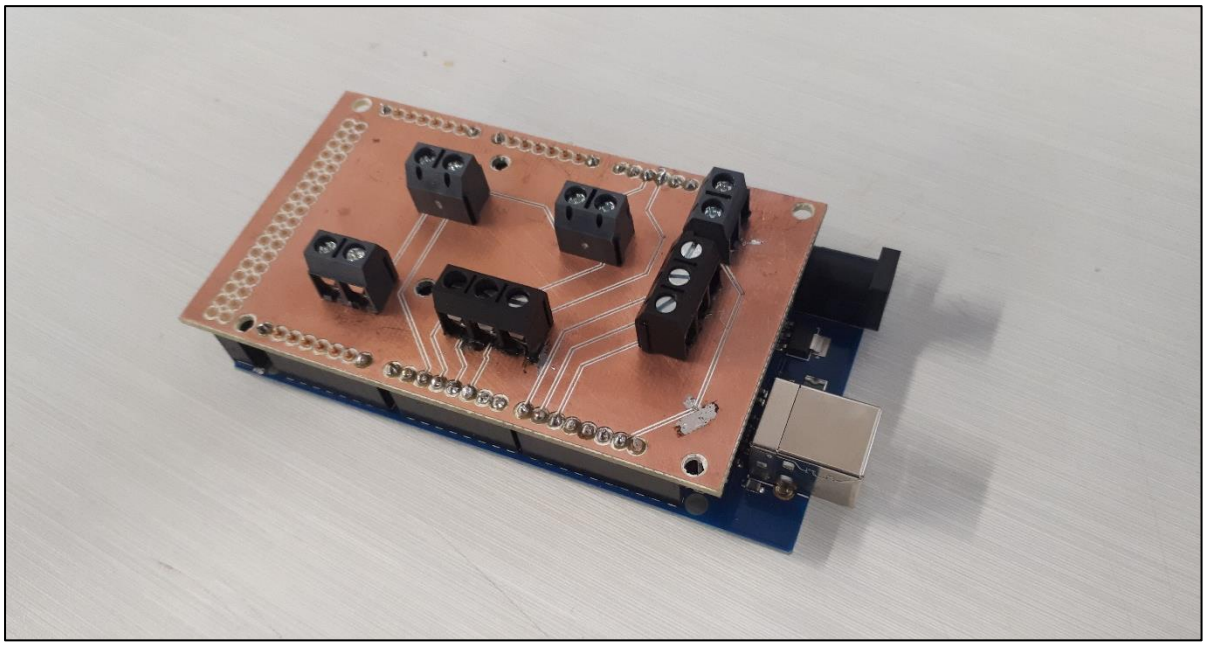

Figure 4-52 - The Shield mounted onto the Arduino Mega with the Screw Terminals Soldered on.

4.3.2.6.2 Programming

The program used to produce the carbon fibre composite filament follows four different loops for the different stages of producing the composite filament. Figure 4-53, Figure 4-54, Figure 4-55 and Figure 4-56 show graphical representations of the four loops and the order that each loop is utilised. Appendix C is the code used for running Prototype 3. The four loops for autonomously running Prototype 3 are as follows:

- Start Loop
- Initial Loop
- Setup Loop
- Curing Loop

The 'Start Loop' is designed to wait for the operator to press a button to begin the process of producing the carbon fibre composite filament. Once the button has been pressed, the program will continue onto the 'Initial Loop'

The 'Initial Loop' is designed to take up any slack in the carbon fibre yarn prior to the production of the composite filament. The 'Initial Loop' will have the stepper motor rotate a set amount of revolutions and the number of revolutions will be constantly monitored. Once the desired amount of revolutions has been achieved, the program will begin the 'Setup Loop'. During the 'Initial Loop, the program will constantly monitor the status of the emergency stop button.

The 'Setup Loop' will have the stepper motor rotate a predetermined amount of revolutions, allow the resin from the pressure pot to contact the carbon fibre and turn on the UV lamp. The number of revolutions will be constantly monitored until the desired number of revolutions is achieved and the status of the emergency stop button is constantly monitored. Once the number of revolutions has been achieved, the program will move onto the 'Curing Loop'.

The 'Curing Loop' is designed to ensure the last section of composite filament within the aluminium tray is solidified by having the stepper motor stop rotating and having the UV lamp remain on for a set amount of time. Once the set amount of time has passed, all components will be turned off and the program will return to the 'Start Loop'. The status of the emergency stop button will be constantly monitored throughout this loop.

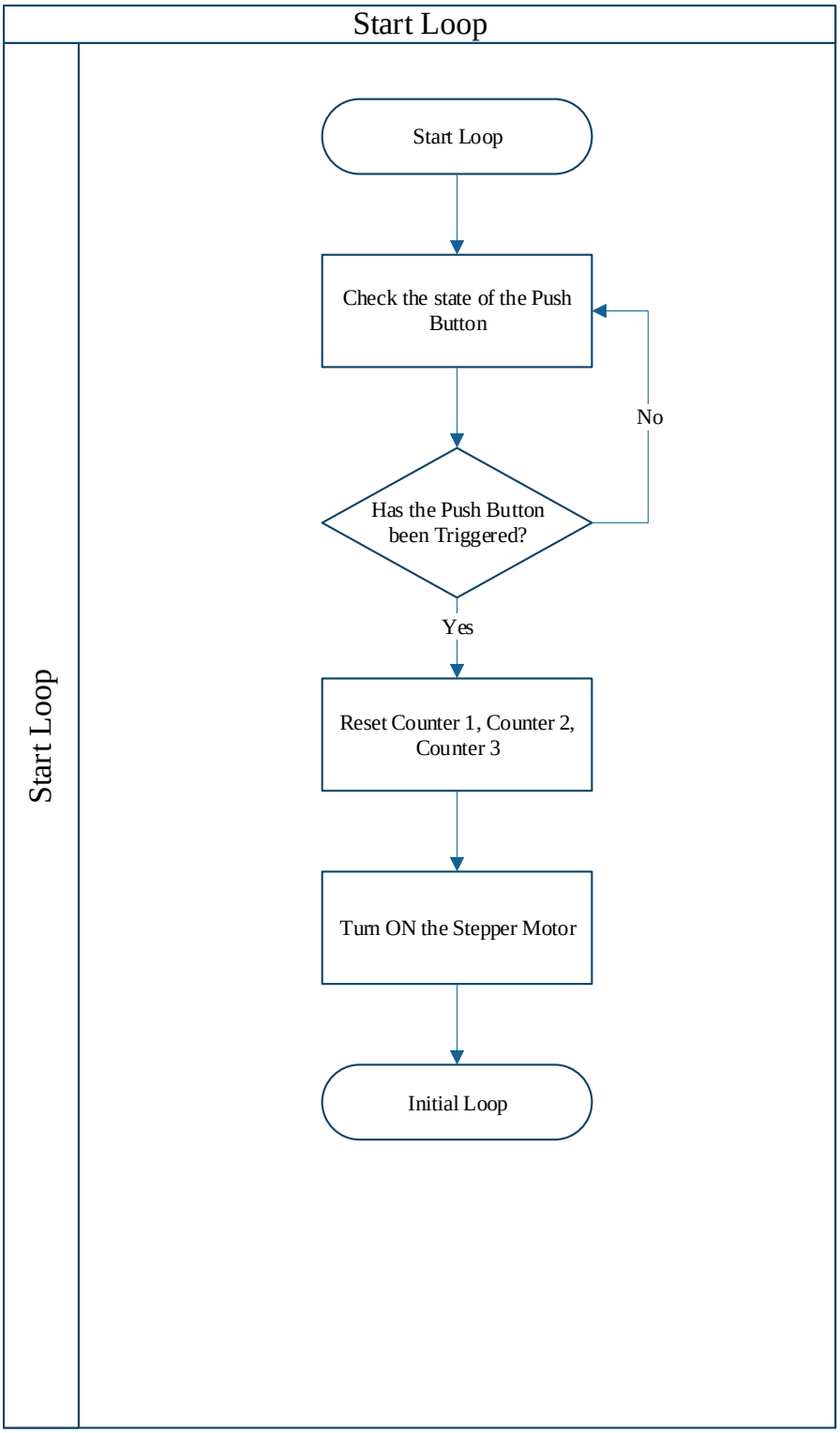

Figure 4-53 - The Start Loop used for Prototype 3.

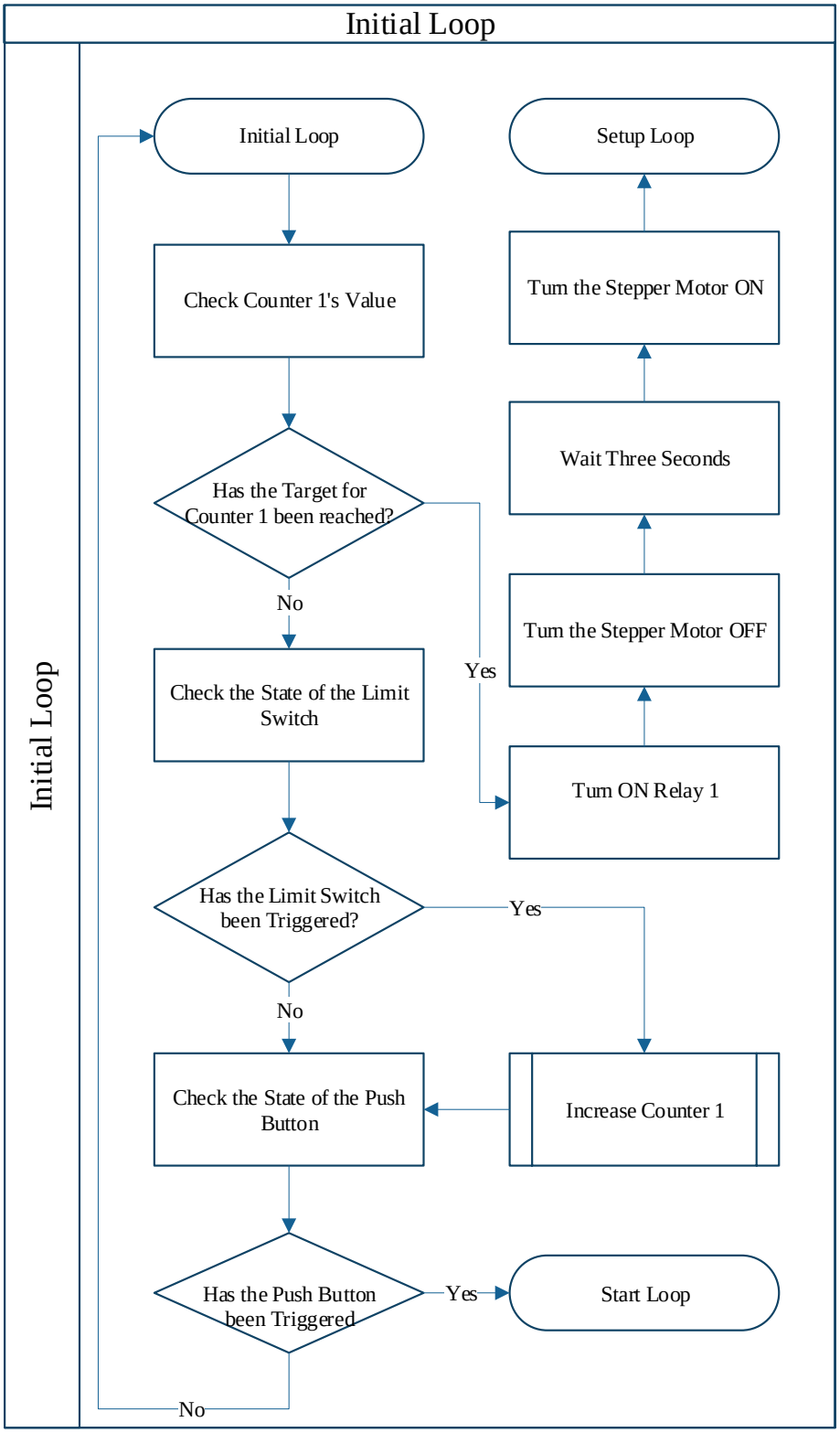

Figure 4-54 - The Initial Loop used for Prototype 3.

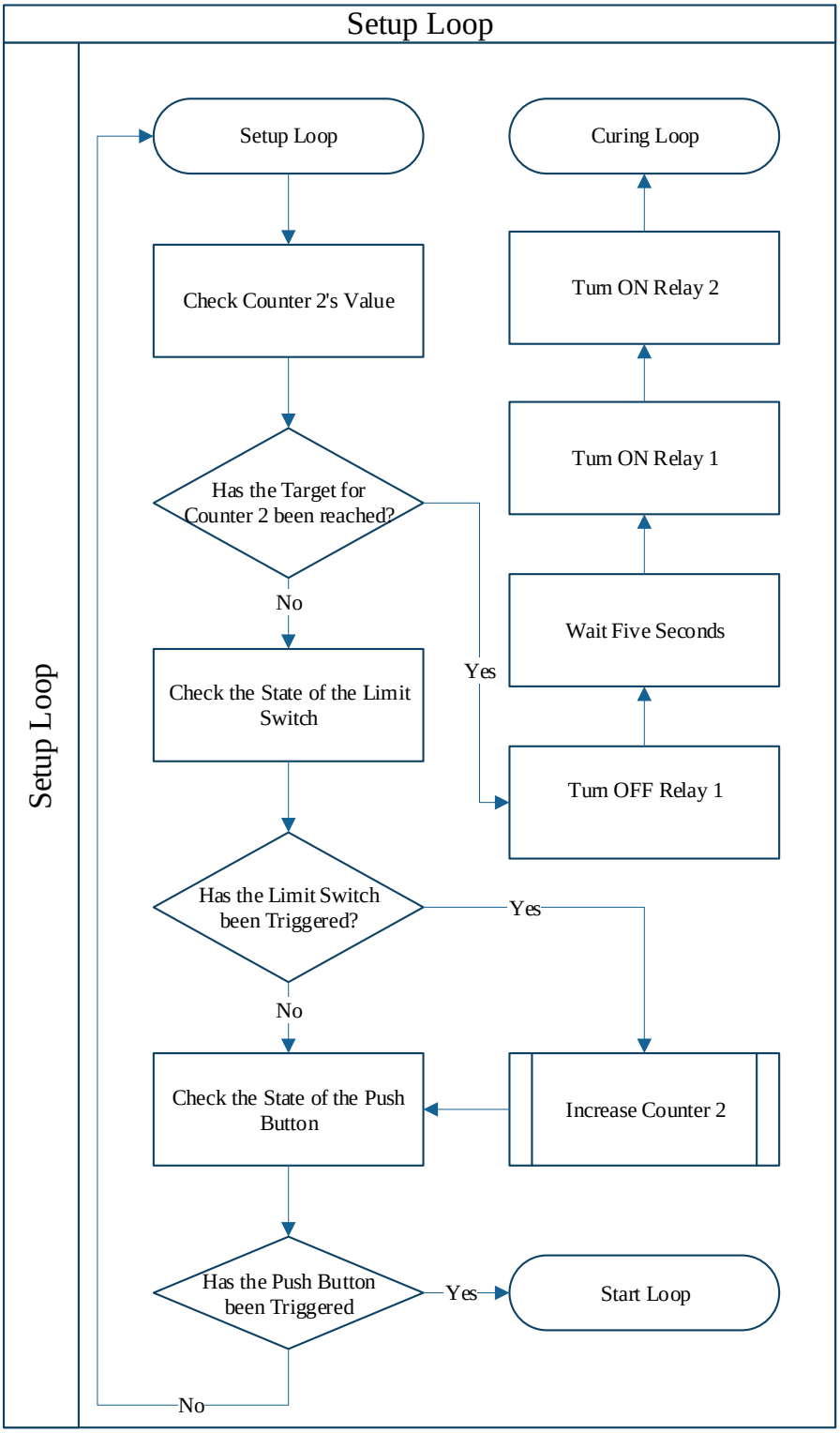

Figure 4-55 - The Setup Loop used for Prototype 3.

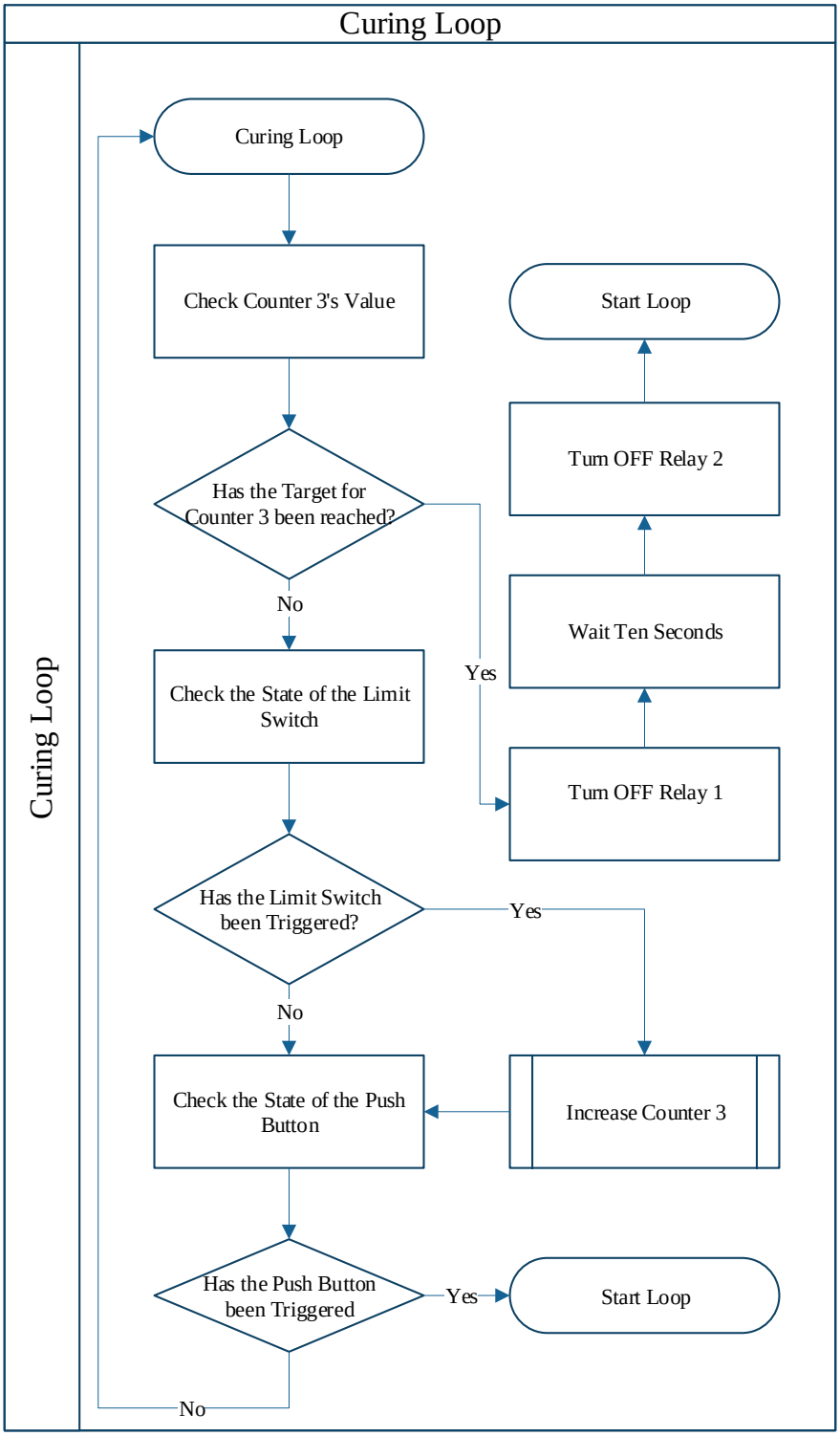

Figure 4-56 - The Curing Loop used for Prototype 3.

5. Analysis of a Commercial Long/Continuous Fibre 3D Printer

One of the main aims of this research was to conduct research into a commercially available 3D printer that can produce long/continuous fibre reinforced composite parts. The purpose of this research was to analyse the capabilities and the limitations of a 3D printer that can produce fibre reinforced composite parts using long/continuous fibres. Additionally, this research could be useful in identifying possible issues with utilising the fibre reinforced composite filament discussed in previous sections.

The analysis of a commercially available 3D printer involves using the 3D printer to produce a variety of specimens sets that comprise of different combination of parameters. These specimen sets will then be subjected to a variety of testing methods to analyse some of the mechanical properties that can be achieved by the 3D printer. The results from this testing will determine the capabilities of the 3D printer and an analysis of the different parts of the 3D printer will identify some of the limitations. The results from this analysis could provide reference material for designing long/continuous fibre reinforced composite parts using the chosen 3D printer with the desired mechanical properties.

The research shown in this section has resulted in several research papers being published. The research papers that have been published using this research are listed below:

- 3D Printing of Fibre Reinforced Honeycomb Structured Composite Materials – M2VIP2016 – Appendix D
- Analysing the Tensile Properties of 3D Printed Fibre Reinforced Thermoplastic Composite Specimens – M2VIP2017 – Appendix E
- Design and FEA Analysis of Knee and Hip Replacements – M2VIP2017 – Appendix F

5.1 The Mark One 3D Printer

The Mark One 3D printer, shown in Figure 5-1, was a commercially available 3D printer developed by a company called Markforged. The Mark One is the first in a line of FDM 3D printers developed by Markforged that can produce long/continuous fibre reinforced composite parts using a range of materials. The Mark One 3D printer can alter various properties that alter the internal structure of parts. The Mark One 3D printer will be used to produce various sets of specimens for testing purposes. Additionally, the Mark One 3D printer and accompanying software will be analysed to determine some of the capabilities and limitations of the Mark One. Please note that the Mark One was commercially available at the time of this research but is no longer available. The Mark One 3D printer has been removed and replaced with the Mark Two 3D printer, but replacement parts are available for the Mark One.

Figure 5-1 - The Mark One 3D Printer [65].

5.2 Mark One 3D Printer Analysis

The Mark One 3D printer is an FDM 3D printer that can create long/continuous fibre reinforced composite parts. A thorough analysis of the Mark One involves analysing the available materials, the software used to prepare the parts for printing and the mechanical systems of the 3D printer. Each of these sections will be discussed in detail to determine the capabilities and limitations of the Mark One.

5.3 Materials

The Mark One 3D printer can print long/continuous fibre reinforced composite parts utilising a variety of materials. The materials for making composite parts using the Mark One can be split into two types of materials: Matrix Material and the Fibre Reinforcement Material. The options for each of the two types of materials are listed in Table 5-1 and the material properties for each material are listed in Appendix G and Appendix H.

5.4 Mechanical Analysis

The Mark One 3D printer is a dual extruder FDM 3D printer that can print parts using two materials. The basic layout of the Mark One is to have the dual extruder connected to a gantry system that control is the x-axis and y-axis and a print bed that is connected to a leadscrew mechanism for controlling the z-axis. The gantry system utilises two steppers motors, one for each axis, to control the movement of the dual extruder. The dual extruder is mounted onto two linear rails, one for each axis, and is driven using tensioned belts that are connected to the respective stepper motor.

Mark One Material	Material Phase
Nylon	Matrix
Fibreglass	Fibre Reinforcement
Carbon Fibre	Fibre Reinforcement
Kevlar	Fibre Reinforcement

Table 5-1 - The Materials Available for the Mark One 3D Printer.

The print bed is placed on a movable platform that is connected to a leadscrew and two guide rods. The leadscrew is connected to motor which rotates the leadscrew. Depending on the rotational direction of the leadscrew, the platform, and the print bed on top of the platform, moves either upwards or downwards. The print bed has three little extrusions on the bottom surface, and these are used to ensure that the print bed is positioned correctly. The platform has three indents that the extrusions from the print bed fit into and are held in place using magnets.

The materials that are used for the Mark One are stored separately. The nylon filament comes in spool form and is stored outside the Mark One within a waterproof box that is designed to keep moisture from reaching the nylon as this can affect the quality of parts. The fibre reinforcement material comes in smaller spools and is stored within the confines of the Mark One. A spool of fibre reinforcement is placed on a shaft within the Mark One and a locking pin is used to hold the spool in place, while still allowing the spool to rotate, with the assistance of magnets. Each of these materials are fed through Bowden tubes towards the dual extruder.

Before the materials reach the dual extruder, the materials pass through the feeding mechanism which controls the movement of both materials. The feeding mechanism utilises stepper motor-controlled pressure rollers that are used to push the materials through the Bowden tubes. These pressure rollers have a rubber-like material coating the pressure rollers to reduce the damage on the materials, particularly the fibre reinforcement.

After the feed mechanism, the nylon passes on through the Bowden tube towards the dual extruder, but the fibre reinforcement material passes onto another mechanism. This mechanism is used to cut the fibre reinforcement. A blade is used to cut the fibre reinforcement each time a new layer is printed. After the cutting mechanism, the fibre reinforcement is fed through the Bowden tube to the dual extruder.

The dual extruder receives the materials from the Bowden tubes and pass the materials through a heating element and out separate nozzles for each material. The heating element is used to heat the two materials to the required temperature for the materials to be suitable for printing. Once the material is heated to the correct temperature, the material can be fed through the nozzles and onto the print bed.

In terms of limitations regarding the design of the mechanical systems of the Mark One, the use of the cutting mechanism introduces one of the first limitations of the Mark One. The distance from the cutting mechanism to the nozzle for the fibre reinforcement material is the

minimum amount of fibre reinforcement that needs to be used for a layer to use the fibre reinforcement. This means that if the area within a part cannot fit this amount of fibre reinforcement material, the part will be printed without fibre reinforcement. This can be a problem for particularly small parts or parts with very complex cross-sections. Whether a part can have fibre reinforcement can be seen through the proprietary software.

The second limitation of the Mark One is due to the Mark One being an FDM 3D Printer. FDM 3D printers are known to produce parts with anisotropic properties with the z-axis being is noticeably weaker than the x-axis and the y-axis. This is due to the bonding between the layers being the weakest point of a part made from an FDM 3D printer. The Mark One can strengthen parts with fibre reinforcement along the x-axis and y-axis but, as with all FDM 3D printer, the Mark One cannot reinforce parts along the z-axis. This limitation needs to be considered when designing or orientating parts during the printing process.

5.5 Software

The Mark One 3D printer utilises a cloud-based software known as Eiger. The Eiger software is responsible for preparing files for the Mark One 3D printer as well as serving as a database of parts and past print jobs that have been printed using the Mark One. An account must be setup to utilise Eiger before Eiger can be used to generate the required files for the Mark One to print parts. As Eiger is a cloud-based software, the software can be accessed using any device that has access to the internet.

Using the Eiger software, the internal structure of parts can be customised using a wide range of parameters. The Eiger software can customize each individual layer of a part but only for certain parameters. This ability to customise the internal structure for different layers of parts allows parts to be customised for specific applications.

5.5.1 Mark One Printing Parameters

The Mark One 3D printer has a range of parameters that can be altered to dictate the internal structure of parts. These parameters can be altered using Eiger and can be split into two sections. The first section is for adjusting the internal structure for the matrix material and the second section of parameters is for controlling the internal structure for the fibre reinforcement material. These parameters will be altered to create several sets of specimens each with a different combination of parameters. Each available parameter for both sections will be

discussed below to explain the capabilities and limitations of the Mark One and to discuss the effect that each parameter has on the internal structure of parts.

5.5.2 Matrix Material Parameters

Layer Height (mm)

The 'Layer Height' parameter determines the layer thickness for parts during the printing process. The layer thickness determines the Z-resolution of parts and the lower the layer thickness, the longer a part will take to be printed. For the Mark One, the 'Layer Height' parameter can be set between 0.1mm to 0.2mm for parts that are made solely of the nylon matrix material. When the Mark One utilises a fibre reinforcement material, the 'Layer Height' parameter becomes a pre-set value depending on what material is used and cannot be altered. For the fibreglass and Kevlar fibre reinforcement material, the layer height is set to 0.1mm and is set to 0.125mm for parts with the carbon fibre reinforcement material.

Fill Pattern

The 'Fill Pattern' parameter determines the pattern that the nylon matrix material is printed for the internal structure of each layer of a part. There are three options, shown in Figure 5-2, for the fill pattern: Triangular Fill, Hexagonal Fill and Rectangular Fill. Regardless of the choice for the fill pattern, a solid section of nylon matrix material is used on the outer surface of parts to protect the internal structure of the parts and provide a solid outer surface.

Fill Density

The 'Fill Density' parameter determines the density of nylon used to create the internal structure of a part based on the chosen 'Fill Pattern'. The 'Fill Density' parameter ranges from 0% to 100%. 0% for the 'Fill Density' does not remove the nylon for the internal structure but provides a predetermined minimum amount of nylon for the internal structure. Figure 5-2 illustrates the differences in the densities for all the available patterns.

Roof & Floor Layers

The 'Roof & Floor Layers' parameter determines the number of solid layers that are positioned on the top and bottom surfaces of parts. The parameter is designed to protect the internal structure of parts by providing a solid outer surface. This parameter can range from one to ten

layers and puts the chosen number of layers at the top and bottom surface. This can result in a total of two to twenty roof and floor layers on parts. The recommend amount of 'Roof & Floor Layers', based on Eiger, is a minimum of two layers.

Wall Layers

The 'Wall Layers' parameter is used to determine the number solid lines of nylon that are printed around the chosen 'Fill Pattern' to create the internal and external walls for all layers of a part. This parameter is designed to protect the internal structure of parts by providing a solid outer surface. This parameter ranges from one to four wall layers with Eiger recommending at least two layers.

5.5.3 Fibre Reinforcement Material Parameters

Fibre Material

The 'Fibre Material' parameter determines the type of material used as the fibre reinforcement for producing fibre reinforced composite parts. The Mark One 3D printer is capable of printing parts with the following fibre reinforcement materials: Fibreglass, Carbon Fibre and Kevlar. The choice of fibre reinforcement material can dictate the availability and options for some of the other parameters.

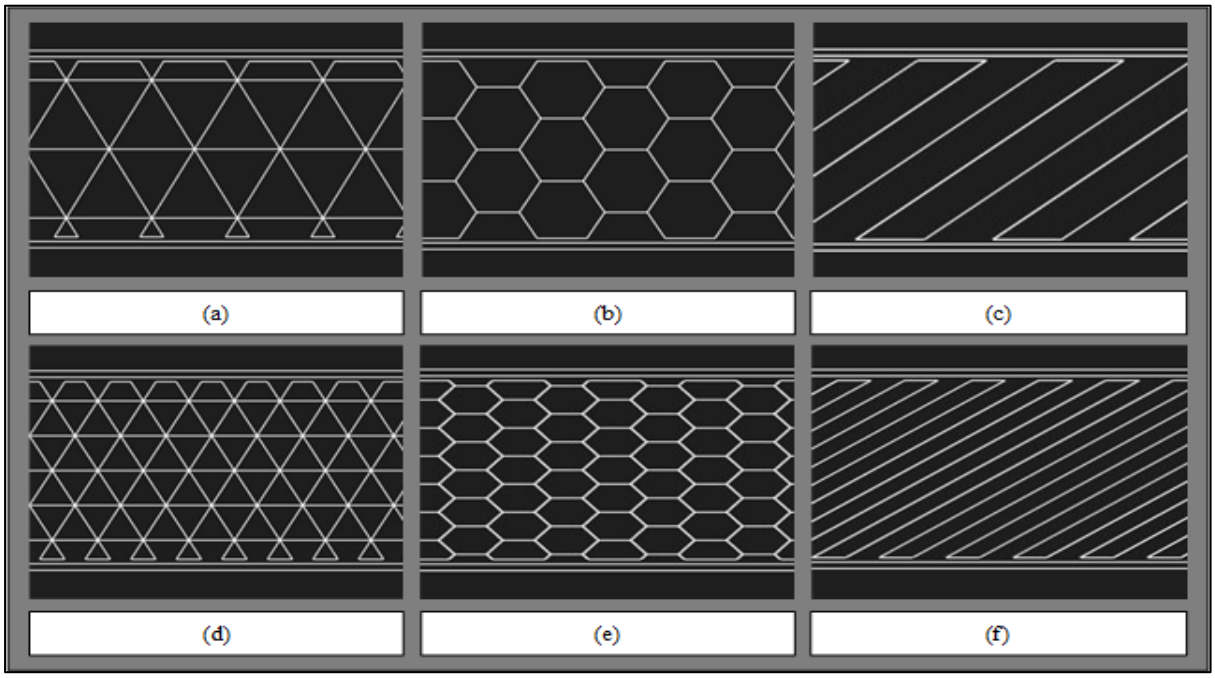

Figure 5-2 - The Nylon Fill Patterns at Different Densities. (a) Triangular Fill at 50% Density, (b) Hexagonal Fill at 50% Density (c) Rectangular Fill at 50% Density, (d) Triangular Fill at 100% Density, (e) Hexagonal Fill at 100 % Density & (f) Rectangular Fill at 100% Density.

Total Fibre Layers

The ‘Total Fibre Layers’ parameter determines the number of layers that will comprise of both nylon and the chosen fibre reinforcement material. This maximum number of layers for this parameter is dependent on the height of the part and the number of ‘Roof & Floor Layers’ in the part. The maximum number of fibre layers is the total number of layers for the part minus the number of ‘Roof & Floor Layers’. Typically, the Eiger software will place the chosen number of layers with fibre reinforcement in a specific layout. The software will, by default, place half of the chosen number of layers with fibre reinforcement just after the ‘Floor Layers’ and the other half just before the ‘Roof Layers’. Eiger does have the ability to customise the layout of the layers that will have the fibre reinforcement.

Fibre Fill Type

The ‘Fibre Fill Type’ parameter determines the pattern used to integrate the fibre reinforcement into the internal structure of parts. There are three options for the ‘Fibre Fill Type’ parameter, shown in Figure 5-3, and are listed as follows: ‘Concentric Fibre’, ‘Isotropic Fibre (Beta)’ and ‘Full Fibre (Beta)’. Each option for this parameter offers different patterns that can alter the mechanical properties of parts based on the chosen pattern. One of the limitations of this parameter is that not all the fibre reinforcement materials can be used for each pattern. For the Mark One, all the fibre reinforcement materials can utilise the ‘Concentric Fibre’ pattern, while the ‘Isotropic Fibre (Beta)’ and ‘Full Fibre (Beta)’ patterns can only be used by fibreglass and Kevlar fibre reinforcement. Additionally, there are several additional parameters that are only available based on the chosen pattern.

Wall to Reinforce

This parameter is only utilised by the ‘Concentric Fibre’ pattern and is used to determine which walls are reinforced with fibre reinforcement. The options for this parameter are dependent on the design and shape of the part. The options for this parameter are as follows: ‘All Walls’, ‘Outer Shell Only’ and ‘Inner Holes Only’.

Concentric Fibre Rings

The ‘Concentric Fibre Rings’ parameter is unique to the ‘Concentric Fibre’ pattern. The ’Concentric Fibre’ pattern reinforces parts along the walls of the part. This is done by having the fibre reinforcement offset from the walls of the part and following the shape of the walls of the part. The ‘Concentric Fibre Rings’ parameter determines the number of times that the fibre reinforcement is placed to follow the shape of the walls of the part, with each successive ring being offset from the previous ring. This parameter requires a minimum of 1 ring and the maximum number of rings is based on the available space within a part. Figure 5-3 shows the effect of additional ‘Concentric Fibre Rings’ on the internal structure of a part.

Fibre Angles

The ‘Fibre Angles’ parameter is only available to composite parts that utilise either Fibreglass or Kevlar fibre reinforcement and utilises either the ‘Isotropic Fibre (Beta)’ or ‘Full Fibre (Beta)’ patterns. This parameter determines the direction that the fibre reinforcement is laid out based on a value that can range between 0 degrees and 360 degrees. This value determines the direction of the longest continuous strands of fibre reinforcement within a part. Figure 5-3 shows a variety of parts reinforced using different values for the ‘Fibre Angles’ parameter.

An additional aspect of this parameter is the ability to create patterns of fibre reinforcement for subsequent layers with fibre reinforcement. By adding multiple values for this parameter separated by a comma, the orientation for fibre reinforcement for each successive layer will alternate between the two values. For example, ‘0,90, will create a pattern of fibre reinforcement that will alternate between 0 degrees and 90 degrees. The total number of values that can be entered this parameter to create a pattern has not been tested but the pattern is limited based on the total number of layers with fibre reinforcement.

Figure 5-3 - (a) Part with 2 Concentric Rings, (b) Part with 5 Concentric Rings, (c) Part with a Fibre Angle of 0 Degrees, (d) Part with a Fibre Angle of 90 Degrees & (e) Part with a Fibre Angle of 45 Degrees.

5.6 Experiment 1 – Initial Analysis

The first method for analysing the capabilities and limitations of the Mark One 3D printer is to conduct preliminary tests to determine the capabilities and limitations of parts created using the Mark One. This involves creating an experiment that uses the Mark One to produce several test specimens. These test specimens will have different combinations of parameters to analyse the effect that parameters have on the mechanical properties of the specimens.

This experimentation will focus on creating specimens that will be used to determine the tensile properties of specimens made using the Mark One. The tensile properties of long/continuous fibre reinforced composite parts are important to know as this is the significant advantage of utilising long/continuous fibres for the fibre reinforcement instead of utilising short fibres. Therefore, the parameters that will be analysed will be the parameters that contribute the most towards the tensile properties of the specimens. The chosen parameters will focus mainly on the parameters that alter the fibre reinforcement within the test specimens.

5.6.1 Specimen Characterisation

The tensile specimens that were created by the Mark One were designed and tested using the ASTM D638 standard (Standard Test Method for Tensile Properties of Plastics) [66]. Within this standard, there are five types of tensile specimens that can be used to determine the tensile properties of specimens made using the Mark One. Of the available types of tensile specimens, the *Type I* specimens were chosen as the *Type I* specimens were the smallest specimen type that would allow the fibre reinforcement to run the length of the specimen multiple time using all the fibre reinforcement patterns. Using the smallest specimen type, with the desired properties, would reduce the time, cost and the material cost used to create the necessary specimens for testing. Figure 5-4 show the technical drawing for a standard *Type I* specimen with the maximum thickness of 7mm.

The preliminary sets of specimens were designed to determine some of the capabilities of long/continuous fibre reinforced composite tensile specimens made using the Mark One. This involves creating tensile specimens using fibreglass, Kevlar and carbon fibre as the fibre reinforcement material.

One of the desired results for this experimentation was for the preliminary sets of tensile specimens to be tested and analysed to determine the effect of adding additional layers with fibre reinforcement has on the tensile properties of specimens. For this analysis to take place, several parameters had to be consistent across all specimens to allow for some form of comparison. Table 5-2 provide the details for the parameters that were consistent across all specimens. The values for these parameters were chosen as these values were either the upper limits or that these values could be used across all fibre reinforcement materials.

The chosen parameters that would be altered to determine the effect that these parameters had on the tensile properties of specimens were the material used for the fibre reinforcement, the 'Fill Density' parameter and the number of layers with fibre reinforcement. Specimens would be created using different values for each of these parameters to do an initial analysis on the effect each parameter had on the tensile properties of specimens. Table 5-3 illustrates the values for each of these parameters for all specimens. Alongside these specimens would be a set of control specimens, shown at the bottom of the table, that were devoid of fibre reinforcement.

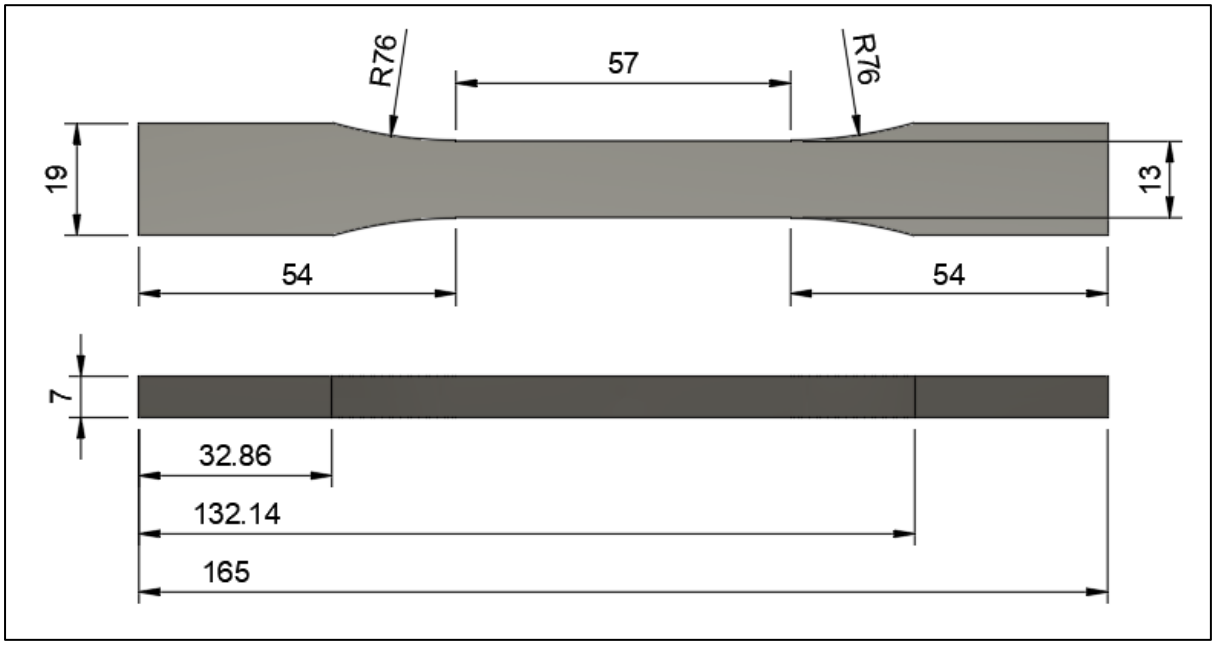

Figure 5-4 - Technical Drawing for a Type I Specimen for ASTM D638.

Set Parameters

Nylon Fill Pattern	Wall Layers	Roof & Floor Layers	Fibre Fill Type	No. of Concentric Rings
Triangular	2	2	Concentric Fibre	5

Table 5-2 - Set Parameters common across all Type I Specimens Subjected to Tensile Testing.

Specimen Number	Fibre Reinforcement Material	Layer Height (mm)	Nylon Fill Density	No. of Fibre Layers
1	Fibreglass	0.1	50%	10
2	Fibreglass	0.1	50%	20
3	Fibreglass	0.1	50%	30
4	Fibreglass	0.1	50%	40
5	Fibreglass	0.1	50%	50
6	Fibreglass	0.1	100%	10
7	Fibreglass	0.1	100%	20
8	Fibreglass	0.1	100%	30
9	Fibreglass	0.1	100%	40
10	Fibreglass	0.1	100%	50
11	Carbon Fibre	0.125	50%	10
12	Carbon Fibre	0.125	50%	20
13	Carbon Fibre	0.125	50%	30
14	Carbon Fibre	0.125	50%	40
15	Carbon Fibre	0.125	50%	50
16	Carbon Fibre	0.125	100%	10
17	Carbon Fibre	0.125	100%	20
18	Carbon Fibre	0.125	100%	30
19	Carbon Fibre	0.125	100%	40
20	Carbon Fibre	0.125	100%	50
21	Kevlar	0.1	50%	10
22	Kevlar	0.1	50%	20
23	Kevlar	0.1	50%	30
24	Kevlar	0.1	50%	40
25	Kevlar	0.1	50%	50
26	Kevlar	0.1	100%	10
27	Kevlar	0.1	100%	20
28	Kevlar	0.1	100%	30
29	Kevlar	0.1	100%	40
30	Kevlar	0.1	100%	50
31	None	0.1	100%	None
32	None	0.1	100%	None
33	None	0.1	100%	None
34	None	0.1	100%	None
35	None	0.1	100%	None

Table 5-3 - Parameters for all Type I Specimens Subjected to Tensile Testing.

All tensile specimens were printed using the same Mark One 3D Printer, were printed using the same orientation and using the same print parameters except for the chosen parameters that would alter the internal structure. For each combination of parameters, a single specimen was printed for tensile testing. Future analysis on the influence parameters had on the tensile properties would result in more specimens being printed for each combination of parameters to provide more valid results.

Regarding the cross-sectional layout of the sections of materials within the composite tensile specimens, the specimens follow a set pattern for materials, but the size of these sections alters as the number of fibre layers is increased. The cross-section of the specimen starts with the solely nylon floor layers. The floor layers are consistent across all specimens and are never altered. After the floor layers are the first set of fibre layers and the size of this section is altered across specimens based on the number of fibre layers. These fibre layers consist of both nylon and the fibre reinforcement and consist of exactly half the total number of fibre layers. The initial fibre layers are then followed by a middle section of just nylon using the 'Triangular Fill' pattern. The size of this section decrease as the number of fibre layers increases. After the middle section of nylon is the second section of fibre layers which contains the remaining half of the total number of fibre layers. The second section of fibre layers also changes in size when the total number of fibre layers is changed. Finally, the last section in the cross-section is the roof layers and the roof layers do not change between specimens. Figure 5-5 illustrates the change in the layout of the fibre reinforcement as the number of layers with fibre reinforcement increases using a diagram.

One areas of concern with the preliminary sets of specimens was the difference in the layer height across different fibre reinforcement materials. Parts printed with carbon fibre on the Mark One are forced into a different layer thickness of 0.125mm compared to the 0.1mm for fibreglass and Kevlar. The inconsistent layer height will make comparing the results from the tensile test specimens with different materials for the fibre reinforcement difficult but will serve as an indication of the capabilities of parts reinforced using the different fibre reinforcement materials.

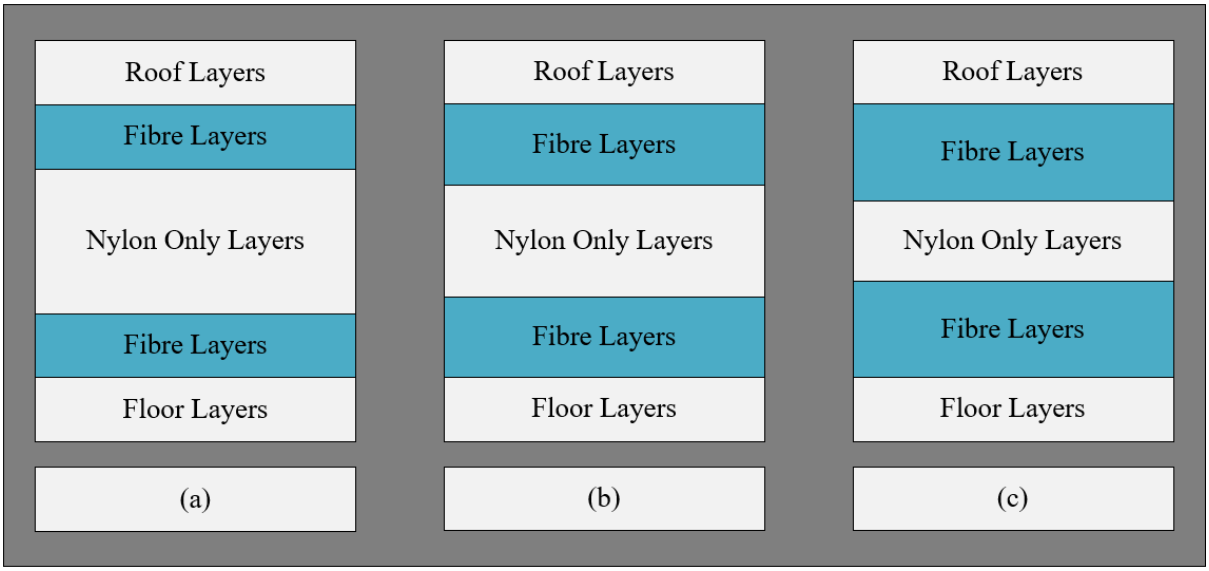

Figure 5-5 - Cross-sectional Structure of Type I Specimens.

5.6.2 Test Procedure & Equipment

The tensile specimens that were made using the Mark One were subjected to tensile testing. An Instron (version 5967) testing machine, with a 30kN load cell, is used for conducting the tensile testing for the specimens. The apparatus used for holding the tensile specimens during the tensile testing were the *2716-015 Wedge Action Grips*. Figure 5-6 shows an image of the Instron and grip used for tensile testing specimens.

The tensile specimens were loaded individually between the grips with a gap of 115mm between the grips, as specified in the ASTM D638 standard specification for a *Type I* specimen. Once the specimens had been loaded into the grips and locked in place, the measured values were zeroed, and the tensile test was conducted at a speed of 10mm/minute. This speed allowed for the tensile specimens to break within the desired period of thirty seconds to five minutes except for the control specimens, as specified in the ASTM D638 standard. Specimens were tested in numerical order starting from *Specimen 1* all the way to *Specimen 35*.

During the tensile testing of specimens, the Instron is measuring and monitoring the key mechanical properties of the specimens. These properties included the tensile stress, the tensile load, the tensile strain and extension of the tensile specimens. Additionally, the Instron would generate a set of graphs and tables for the desired properties of all the specimens and would also provide a readout of the raw data for each of the chosen properties for analysis.

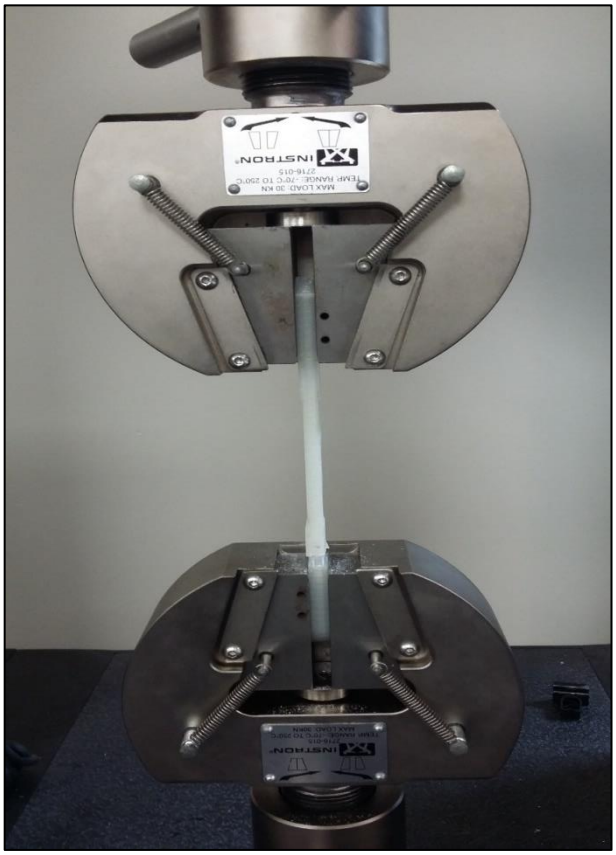

Figure 5-6 - Type I Specimen inside an Instron using the 2716-015 Wedge Action Grips.

During the tensile testing of specimens, several calculations will be made to determine some of the tensile properties of the tensile specimens. These calculations include the tensile stress, tensile strain and Young's Modulus. These calculations will utilise some of the date gathered from the Instron.

The first tensile property that will be recorded is the tensile load experienced by the tensile specimens during testing and up to the point that the specimen fractures. The tensile load will provide information that can be used to for designing part to handle a specific level of tensile load. The tensile load will be used to calculate the tensile stress for the tensile specimens up until the point that the specimens have fractured. The tensile stress can be defined as the force per unit area applied to a material. The tensile stress will provide a more accurate representation of the tensile properties, compared to the tensile load, for the materials used to make the composite tensile specimen by the Mark One. For the tensile stress of the tensile specimens this will involve dividing the tensile load experienced by the tensile specimens during the tensile test by the cross-sectional area of the tensile specimen and is shown below.

$$\sigma = F/A$$

σ – Tensile Stress (MPa)

F – Tensile Force/Load (N)

A – Areas (m^2)

The second tensile property that will be measured during the tensile testing of specimens is the tensile extension of the specimens up until the specimen fractures. The tensile extension of the specimens is the amount that the tensile specimens stretch/extend during the tensile test. The tensile extension provides insight into how parts, made using the materials available from the Mark One, will extend when subjected to tensile load.

The tensile extension will be used to calculate the tensile strain experienced by the tensile specimens. Tensile strain can be defined as the relative deformation of a specimen subjected to a tensile force. The tensile strain will be used to calculate the Young's Modulus of the tensile specimens and the calculation for the tensile strain is shown below.

$$\varepsilon = \frac{L - L_O}{L_O}$$

ε – Tensile Strain (m/m)

L – Instantaneous Length (m)

L_O – Initial Length before testing (m)

The final tensile property that will be calculated is the Young's Modulus of the tensile specimens. Young's Modulus can be defined as the ability for a material to withstand changes in length under either tension or compression. The calculation for the Young's Modulus, shown below, involves dividing the tensile stress of a specimen by the tensile strain of the specimen.

$$E = \frac{\sigma}{\varepsilon}$$

E – Young's Modulus (MPa)

σ – Tensile Stress (MPa)

ε – Tensile Strain (m/m)

5.6.3 Results & Discussion

After conducting the tensile tests for all the tensile specimens produced using the Mark One, the tensile properties and raw data garnered from the Instron were assessed to provide some analysis on the results from the tensile tests. This analysis would provide some insight into the effect that certain parameters had on the tensile properties of specimens. The results from the tensile testing are shown in Table 5-4. The results from the tensile tests are also illustrated using graphs based on the material used for the fibre reinforcement. Figure 5-7 shows the results for the fibreglass specimens, Figure 5-8 shows the results for the carbon fibre specimens, Figure 5-9 shows the results for the Kevlar specimens and Figure 5-10 shows the results for the control specimens.

Analysing the results from the tensile testing does provide some insight into the capabilities and limitations of the Mark One 3D printer. The control specimens achieved an average tensile stress of 12.21MPa with an average extension of 168.83mm at the point of fracturing. As expected, the addition of fibre reinforcement greatly increased the tensile stress for specimens for all fibre reinforcement materials compared to the control specimens. Additionally, the addition of the fibre reinforcement reduced the elongation of specimens prior to fracturing compared to the control specimens.

The maximum tensile stress achieved was from *Specimen 23* with a tensile stress of 132.31MPa. This specimen has a tensile stress almost twelve times higher than the control specimens. The interesting aspects of this specimen are that the specimen was made using Kevlar as the fibre reinforcement material and that the specimen did not have the highest amount of fibre layers or nylon fill density. This specimen was not expected to have the highest tensile stress, however, there are few reasons that might explain this result.

The first possible reason for explaining the specimen with the highest tensile stress is that only one specimen was made for each combination of parameters. Having only a single specimen instead of several copies of the same specimens for testing can lead to anomalies in the results. This experimentation serves as a baseline for subsequent experimentation by providing insights into the capabilities and limitations of tensile specimens made using the Mark One. Therefore, subsequent experimentations will have tensile specimens with multiple copies for each set of tensile specimens.

Specimen Number	Load at Tensile Strength (N)	Tensile Stress at Tensile Strength (MPa)	Extension at Tensile Strength (mm)	Tensile Strain at Tensile Strength (mm/mm)
1	4302.75	47.28	7.42	0.04
2	4753.95	52.24	7.90	0.05
3	8029.78	88.24	18.41	0.11
4	9293.30	102.12	15.18	0.09
5	9318.79	102.40	11.50	0.07
6	3858.17	42.40	9.84	0.06
7	4862.40	53.43	14.69	0.09
8	9587.31	105.36	23.35	0.14
9	9406.55	103.37	15.33	0.09
10	10131.64	111.34	13.02	0.08
11	5784.87	63.57	16.02	0.10
12	10529.19	115.71	16.16	0.10
13	12037.87	132.28	15.19	0.09
14	11740.14	129.01	9.80	0.06
15	9588.27	105.37	7.83	0.05
16	4984.84	54.78	13.51	0.08
17	9761.82	107.27	14.13	0.09
18	10534.23	115.76	12.71	0.08
19	11452.88	125.86	9.02	0.05
20	11155.24	122.59	9.02	0.05
21	4648.12	51.078	6.59	0.04
22	8349.36	91.75	12.24	0.07
23	12039.88	132.31	14.03	0.09
24	11555.75	126.99	11.02	0.07
25	10833.23	119.05	10.07	0.06
26	4155.14	45.66	12.86	0.08
27	8524.29	93.67	13.37	0.08
28	10792.15	118.60	15.67	0.09
29	9969.10	109.55	12.72	0.08
30	9193.11	101.02	10.38	0.06
31	1192.52	13.10	172.86	1.05
32	1112.48	12.23	160.37	0.97
33	1122.68	12.34	171.54	1.04
34	1086.27	11.94	182.90	1.11
35	1039.74	11.43	156.47	0.95

Table 5-4 - Tensile Test Results for all Type I Specimens.

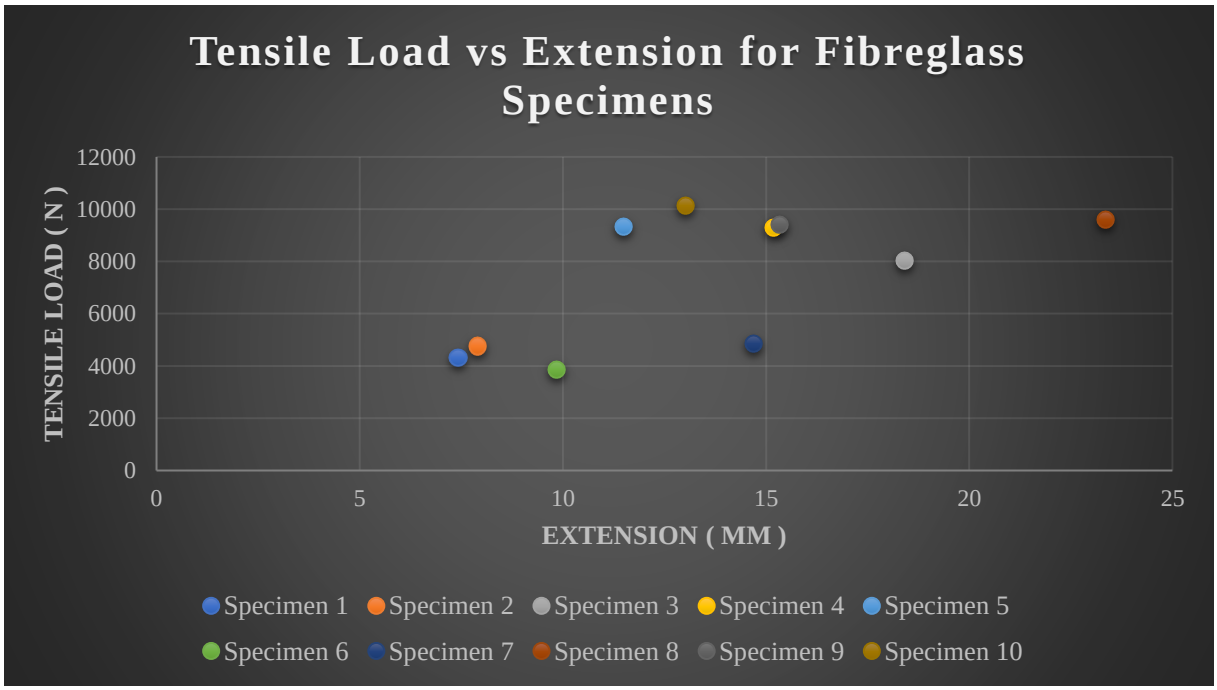

Figure 5-7 - Tensile Load vs Extension Graph for Fibreglass Specimens.

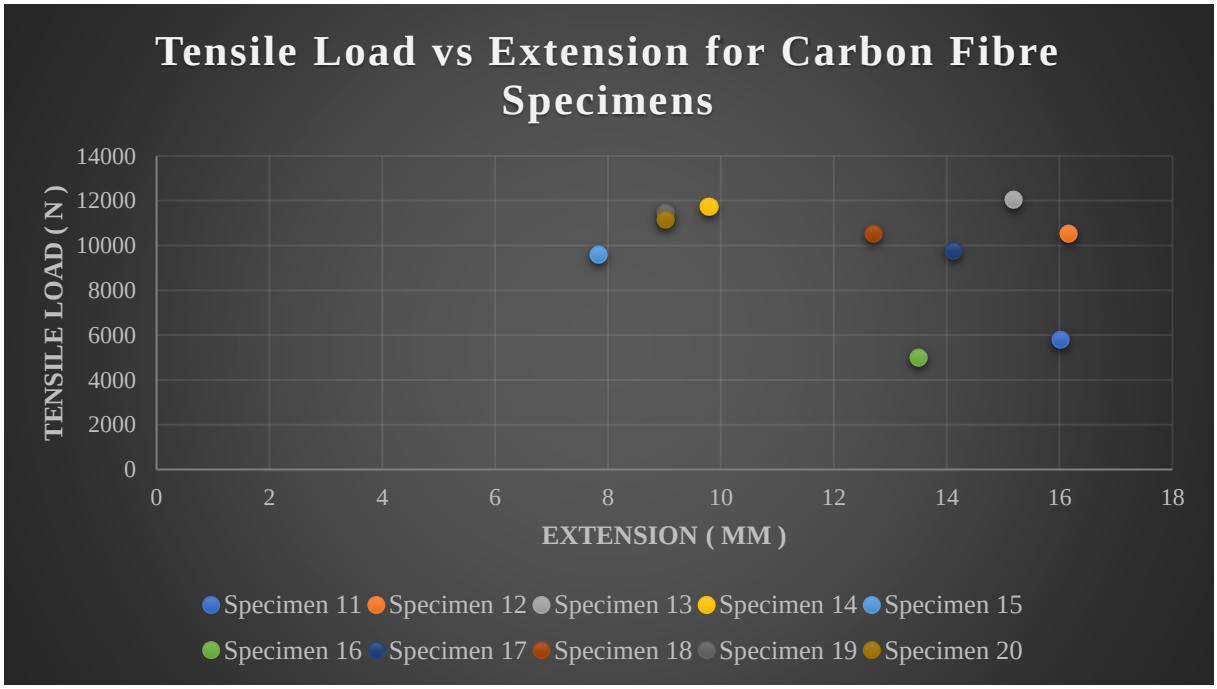

Figure 5-8 - Tensile Load vs Extension Graph for Carbon Fibre Specimens.

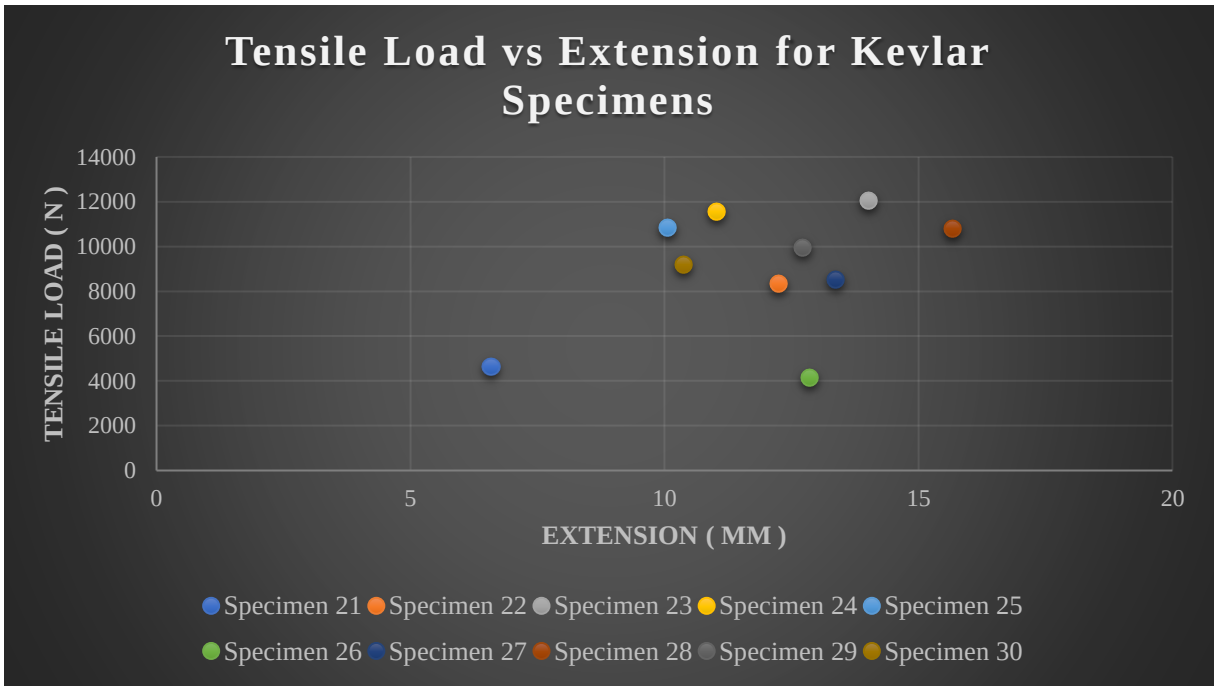

Figure 5-9 - Tensile Load vs Extension Graph for Kevlar Specimens.

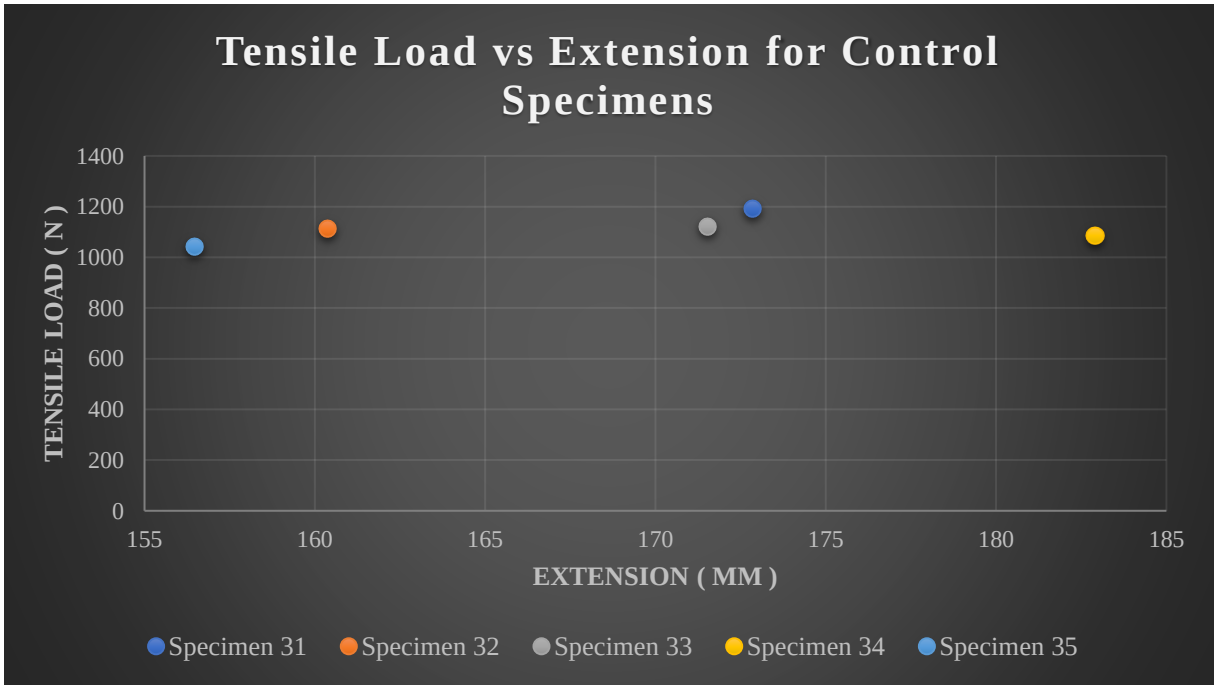

Figure 5-10 - Tensile Load vs Extension Graph for Control Specimens.

The second reason behind the surprising results is the way that the specimens were fracturing during the tensile test. The specimens for ASTM D638 are designed to fracture in the narrower section of specimens. If the specimens do not fracture in this section, the results from this testing are not accurate. The specimens made using the Mark One were not fracturing in the narrow section of the specimens during the tensile test but would fracture where the grips contacted the specimens. The grips would penetrate through the roof and floor layers of solid nylon and contact the fibre reinforcement. This fibre reinforcement would fracture under the contact from the grips and this fracture would propagate throughout the specimen, as shown in Figure 5-11. This leads to the results gathered using these specimens to not be accurate and can partially attribute to *Specimen 23* having the highest tensile stress.

The specimens fracturing in the section inside the grips was consistent across all specimens excepts for the control specimens. These results indicate two key observations with the tensile specimens. The first observation is that the results gathered are not an accurate representation of the tensile properties of the specimens and that the specimens would reach a higher tensile stress if the grips did not cause the fibre reinforcement to fracture. If a method was devised to protect the fibre reinforcement up until the point that the specimens would fracture as expected, this would provide a more accurate representation of the tensile properties of the specimens made using the Mark One.

Figure 5-11 - Type I Specimen that has Fractured prematurely during Tensile Testing.

The second observation is that the compressive force of the grips onto the specimen during the tensile test reaches the point of fracture before the force of elongating the specimens reaches the point of fracture. This is the reason behind the specimens not fracturing as intended. Possibly, the amount of fibre reinforcement could be reduced drastically to increase the likelihood of the specimens fracturing due to the elongation of the specimen rather than fracturing due to the compressive force of the grips.

5.6.4 Conclusion

The conclusions from this experimentation have shed light on some of the capabilities and limitations of the Mark One. The tensile specimens were made and tested in accordance with the ASTM D638 standard but the results from the tensile tests are not accurate. The results did provide some interesting insights into the capabilities of tensile specimens made using different materials for the fibre reinforcement as well as the effect that altering certain parameters can have on the tensile properties. All the gathered data and insight will be useful for the development of future experimentation.

The problem with the tensile specimens fracturing in the sections within the grips is a problem that indicates that the tensile specimens could reach a higher tensile stress. Therefore, the next stage of this research will be focussed on developing methods for tensile testing specimens from the Mark One that do not result in the specimens fracturing between the grips. Once this problem has been solved, a more thorough analysis can be conducted on the tensile specimens from the Mark One.

5.7 Altered Specimen Designs

The next stage for analysing the capabilities and limitations of the Mark One 3D printer is to devise a method for tensile testing the tensile specimens without the specimens fracturing within the grips. Devising a method that allows the specimens to fracture in the narrower section of the specimen will allow for a more accurate representation of the tensile properties of parts made using the Mark One.

Several designs were devised and tested to ensure that the specimens would fracture along the narrow section of the tensile specimens. Most of these designs followed the basis of reducing the amount of fibre reinforcement within the tensile specimens and/or protecting the fibre reinforcement. Of the designs that were tested to solve the problem of the specimens fracturing

within the grips, three designs were tested more thoroughly than the other designs. These designs either showed more promise or provided interesting observations during development or during the tensile testing.

5.7.1 Design 1 – Stainless-Steel Tabs Design

The first design for solving the problem of the tensile specimens fracturing within the grips was the implementation of two 3D printed stainless-steel tabs to protect the thicker sections of the tensile specimens. The aim of the tabs was to stop the grips from contacting the fibre reinforcement within the specimens. Preventing the grips from contacting the fibre reinforcement would reduce the possibility of the specimens fracturing within the grips and produce an accurate result.

The stainless-steel tabs were designed to consist of two parts that would fit together to an end of the tensile specimen and protect the ends from the grips. The two parts were the same part and would have a cavity that one end of the tensile specimen could be press fit into and secured. The two parts for the stainless-steel tabs were made using the 3D ProX 100 3D printer and a CAD model of one part of the stainless-steel tabs is shown in Figure 5-12.

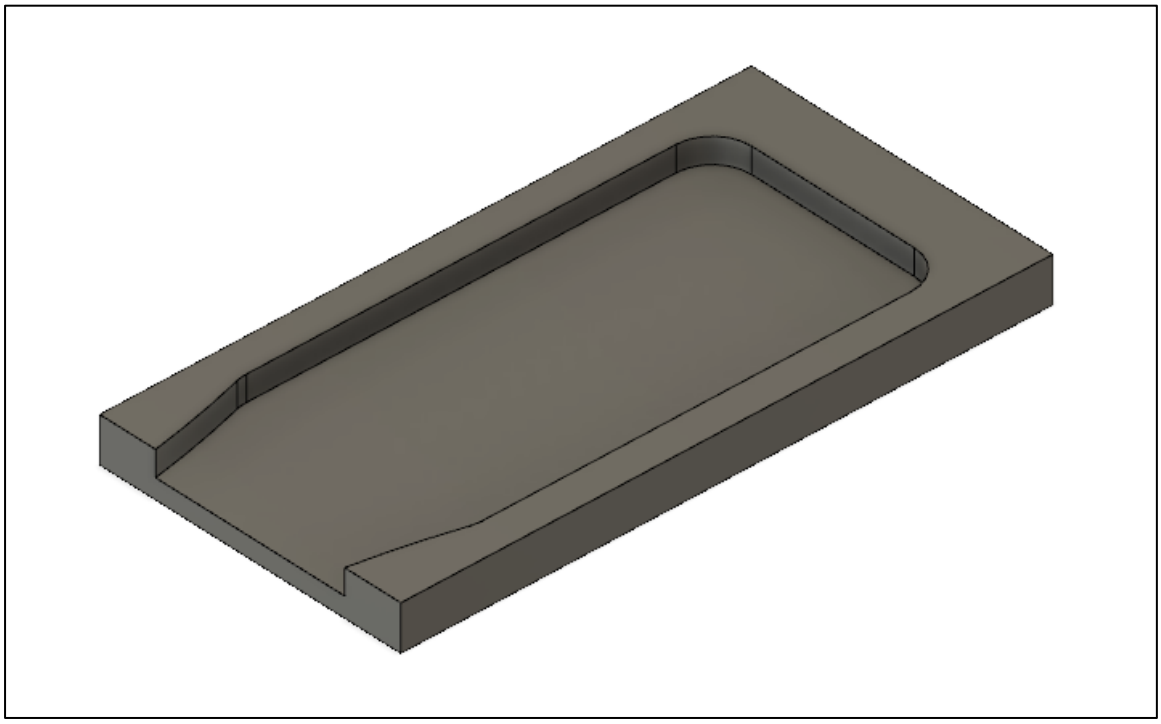

Figure 5-12 - CAD Model of the Stainless-Steel Grippers.

Implementing the stainless-steel tabs into tensile testing of the specimens required the specimens to be altered. The grips used for tensile testing had maximum gap between the grips of about 7.5mm. With the tensile specimens having a thickness of 7mm, this would allow only 0.25mm thick section of stainless stainless-steel to be positioned on either side of the specimen before the specimen would not fit between the grippers. Therefore, the thickness of the specimens was reduced to 4mm and this allowed a section of 1.5mm of stainless-steel to be positioned on either side of specimens.

For tensile testing the specimens with the stainless-steel tabs, fibreglass was chosen as the material for the fibre reinforcement as it was the weakest and cheapest material to conduct testing. The internal structure for the specimens used to test the stainless-steel tabs effectiveness had the same internal structure as the initial experimentation specimens with a few minor differences. These specimens had a 100% density for the 'Nylon Density' parameter, had ten fibre layers and the number of concentric rings was set to five.

The results from tensile testing with the stainless-steel tabs lead to some interesting results. The stainless-steel tabs were able to stop the specimens from fracturing in the thicker section within the grippers but stopped the specimens from fracturing at all. The results from testing several specimens were that the nylon within the thicker sections of the specimens would begin to deform and stretch during the tensile test. This deformation of the tensile specimens would be pulled out of the stainless-steel tabs. This result means that the stainless-steel tabs could not be used for tensile testing the specimens

An interesting observation from this testing is that the thicker sections of the specimens deformed before the tensile specimen would fracture. There is a possibility that if the amount of fibre reinforcement would be reduced, that the tensile specimens might fracture before the specimens begun to deform, but there is no guarantee of the fracture happening within the narrow section of the specimens. Therefore, the stainless-steel tab design was not utilised.

5.7.2 Design 2 – Steel Insert Design

The second design for solving the problem of the tensile specimens fracturing at the thicker sections within the grips was the addition of steel inserts. The steel inserts were designed to be integrated into the specimens and would be situated at the ends of the tensile specimens. The steel inserts would be used to resist the grips from compressing the specimens and reaching the fibre reinforcement within the specimens.

For the steel inserts to be used with the tensile specimens, the tensile specimens were redesigned to have a single hole on each end of the specimens for the inserts to be placed. These holes would allow for steel inserts to be inserted into prior to tensile testing. The steel inserts were made from 7mm lengths of steel rod with a diameter of 7mm.

A possible problem with altering the design with holes was that this could lead to possible stress concentrations in the areas around the holes and that these stress concentrations could lead to specimens failing prematurely. Therefore, a second alteration was made to the design to attempt to alleviate the stress concentrations that could cause the fibre reinforcement to fail prematurely. The second alteration was to round the ends of the tensile specimens, shown using a CAD model in Figure 5-13. This alteration would result in the fibre reinforcement being rounded at the end of the tensile specimens rather than being at sharp angles. Figure 5-14 shows the difference in the fibre reinforcement for a normal tensile specimen and a tensile specimen with the rounded ends.

There were two types of specimens that were tested to analyse the performance of this new design. The first set of specimens had fibre reinforcement levels less than the specimens used in the initial experimentation and the second set of specimens had fibre reinforcement that is similar to the levels of fibre reinforcement used in the initial experimentation. Each set of specimens used the fibreglass fibre reinforcement as it is the weakest fibre reinforcement material and is the most cost-effective.

The results from the tensile testing specimens with the steel inserts is that the design is not suitable for several reasons. The aim of the steel insert design was to stop the specimens from fracturing within the grips and this design did not solve this problem. The first set of specimens were fracturing within the grips and the fracturing was caused by stress concentrations around the holes. The stress concentrations generated results that were lower than the results garnered from the initial experimentation. The sections around the holes would fracture as the specimens elongated and then the fracture would propagate throughout the specimen. Attempts to relocate and alter the size of the holes for the inserts did little to stop the specimens from fracturing within the grips.

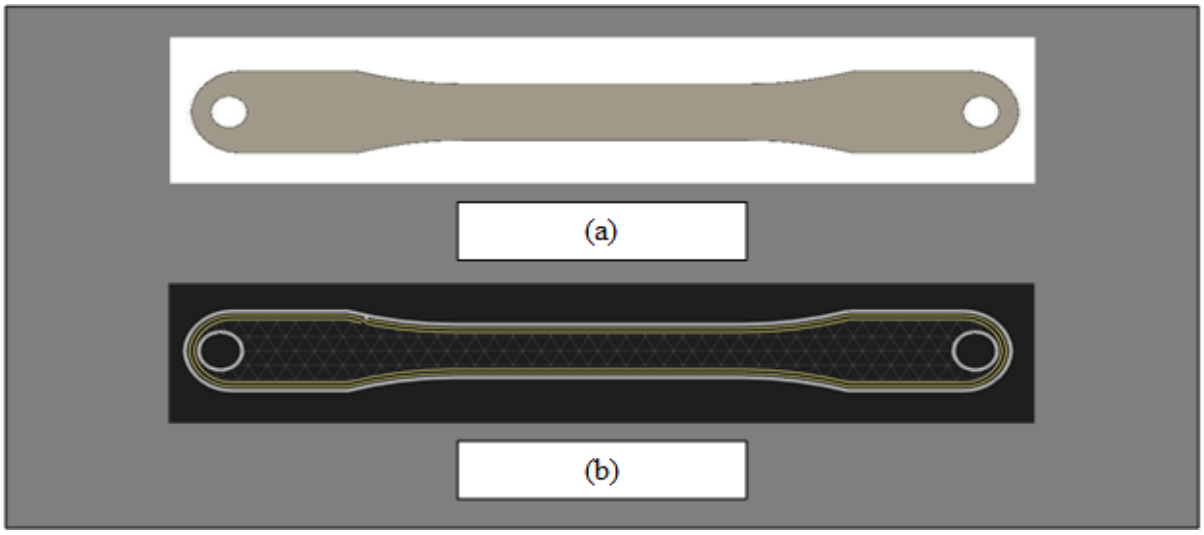

Figure 5-13 - (a) A Top View of a CAD Model of the Altered Specimen Design, (b) The Fibre Reinforcement within the Altered Specimen Design.

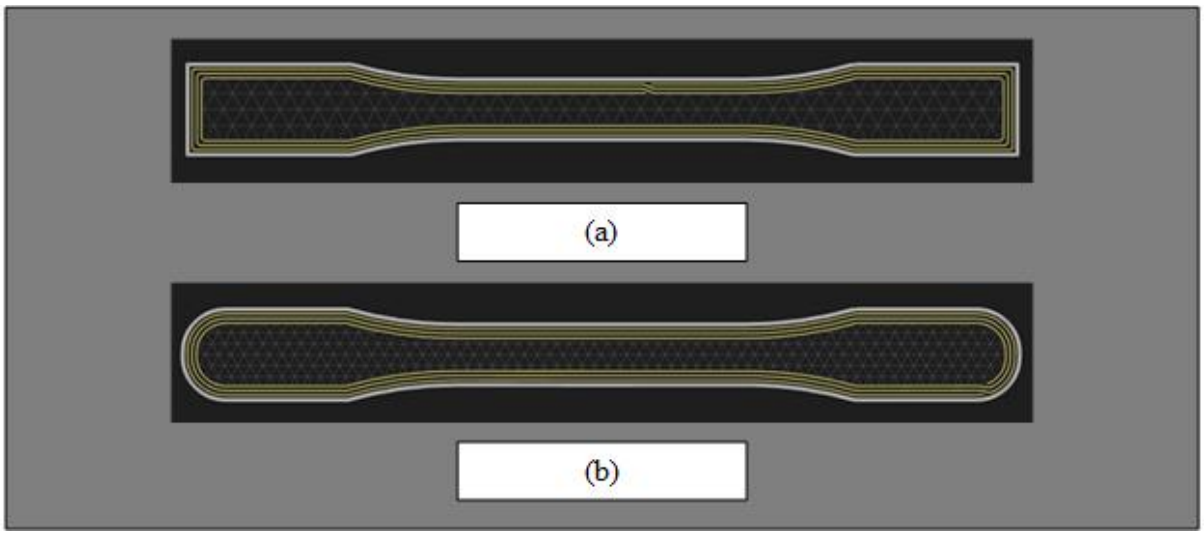

Figure 5-14 - (a) The Fibre Reinforcement within a Type I Specimen using a Concentric Fill Pattern, (b) The Fibre Reinforcement within an Altered Specimen Design without holes using a Concentric Fill Pattern.

The second set of specimens were more rigid, due to the increased fibre reinforcement, and these specimens also failed within the grips, but the reasoning was slightly different. During the tensile testing of these specimens, the steel inserts within the specimens started to compress and deform before the specimens would fracture. This deformation allowed the grips to reach the fibre reinforcement within the specimen and caused the specimens to fracture within the grips.

5.7.3 Design 3 – Built-in Tabs Design

The final design for solving the problem of the tensile specimens fracturing within the grips involved a similar design as the stainless-steel tabs. The tabs would be used to protect the fibre reinforcement within the specimens, but the design of these tabs would built-in to the specimens during the printing process rather than being added after printing. The tensile specimens would be printed with tabs to protect the fibre reinforcement within the specimens. The built-in tabs to protect the fibre reinforcement will be made using the nylon material.

The design for the specimens with the built-in tabs is based on increasing the thickness of the tensile specimens at the areas of the specimens that will be within the grips. Increasing the thickness at these areas will provide additional protection for the fibre reinforcement within these areas. As these built-in tabs are a part of the specimens rather than being added afterwards, there is less of a chance of repeating the result of the stainless-steel tabs where the tabs and specimens separated from one another during the tensile tests.

With the new design of the tensile specimen having different thicknesses, the change of thickness has been made to be a gradual change rather than a sudden change. The gradual change reduces the chances of the specimens failing at the change in thickness compared to a sudden change in thickness. Additionally, the new design has had the ends of the specimens rounded off to reduce the build-up of stress concentrations on the ends of the specimens. Figure 5-15 shows the technical drawing for the tensile specimen with the built-in tabs.

Regarding the fibre reinforcement for the tensile specimens with built-in tabs, the level of fibre reinforcement would be less than the amount of fibre reinforcement used in the specimens for the initial experimentation. The reduction in fibre reinforcement follows the idea of strengthening the thicker sections within the grips and weakening the thinner sections to increase the likelihood of the specimens fracturing in the thinner sections. The fibre reinforcement will be situated within the specimens using the same layout as used in previous specimens to reinforce the specimens along the total length of the specimens.

One additional aspect that will be tested will be the effect that adding fibre reinforcement into the built-in tabs to increase the rigidity of the tabs and possibly improve the protection for the fibre reinforcement running along the length of the specimens. Figure 5-16 and Figure 5-17 shows diagrams illustrating the difference between adding extra fibre reinforcement within the built-in tabs to the internal structure of tensile specimens.

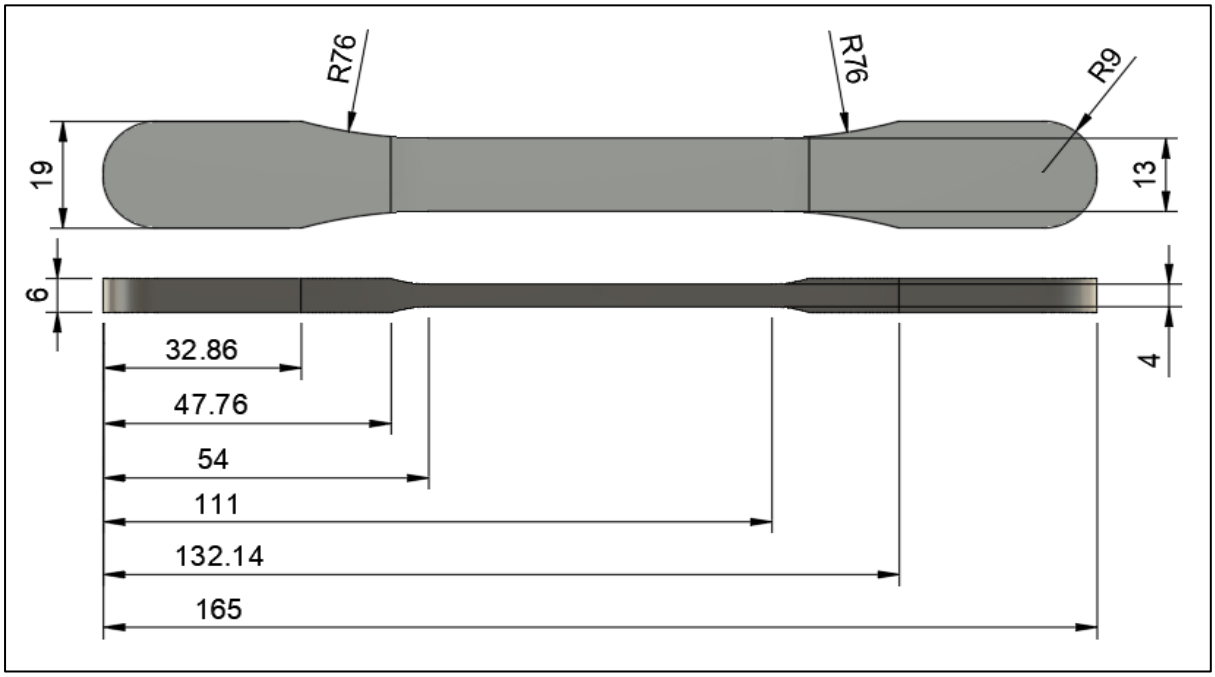

Figure 5-15 - Technical Drawing for the Type I Specimens with Built-in Tabs.

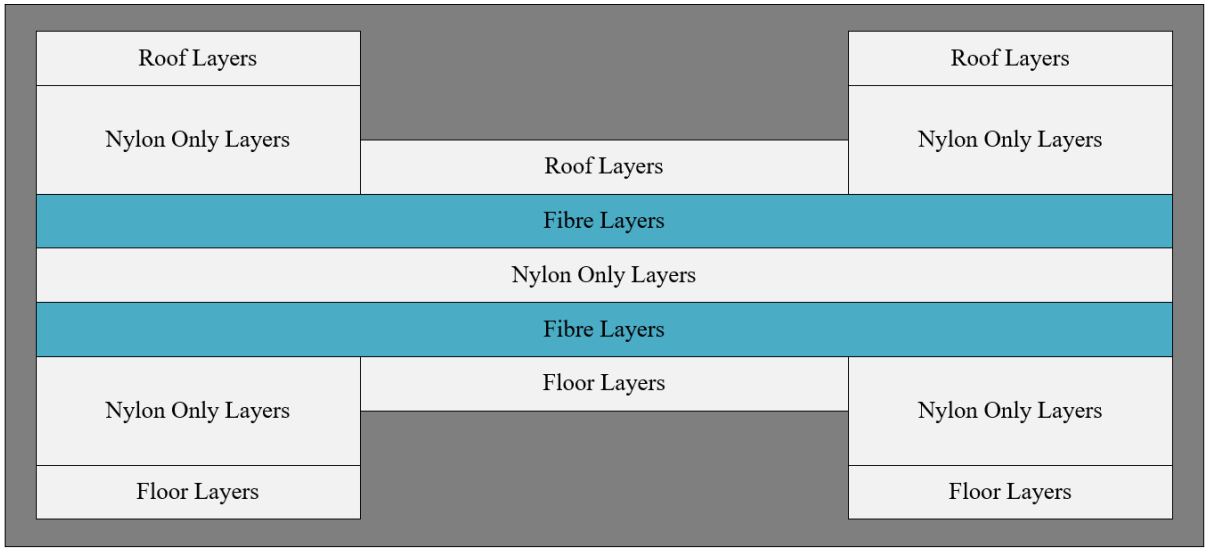

Figure 5-16 - The Cross-sectional Structure for a Type I Specimen with no Additional Fibre Reinforcement.

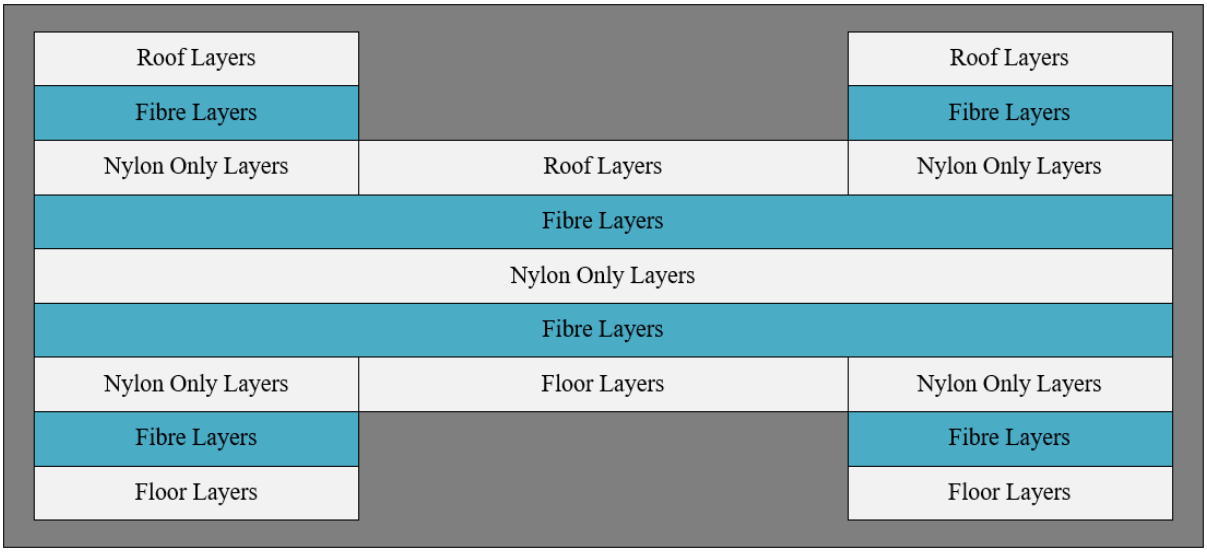

Figure 5-17 - The Cross-sectional Structure for a Type I Specimen with Additional Fibre Reinforcement.

The results from testing multiple iterations of the specimens with the built-in tabs are that these specimens are reliably able to fracture in the intended section of the specimens and that the addition of the extra fibre reinforcement in the thicker sections of the specimens resulted in specimens being more likely to fracture as intended. The results from using this design show that this design can be used to do a more thorough analysis of the capabilities and limitations of the Mark One.

During the tensile testing of the built-in specimens, several observations were made regarding some of the parameters that dictate the internal structure of the specimens. These observations include several set values for different parameters and several value limits for other parameters. These set values and value limits were essential for ensuring that the tensile specimens fractured at the narrow section of the specimens and will be used to determine the parameters that will be altered for a more thorough analysis of the Mark One's capabilities.

5.8 Experiment 2 – Thorough Analysis

The next stage of this research is to conduct a thorough analysis on the limitations and capabilities of the Mark One. The experimentation will utilise the altered specimen design using the built-in tabs with additional fibre reinforcement. The analysis will subject several tensile specimens, with various combinations of parameters, to tensile testing to detail the tensile properties of specimens made using the Mark One and to understand the effect that the chosen parameters have on the tensile properties of specimens.

One of the key aspects of this experimentation is that there will be two separate sets of specimens that will be subjected to tensile testing. The first set of specimens would be made using fibreglass for the fibre reinforcement and the second set of specimens would use the carbon fibre as the fibre reinforcement. The main reason behind testing two sets of specimens is that the layer thickness between the carbon fibre reinforcement and the fibreglass and Kevlar fibre reinforcement is different. Therefore, any results from the fibreglass testing could not be utilised for carbon fibre parts. A similar study was needed to gather results related to the use of carbon fibre as the fibre reinforcement as well as provide a link towards the carbon fibre composite filament research.

5.8.1 Design of Experiment

The design of experiment for analysing the limitations and capabilities of the Mark One and to analyse the effect certain parameters have on the tensile properties of specimens follows the Taguchi method. The Taguchi method is used widely in engineering with a focus on manufacturing. The Taguchi method has been used to analyse the effect that certain parameters can have on a manufacturing process to yield a desired outcome [67]. The Taguchi method can be used to determine the optimal combination of parameters to yield the desired outcome for a manufacturing process but can also be used to determine the optimal combination of parameters to achieve the best levels of tensile properties for specimens made using the Mark One.

The Taguchi method has an additional benefit that reduces the required number of experiments to be conducted to achieve the desired results using orthogonal arrays. These orthogonal arrays are used to determine the minimal amount of experiments that need to be conducted based on the number of parameters being analysed and the number of levels for each parameter. The number of parameters and levels for each parameter determines which orthogonal array is used to determine the amount of experiments that need to be conducted.

The Taguchi method starts by identifying the objective function that needs to be optimised and the method for testing the optimisation. The method for optimising the objective function needs to include noise factors, failure modes and testing conditions. For the objective function to be optimised, the control parameters and levels for each of these parameters that contribute towards the objective function need to be identified. Note that the number of levels across each parameter must be same. Once the parameters and the levels have been identified, an orthogonal array matrix is chosen based on the number of parameters and levels for each of the

parameters. The orthogonal array matrix is then used to determine the minimum number of experiments that need to be conducted to optimise the objective function.

Following the orthogonal array matrix, the experimentations specified in the matrix will be conducted and the results gathered. The results will be analysed to optimise the objective function. The analysis includes an ANOVA to determine the significance of the different parameters, a main effect plot analysis to determine the optimal level for each of the parameters and a factor contribution rate analysis to determine the contribution of each parameter towards the objective function.

After the analysis of the results from the experiments, a final experiment will be conducted using the optimum levels for each parameter. This experiment will verify the findings from the analysis for the optimal parameter levels and prove that the optimal parameter levels achieve an optimised objective function.

For this experimentation, the objective function that needs to be optimised is the tensile properties of the tensile specimens made using the Mark One. The method for testing the optimisation of the tensile properties will involve the tensile testing of tensile specimens in accordance with the ASTM D638 standard. The parameters and levels for the experimentation will be the parameters that will contribute significantly towards the tensile properties of specimens while ensuring that the tensile specimens will fracture as required by the standard. These parameter and levels for each parameter will be put into an orthogonal array matrix to determine the minimum amount of experiments needed to optimise the tensile properties of tensile specimens using the chosen parameters and parameter levels. Each experiment will involve the tensile testing of tensile specimens using the parameter levels specified in the matrix.

After conducting each of the tensile tests, analysis will be conducted to determine the contribution that each parameter has on the tensile properties of specimens and determine the optimal level for each parameter. The final experiment will utilise a set of tensile specimens with the optimal level for each parameter to verity that these are the optimal parameter levels for the tensile properties for tensile specimens made using he Mark One.

5.8.1.1 Specimen Characterisation

The tensile specimens that will be used will have the built-in tab design for both the fibreglass and carbon fibre reinforced specimens. For each of the sets of specimens, there are several parameters that will be set across all specimens, depending on the material being used for the fibre reinforcement. Table 5-5 show the set parameters for the specimens with fibreglass as the fibre reinforcement material and Table 5-6 shows the set parameters for the specimens with carbon fibre as the fibre reinforcement material.

One aspect of the design for the tensile specimens with the built-in tabs, is the additional fibre reinforcement that is placed into the tabs. This fibre reinforcement provides additional protection for the fibre reinforcement material running the length of the specimens. The fibre reinforcement for the tensile specimens will involve four layers of the fibre reinforcement, two layers each on the top and bottom section of the specimens, with the 'Concentric Fill' pattern with seven 'Concentric Rings'. Figure 5-18 illustrates the additional fibre reinforcement used for the fibreglass and carbon fibre reinforced tensile specimens.

For the Taguchi method to be used to determine the levels for each parameter to achieve the desired outcome, the parameters that have the greatest impact on the desired outcome must be identified. As the desired outcome for this experimentation is the tensile properties of specimens made using the Mark One, the parameters that will have the greatest impact on the tensile properties of specimens will be utilised. The parameters that will have the greatest impact on the tensile properties of specimens, based on the set parameters, are the following: 'Nylon Fill Pattern', 'Number of Concentric Rings' and 'Number of Fibre Layers'. The levels for these parameters are based on previous research towards getting tensile specimens to fracture correctly and are shown in Table 5-7.

Based on the number of parameters and the number of levels for each parameter, an orthogonal array can be made to determine the combinations of parameter levels that will be produced for tensile testing. The orthogonal array that is used in this experimentation is shown in Table 5-8 and is made in accordance with the Taguchi method. In addition to the tensile specimens detailed in the orthogonal array, a set of control specimens will be printed with the set parameters specified earlier and a 'Hexagonal Nylon Fill Pattern', but without the fibre reinforcement running the length of the specimens. Table 5-9 and Table 5-10 illustrate some of the important properties for each set of specimens. Please note that the information in this

table is generated using the Eiger software and that three copies of each specimen type were printed for tensile testing.

Figure 5-18 - Fibre Reinforcement within the Built-in Tabs.

Fibreglass Set Parameters

Fibre Material	Fibre Fill Type	Layer Height (mm)	Roof & Floor Layers	Wall Layers	Nylon Fill Density
Fibreglass	Concentric Fibre	0.1	8	2	100%

Table 5-5 - Set Parameters for Fibreglass Specimen using the Built-in Tab Design.

Carbon Fibre Set Parameters

Fibre Material	Fibre Fill Type	Layer Height (mm)	Roof & Floor Layers	Wall Layers	Nylon Fill Density
Carbon Fibre	Concentric Fibre	0.125	8	2	100%

Table 5-6 - Set Parameters for Carbon Fibre Specimen using the Built-in Tab Design.

Parameter	Parameter Name	Levels of Parameters		
		1	*2*	*3*
A	Nylon Fill Pattern	Hexagonal	Triangular	Rectangular
B	Number of Concentric Rings	2 Rings	3 Rings	4 Rings
C	Number of Fibre Layers	2 Fibre Layers	4 Fibre Layers	6 Fibre Layers

Table 5-7 - The Parameters & Levels for Each Parameter used for the Taguchi Method.

Specimens Type	Parameter A	Parameter B	Parameter C
A	A1	B1	C1
B	A1	B2	C2
C	A1	B3	C3
D	A2	B1	C2
E	A2	B2	C3
F	A2	B3	C1
G	A3	B1	C3
H	A3	B2	C1
I	A3	B3	C2

Table 5-8 - The Orthogonal Array used for the Taguchi Method.

Specimen Type	Nylon Volume (cm^3)	Fibre Volume (cm^3)	Part Weight (g)	Material Cost (USD)
Control	13.85	1.04	16.91	4.49
A	11.66	1.17	14.7	4.22
B	11.5	1.42	14.93	4.56
C	11.28	1.78	15.26	5.06
D	11.22	1.3	14.43	4.32
E	11.06	1.61	14.73	4.75
F	11.22	1.29	14.4	4.31
G	13.83	1.43	17.54	5.07
H	14.05	1.23	17.43	4.82
I	13.75	1.54	17.58	5.21

Table 5-9 - Material Properties for the Types of Fibreglass Specimens being Tensile Tested.

Specimen Type	Nylon Volume (cm^3)	Fibre Volume (cm^3)	Part Weight (g)	Material Cost (USD)
Control	11.18	0.6	13.14	4.16
A	12.48	0.77	14.8	4.92
B	12.29	1.07	15.03	5.8
C	12.01	1.52	15.35	7.08
D	12.07	0.93	14.58	5.31
E	11.86	1.31	14.88	6.4
F	12.07	0.91	14.55	5.26
G	14.38	1.09	17.34	6.28
H	14.61	0.84	17.25	5.59
I	14.23	1.22	17.36	6.64

Table 5-10 - Material Properties for the Types of Carbon Fibre Specimens being Tensile Tested.

5.8.1.2 Test Procedure & Equipment

For the tensile testing of the tensile specimens made using the Mark One, an Instron, with a 30kN load cell, will be used to administer the tensile test. *2716-015 Wedge Action Grips* will be used to hold the tensile specimens during the tensile test. Specimens will be loaded individually into the grips for the tensile test with the grips situated at 115mm apart from one another, in accordance with ASTM D638.

The Instron will be used to gather information regarding the tensile properties of the specimens up until the point that the specimens will fracture. These tensile properties include the tensile load, the tensile stress and tensile strain for specimens during the tensile test. The information gathered from the Mark One will be collated into the form of tables and graphs to illustrate this information for interpretation. Additionally, the Instron will generate the raw data for the desired the tensile properties throughout the tensile tests for further analysis. This raw data will also serve as assurance for the tables and graphs generated from Instron to ensure that the correct values are shown for each of the tensile properties.

For the tensile testing of specimens, the gap between the grips will increase at a rate of 5mm/s for the fibreglass specimens and 3mm/s for the carbon fibre specimens. This rate was chosen as it consistently allowed the specimens to fracture between thirty seconds and five minutes, as stated in ASTM D638. The rate at which the distance between the grips increases will be adjusted for control specimens as the control specimens do not have fibre reinforcement running the length of the specimens and will be more likely to extend further than the other specimens.

The results garnered from the tensile testing have only been used for specimens that have fractured along the thinner section of the tensile specimens. Overall, most of the specimens fractured as intended for both the fibreglass and carbon fibre reinforced specimens. If a specimen were to fail within the thicker section of the specimens, the results would be discarded, and a new specimen would be made.

5.8.2 Results & Discussion

The results from testing both fibreglass and carbon fibre specimens have been collated and used to generate graphs and tables that allow for comparisons to be made between the different specimens sets but not for comparing the different fibre reinforcement materials. This method of illustrating the data allows for comparison between the sets of specimens rather than for comparison between the individual specimens. The individual results for the fibreglass specimens can be seen in Appendix I and the individual results for the carbon fibre specimens can be seen in Appendix J.

Regarding having to reproduce specimens that fractured along the thicker section of the specimens, there were no specimens that fractured within the thicker sections of the specimens. All specimens fractured as intended and there was no need to reproduce specimens for testing. This was the case for both the fibreglass and the carbon fibre tensile specimens.

5.8.2.1 Fibreglass Specimens

The results from tensile testing of the tensile specimens with the fibreglass fibre reinforcement are shown in Table 5-11 and are illustrated using a graph in Figure 5-19. The table and graph depict the average results across all the specimens for each specimen set. Basic analysis of the table and graph shows that the *Specimen C* was the set of specimens that was able to achieve the highest average tensile properties. *Specimen C* was able to achieve a tensile load of

4586.10N and a tensile stress of 88.19MPa at the point of fracture. Having the *Specimen C* set of specimens provide the highest tensile stress is unsurprising as this set of specimens has the highest volume of fibre reinforcement.

One of the interesting observations from analysing the tensile stress vs tensile strain graph is that there are three specimen sets that have tensile stresses that are below the tensile stress of the control specimens at the point of fracture. This could a result of the control specimens for the fibreglass specimens undergoing a ductile fracture rather than the brittle fracture experienced by the specimens with fibre reinforcement.

The next stage of analysing the results using the Taguchi method is to determine the optimal combination of levels for each of the parameter. After running through all the calculations to determine the level for each parameter that yields the highest tensile stress, the optimal combination of levels for each parameter was found and illustrated in graph form in Figure 5-20. Based on the graph, the optimal combination of levels for each parameter are as follows: 'Rectangular Fill' for the 'Nylon Fill Density', '4 Rings' for the 'Number of Concentric Rings' and '6 Fibre Layers' for the 'Number of Fibre Layers'.

The next stage of the Taguchi method is to analyse and determine the effect that each parameter has on the tensile properties of specimens. After running through the necessary calculations, the results from these calculations are illustrated, using a graph, in Figure 5-21. The graph shows that the parameter that have the most impact on the tensile properties of the specimens was the 'Number of Fibre Layers' parameter contributing 51.41% towards the tensile properties of the specimens, followed by the 'Number of Concentric Rings' parameter with 36.19% and the 'Nylon Fill Pattern' parameter with a contribution of 12.40%. This result means that altering the 'Number of Fibre Layers' will have the most impact on the tensile properties of the tensile specimens designed using the built-in tab design. The result for determining the impact that each parameter has on the tensile properties of specimens are not unexpected. The fibre reinforcement phase, for a fibre reinforced composite part, contributes significantly more to the tensile properties of a composite part when compared to the matrix phase and the results from the experimentation illustrate this fact.

One of the interesting aspects of the results is that the 'Number of Fibre Layer' contributes more than the 'Number of Concentric Rings' towards the tensile properties of specimens. This result can be partially explained by focussing on these two parameters and analysing the change

in the volume of fibre reinforcement across all specimens. If the level is set for the 'Number of Concentric Rings' and the level for the 'Number of Fibre Layers' is changed, the range for the volume of fibre reinforcement can be determined. If the volume is garnered for all levels for the 'Number of Concentric Rings', these ranges can be used for comparison. When these ranges are compared to when the level for the 'Number of Fibre Rings' is set and the 'Number of Concentric Rings' are changed, the range for the volume of fibre reinforcement when the 'Number of Fibre Layers' is changed is greater. This means that the effect of altering the 'Number of Fibre Layers' has a greater effect on the amount of fibre reinforcement within specimens compared to when the 'Number of Concentric Layers' is altered. As the fibre reinforcement contributes significantly to the tensile properties, the greater the change in volume of fibre reinforcement, the greater the impact on the tensile properties of specimens. Table 5-12 illustrates the effect on the ranges for the volume of fibre reinforcement when one of the parameters is set and the other alters between the different levels.

The final stage of the Taguchi analysis is to utilise the optimal levels for each parameter and to print specimens using the optimal combination to prove that this is indeed the case. Five specimens were printed using the optimal combination of parameter levels and the results from the tensile testing these specimens are shown in Figure 5-22 and the average tensile properties are shown in Table 5-13.

As expected, the average tensile properties for the specimens with the optimal combination of parameters showed an increase in tensile properties compared to the specimens from the orthogonal array. The optimal combination tensile specimens showed an approximate increase of 260N or 5MPa compared to the best performing specimen set, *Specimen C*. The only difference between *Specimen C* and the optimal combination specimens was the change in the 'Nylon Fill Pattern' parameter with a 'Hexagonal Fill' for the *Specimen C* set and a 'Rectangular Fill' for the optimal combination specimen set. As the 'Nylon Fill pattern' parameter only contributes roughly 13.21% towards the tensile properties of the tensile specimens, this explains the minor increase in the tensile properties for the optimal combination specimens.

Specimen Set	Tensile Load at Tensile Strength (N)	Tensile Stress at Tensile Strength (MPa)	Tensile Extension at Tensile Strength (mm)	Tensile Strain at Tensile Strength (mm/mm)
A	1522.67	29.28	3.61	0.02
B	2570.67	49.44	3.65	0.02
C	4586.10	88.19	4.65	0.03
D	1792.95	34.48	3.90	0.02
E	3474.84	66.82	4.72	0.03
F	2016.40	38.78	3.53	0.02
G	3158.88	60.75	3.97	0.02
H	2599.19	49.98	3.95	0.02
I	4106.42	78.97	4.29	0.03
Average	2869.79	55.19	4.03	0.02
Control	2416.20	46.47	155.17	0.94

Table 5-11 – The Average Tensile Properties for the Fibreglass Tensile Specimens.

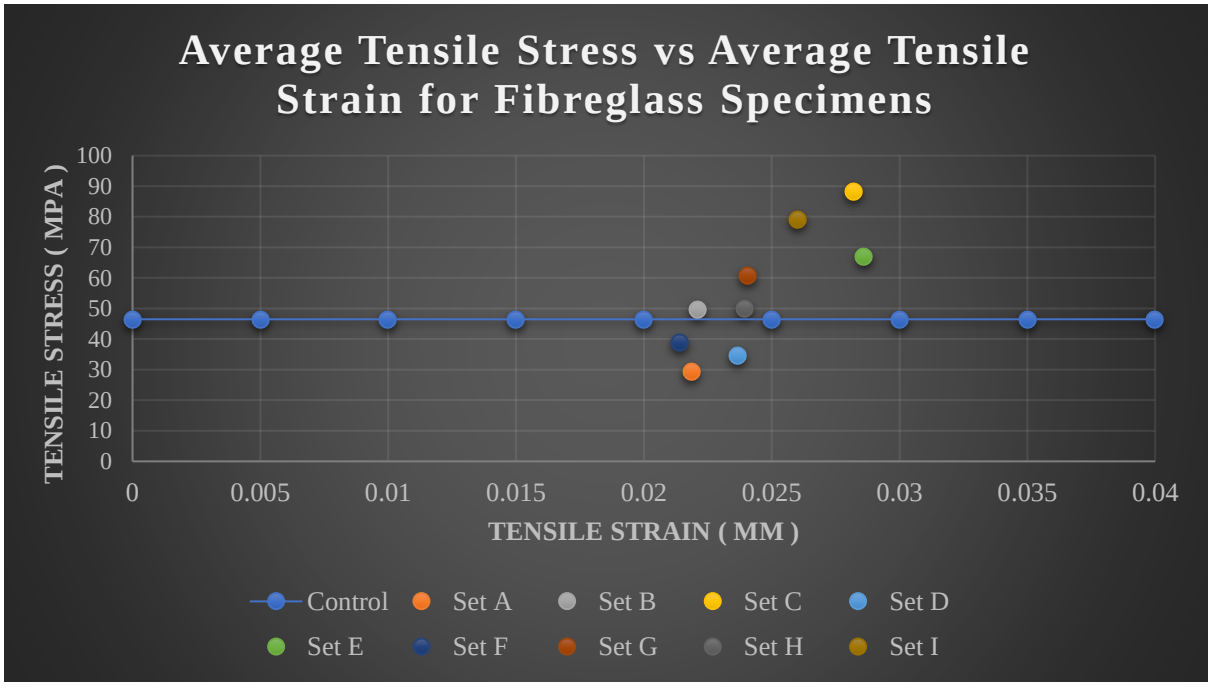

Figure 5-19 -Average Tensile Stress vs Average Tensile Strain for Fibreglass Specimens.

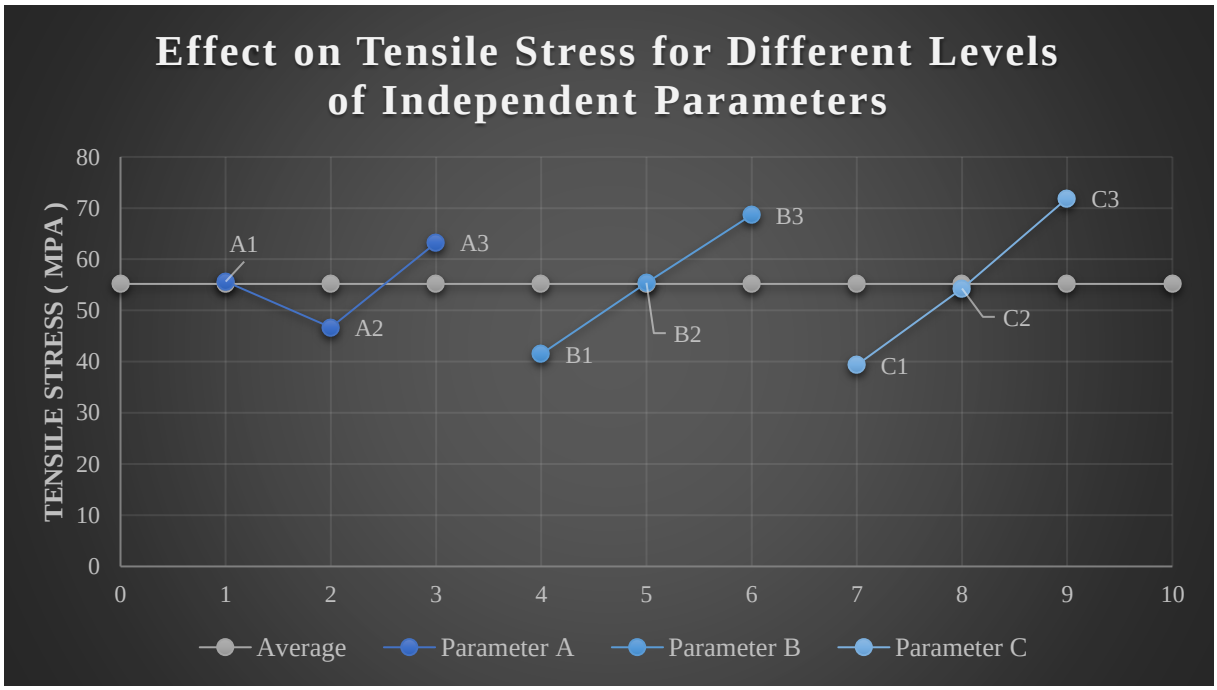

Figure 5-20 – The Tensile Stresses achieved by each Parameter Level used for Fibreglass Specimens.

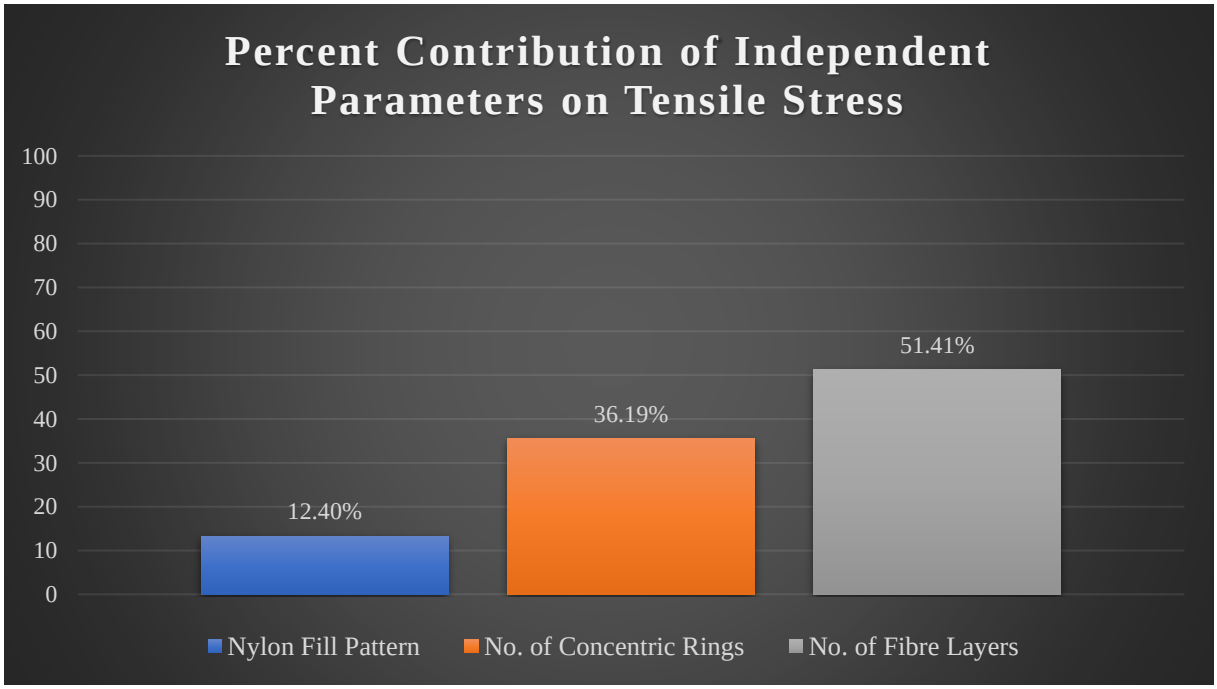

Figure 5-21 - The Contribution of Independent Parameters have on the Tensile Stress of Fibreglass Specimens.

Set Parameter Level	Parameter Level	Fibre Reinforcement Volume (cm^3)	Volume Range (cm^3)
B1	C1	1.17	0.26
	C2	1.3	
	C3	1.43	
B2	C1	1.23	0.38
	C2	1.42	
	C3	1.61	
B3	C1	1.29	0.49
	C2	1.54	
	C3	1.78	
C1	B1	1.17	0.12
	B2	1.23	
	B3	1.29	
C2	B1	1.3	0.24
	B2	1.42	
	B3	1.54	
C3	B1	1.43	0.35
	B2	1.61	
	B3	1.78	

Table 5-12 - The Range of Volumes for each Parameter Level for Fibreglass Specimens.

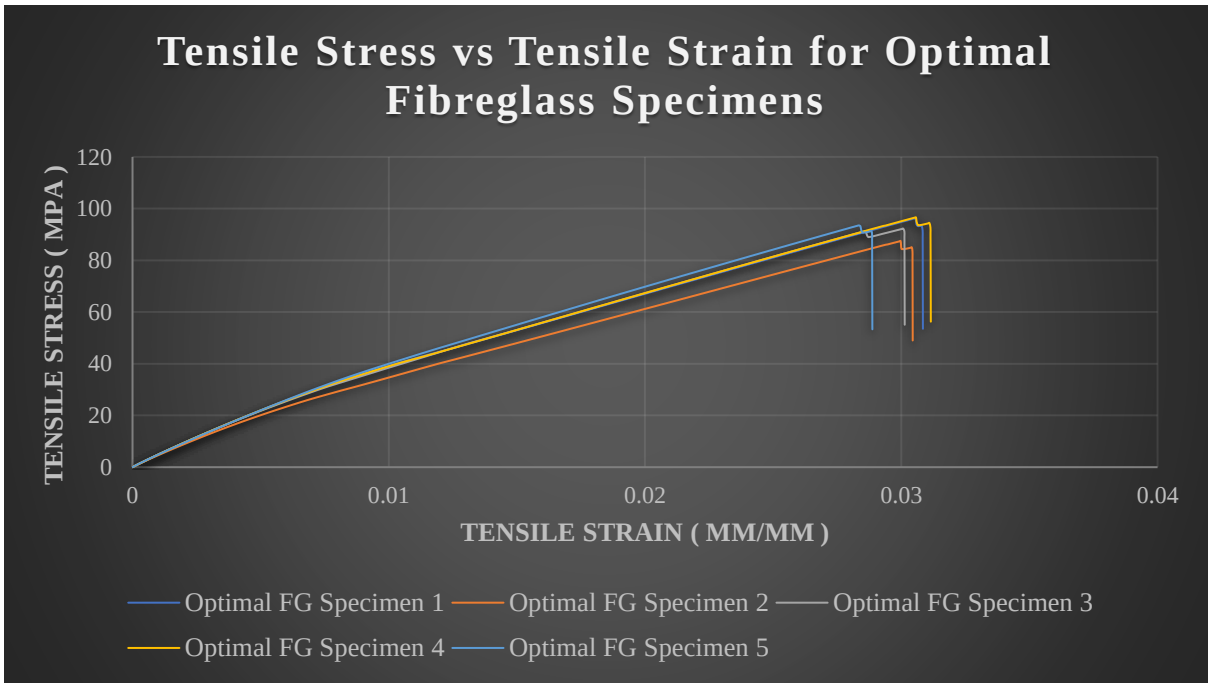

Figure 5-22 - The Tensile Stress vs Tensile Strain for the Fibreglass Specimens using the Optimal Combination of Parameters.

Tensile Load at Tensile Strength (N)	Tensile Stress at Tensile Strength (MPa)	Tensile Extension at Tensile Strength (mm)	Tensile Strain at Tensile Strength (mm/mm)
4845.86	93.19	4.93	0.03

Table 5-13 - The Average Tensile Properties for the Fibreglass Specimens with the Optimal Combination of Parameters.

5.8.2.2 Carbon Fibre Specimens

The results from the tensile specimens with carbon fibre reinforcement are illustrated in graph form in Figure 5-23 and are shown in Table 5-14. As with the fibreglass specimens, the results for the carbon fibre specimens show the average results for each set of specimens. Analysing the table and graph shows that the *Specimen C* set of specimens provided the highest tensile properties with an average tensile load of 6371.27 N and an average tensile stress of 122.52 MPa. This results in approximatly a 39% increase in the tensile properties when comparing the *Specimen C* results for the fibreglass specimens against the carbon fibre specimen results.

An interesting observation when analysing the results is that there is only one specimen set, *Specimen A*, that is below or close to the control set of specimens in terms of tensile stress. Every other specimen set has a tensile stress of at least double the control specimens set. These results are unlike the results for the fibreglass specimens which had numerous specimen sets below or close to the tensile stress for the control specimens. This can be explained by analysing the type of break experienced by the carbon fibre control specimens in Appendix J. The fracture of the carbon fibre control specimens was similar to a brittle material while the control specimen for the fibreglass control specimens exhibited a more ductile fracture. A possible reason for this is that the fibreglass control specimens had a higher volume of nylon compared to the carbon fibre control specimen, which allowed the fibreglass specimen to have a more ductile fracture during tensile testing.

Another observation is the reduction in the tensile extension of the carbon fibre specimens compared to the fibreglass specimens. The carbon fibre specimens exhibit superior tensile properties compared to the fibreglass specimens but at a cost to elongation. The reason behind this is that carbon fibre has a higher rigidity compared to fibreglass.

The next stage for the Taguchi method is to determine the optimal levels for each parameter to determine the optimal combination of parameters to achieve the highest tensile properties in a specimen. After running through the calculations, the results for the optimal combination of parameters is the same as those for the fibreglass specimens. The optimal combination of parameters are ‘Rectangular Fill’ for the ‘Nylon Fill Pattern’ parameter, ‘ 4 Rings’ for the “Number of Concentric Rings’ parameter and ‘6 Fibre Layers’ for the ‘ Number of Fibre Layers’ parameter. This result is illustrated using the graph in Figure 5-24.

The graph depicting the optimal combination of parameters in terms of tensile properties is similar to the graph for the optimal combination of specimens for the fibreglass specimens except for the range in tensile stress for the “Number of Concentric Rings’ and ‘Number of Fibre Layers’ parameters. The ranges for these two parameters are much larger for the carbon fibre specimens than the fibre glass specimens and this can be attributed to carbon fibre having superior tensile properties to fibreglass. This indicates that these two parameters will have a greater influence on the tensile properties of carbon fibre specimens compared to the fibreglass specimens.

The next stage for the Taguchi method is the identification of the contribution that each parameter has on the tensile properties of the specimens. After conducting the calculations, Figure 5-25 illustrates the contribution that each parameter has on the tensile properties of the specimens. As expected, the two parameters that control the amount of fibre reinforcment have the highest contributions while the parameter that handles the matrix material contributes the least to the tensile properties of specimens. The ‘Number of Fibre Layers’ parameter has a contribution of 65.35%, the ’Number of Concentric Rings’ parameter has a contribution of 32.10% and the ‘Nylon Fill Pattern’ parameter has a contribution of 2.55%.

One of the intersting observations for this result is the decrease in the contribution towards the tensile properties exhibited by the ‘Nylon Fill Pattern’ parameter between the carbon fibre specimens and the fibreglass specimens. This parameter has decreased for the carbon fibre specimens, compared to the fibreglass specimens, due to the increase in tensile properties with carbon fibre as the fibre reinforcment material. As carbon fibre has superior tensile properties to fibreglass, the contribution that the nylon matrix material will naturally decrease with a material with superior tensile properties.

Another intersting observation is the increase in the contribution for the ‘Number of Fibre Layers’ paramter compared to the contribution exhibited by the parameter for the fibreglass specimens. After conducting an analysis on the change in volume for the fibre reinforcment when either the ‘Number of Fibre Layers’ or the ‘Number of Concentric Rings’ parameter levels are set and the levels for the other parmeter is altered, the range in the volume for carbon fibre specimens is greater for when the ‘Number of Fibre Layers’ parameter is increasedTable 5-15 depicts the range in volume of fibre reinforcment when one of the parmeters is set and the level for the other parmeter is altered.

When comparing the volume ranges between the parameters for carbon fibre and fibreglass specimens, the ranges for the volume of fibre reinforcement when the ‘Number of Concentric Rings’ parameter level is changed does not differ much between carbon fibre and fibreglass specimens. When the ‘Number of Fibre Layers’ parameter is altered, there is a significant increase in the ranges for the volume of fibre reinforcment for carbon fibre specimens compared to fibreglass specimens. This support the premise that the ‘Number of Fibre Layers’ parameter has a greater contribution compared to the ‘Number of Concentric Fibre’ parameter and has increased with the introduction of a fibre reinforcment material with superior tensile properties.

The final section of the Taguchi analysis is the production and testing of specimens with the optimal combination of parameter levels. As with the fibreglass specimens, five copies of the carbon fibre tensile specimens with the optimal combination of parameter levels were made for tensile testing. The results from the tensiel testing of the optimal combination specimens are shown in Figure 5-26 and the average tensile proeprties are shown in Table 5-16.

As expected, the results from the optimal combination specimens show an increase in the tensile properties compared to the specimens from the orthogonal array. When comparing the optimal combination specimen set against *Specimen C* specimen set, the optimal combination specimen exhibit an average increase of approximatly 537N or 10MPa. This increase is the result from altering the ‘Nylon Fill Pattern’ parameter from the ‘Hexagonal Fill’ used for the *Specimen C* specimen set to the ‘Rectagular Fill’ used for the optimal combination specimens set.

One interesting observation is that the carbon fibre specimens with the optimal combination of parameter levels had a greater increase in tensile properties compared to the equivalent fibreglass specimens. Another observation is that the contribution towards the tensile properties for specimens for the ‘Nylon Fill Pattern’ parameter was deemed to be smaller for the carbon fibre specimens compared to the fibreglass specimens. Overall, the results from the optimal combination specimens for both materials exhibited a result that was fairly expected.

Specimen Set	Tensile Load at Tensile Strength (N)	Tensile Stress at Tensile Strength (MPa)	Tensile Extension at Tensile Strength (mm)	Tensile Strain at Tensile Strength (mm/mm)
A	1108.76	21.32	1.37	0.01
B	3088.27	59.39	1.93	0.01
C	6371.27	122.52	3.29	0.02
D	2263.04	43.52	1.72	0.01
E	4745.18	91.25	3.04	0.02
F	2187.32	42.06	1.60	0.01
G	3714.60	71.43	2.11	0.01
H	2152.19	41.39	1.58	0.01
I	5094.03	97.96	2.34	0.01
Average	3413.85	65.65	2.11	0.01
Control	1136.25	21.85	131.41	0.80

Table 5-14 - The Average Tensile Properties for the Carbon Fibre Tensile Specimens.

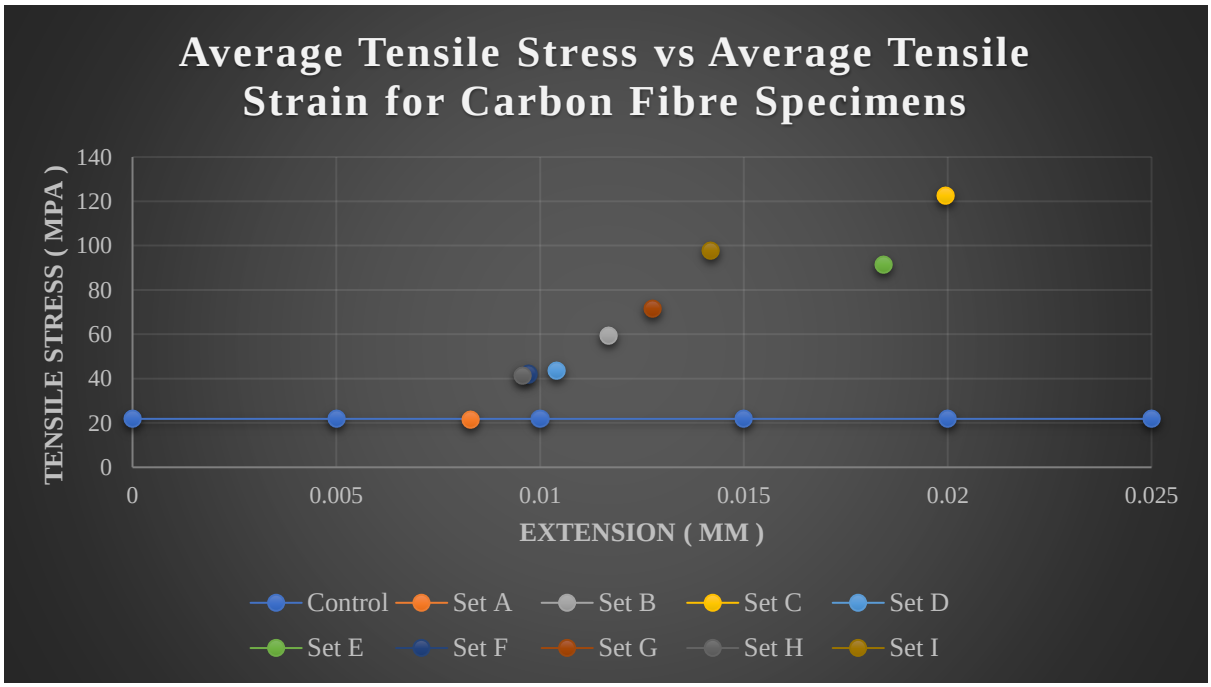

Figure 5-23 - Average Tensile Stress vs Average Tensile Strain for Carbon Fibre Tensile Specimens.

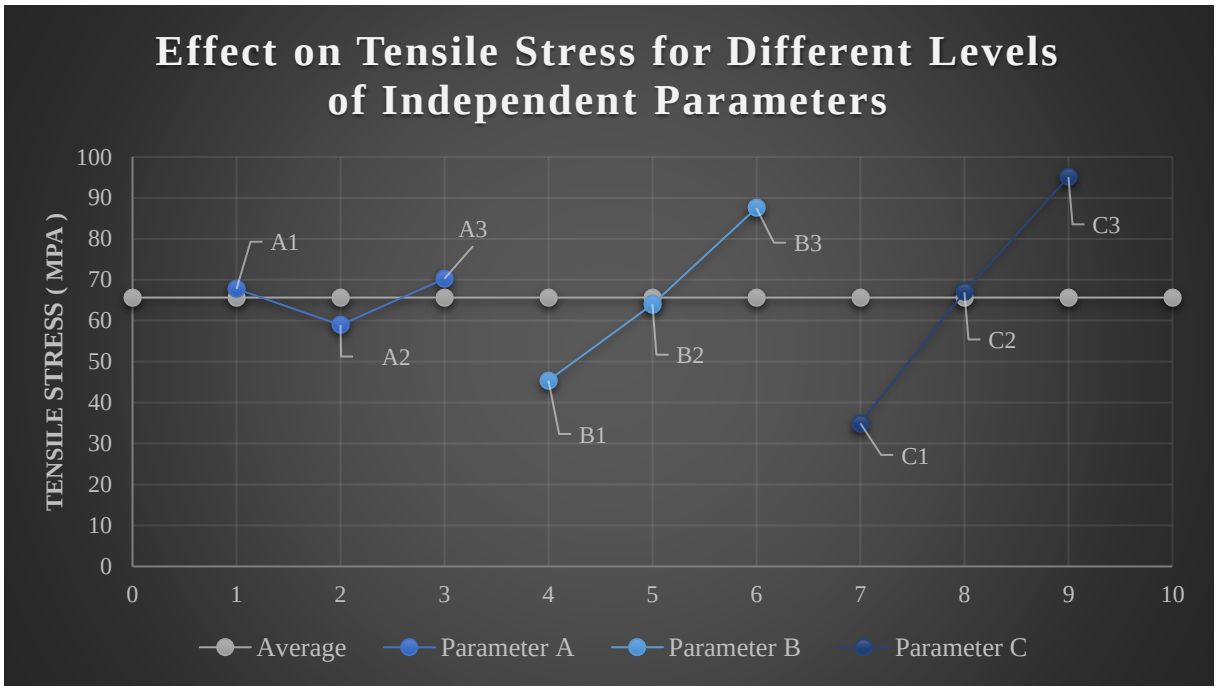

Figure 5-24 - The Tensile Stresses achieved by each Parameter Level used for Carbon Fibre Specimens.

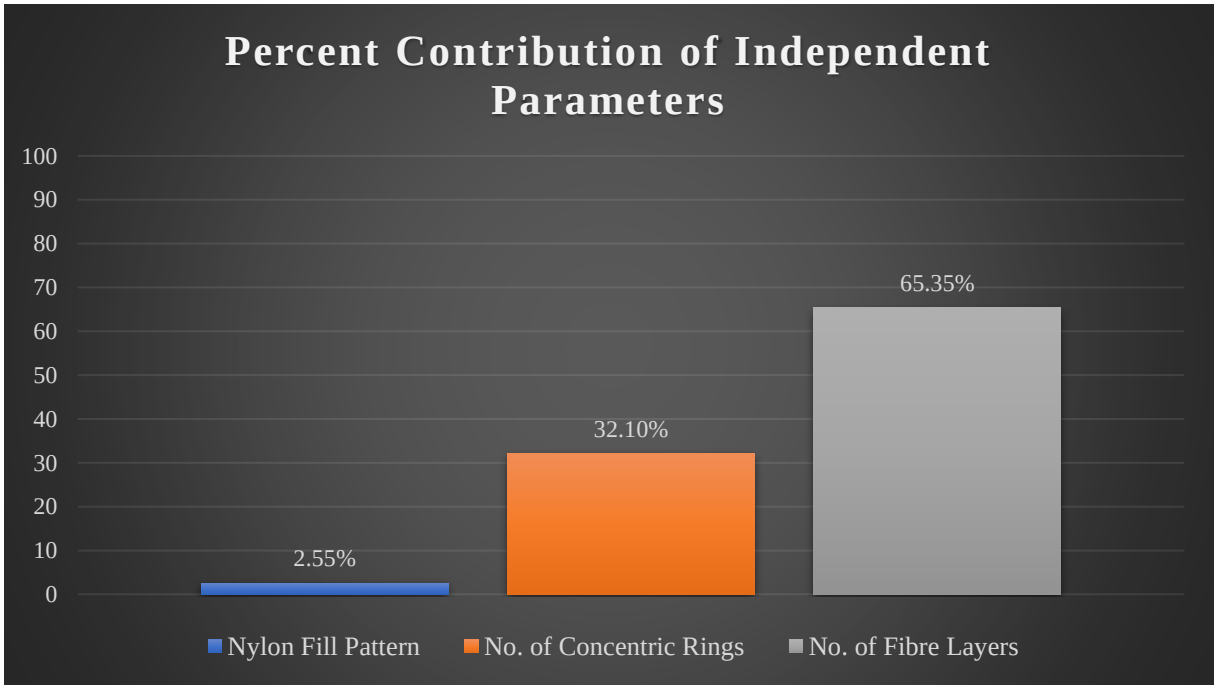

Figure 5-25 - The Contribution of Independent Parameters have on the Tensile Stress of Carbon Fibre Specimens.

Set Parameter Level	Parameter Level	Fibre Reinforcement Volume (cm^3)	Volume Range (cm^3)
B1	C1	0.77	0.32
	C2	0.93	
	C3	1.09	
B2	C1	1.07	0.47
	C2	1.31	
	C3	0.84	
B3	C1	1.52	0.61
	C2	0.91	
	C3	1.22	
C1	B1	0.77	0.14
	B2	0.91	
	B3	0.84	
C2	B1	1.07	0.29
	B2	0.93	
	B3	1.22	
C3	B1	1.52	0.43
	B2	1.31	
	B3	1.09	

Table 5-15 - The Range of Volumes for each Parameter Level for Carbon Fibre Specimens.

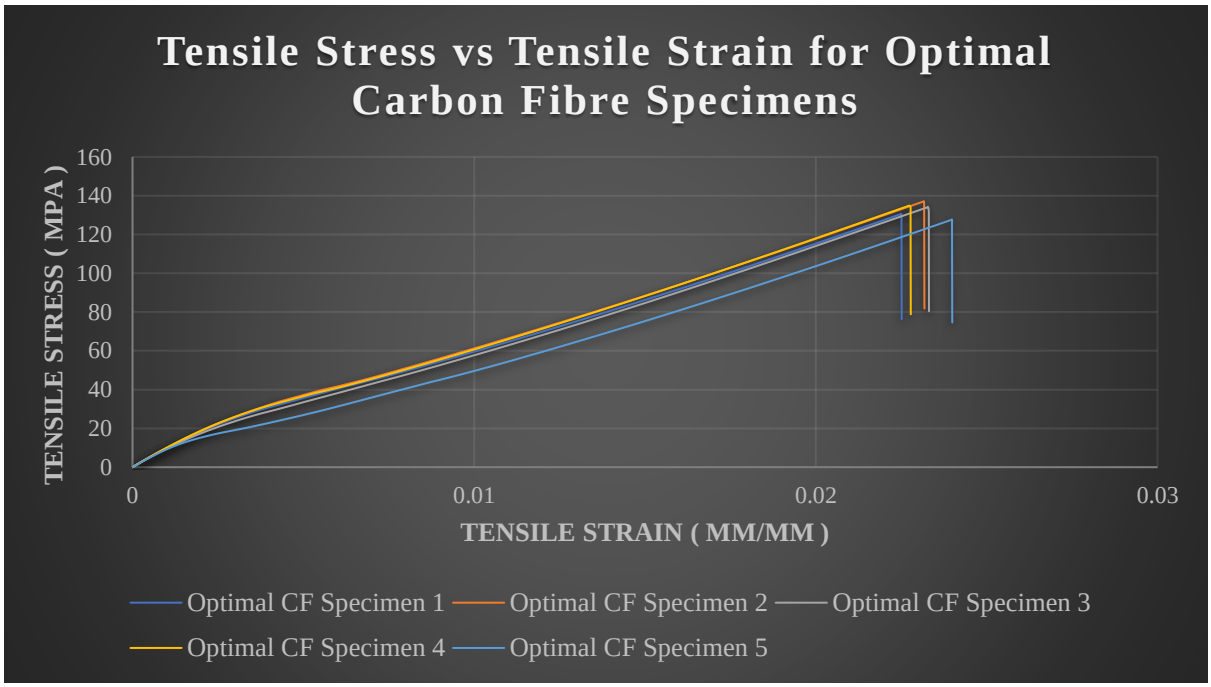

Figure 5-26 - The Tensile Stress vs Tensile Strain for the Carbon Fibre Specimens using the Optimal Combination of Parameters.

Tensile Load at Tensile Strength (N)	Tensile Stress at Tensile Strength (MPa)	Tensile Extension at Tensile Strength (mm)	Tensile Strain at Tensile Strength (mm/mm)
6908.30	132.85	3.82	0.02

Table 5-16 - The Average Tensile Properties for the Carbon Fibre Specimens with the Optimal Combination of Parameters.

5.8.3 Recommendations

The results from the conducted experiments lead to valuable research and observations that will be useful for future development of parts using the Mark One and for 3D printed long/continuous fibre reinforced composite parts. This research does open some leads for future work to be done to provide a more holistic take into the production of fibre reinforced composite parts using 3D printing. Listed below are a range of recommendations to improve upon the current research and ideas for future research areas.

1. Conduct a similar experiment with Kevlar fibres used as the fibre reinforcement material.
2. Conduct similar experiments to test other mechanical properties of parts made using the Mark One, including flexural strength and compression strength.
3. Conduct a more thorough analysis of the materials utilised in the Mark One filament including a cross-sectional analysis and a chemical composition analysis and testing.

5.8.4 Conclusion

The overall aim of this research was to understand some of the capabilities and limitations of the Mark One through analysis of the mechanical systems, cloud-based software and through the experimentation of several tensile specimens made using the Mark One. Following these steps provided a sound analysis of what the Mark One 3D printer can achieve with 3D printed long/continuous fibre reinforced parts.

Analysis of the software provides insight into how the internal structure of parts made using the Mark One can be adjusted or fine-tuned to achieve the desired outcome. Analysis of the limitations in the design of the mechanical systems provides some insight into what the Mark One 3D printer cannot do.

The experimentation using the Taguchi method provided several interesting results and provided valuable information regarding the capabilities of the Mark One in terms of the tensile properties for parts. Although the tensile specimens had to undergo changes for the specimens to be suitable for tensile testing, the experimentation provided the necessary results to determine the optimal combination of levels for the chosen parameters and detail the contribution that the chosen parameters had on the tensile properties of specimens.

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7. Appendices

7.1 Appendix A: Polyester Resin Technical Datasheet

Technical Data Sheet

nuplex® composites

POLYPLEX CLEAR ORTHO CASTING RESIN C200036

(Formerly F61209)

POLYPLEX CLEAR ORTHO CASTING RESIN is a pre-promoted, low reactivity, orthophthalic polyester resin especially formulated for use in clear casting applications. The resin is pre-promoted for room temperature cure with methyl ethyl ketone peroxide (MEKP) initiators. **POLYPLEX CLEAR ORTHO CASTING RESIN** is non-thixotropic and wax-free.

PERFORMANCE CHARACTERISTICS

FEATURES	BENEFITS
Positive cure characteristics after gelation	Allows rapid cycle times
Low colouration and excellent clarity in castings	Suitable for colour critical clear casting applications
Low exotherm cure characteristics following gelation	Reduced tendency towards shrinkage problems in thick cast sections.
Non thixotropic	Air release is unimpaired

RECOMENDED CATALYSTS
Curox MEKP NR20
Norox MEKP 9

TYPICAL LIQUID RESIN PROPERTIES @ 25°C

PROPERTY	TYPICAL VALUE	TEST DETAILS
Appearance	Clear liquid	
Viscosity	300 - 450 cP	Brookfield RVT sp.3/100 rpm
Gel Time (1% MEKP Curox NR20)	15 – 20 minutes	100 gram mass
Density	1.10 gcm $^{-3}$	
Flash Point	31°C	Setaflash
Styrene Content	36 - 39% w/w	
Shelf Life	6 months	when stored in original closed container, in the shade

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7.2 Appendix B: Epoxy Resin Technical Datasheet

ADHESIVE TECHNOLOGIES NZ LTD.
17 Corban Avenue, Henderson, Auckland ■ P.O. Box 21169, Henderson, Auckland 8, New Zealand
Phone: +64 9 838-6961 ■ Facsimile: +64 9 836-4849 ■ Website: www.adhesivetechnologies.co.nz

Technical Data Sheet

ADR270

Version 2.1 March 2016

ADR270 Epoxy Resin

Introduction

Adhesive Technologies ADR 270 is a low viscosity, solvent free epoxy resin specifically formulated for the use with the ADH range of hardeners and in many cases can cure at room temperature with minimal post cure requirements.

ADR 270 is a development of ADR 246 but with a lower mixed viscosity and has additional toughness. ADR 270 offers good working times and will typically give reasonable overnight hardness at room temperature.

The increase in toughness is achieved while still retaining extremely low viscosity; which is a significant aid to both Impregnation machine operations and to hand lamination.

Typical Applications

- Selected Infusion systems
- Hand laminates
- Sports Equipment
- Yachts
- Composite structures

Mix Ratio

See table below

Note: Care should be taken when dispensing and mixing.
Optimum results are achieved when recommended ratios are used.

Uncured Properties

ADR270	
Physical state Specific Gravity (g/ml)	Colourless liquid 1.14
Viscosity @ 20°C (cps)	975

Cured Characteristics

	ADH 25		***ADH 26***		***ADH 28***	
Mix Ratios 100parts ADR270 with (by weight)	25		25		25	
Mixed Viscosity (cps) @ 20°C	985		920		800	
	20°C	***30°C***	***20°C***	***30°C***	***20°C***	***30°C***
Pot Life - 100g (hr : min)	0:20	0:10	0:30	0:15	0:45	0:20
Thin Film (hr : min)	1:00	0:20	1:30	0:42	2:00	1:00
HDT after 7days (°C)	55	66	55	68	55	69
Ultimate HDT(°C)	70		74		80	
Typical post cure requirement	24hrs @ 20°C followed by 6hrs @ 50°C					

7.3 Appendix C: Prototype 3 Autonomous Program

```
// Automated Design Code - Andrew Kvalsvig

// Relay Pins

int R1 = 5;           //  Relay Signal for the Solenoid
int R2 = 4;           //  Relay Signal for UV Light

// Stepper Motor Driver Pins

int PullPin = 8;
int DirPin = 9;
int EnablePin = 10;

// Push Button + Limit Switch Paramters

int L1 = 2;           //  Pin for Starting and Stopping the System using the Push Button
int L2 = 3;           //  Pin for Counting the Number of Revolutions using the Limit Switch

int Reading1;         //  Push Button Signal
int Reading2;         //  Limit Switch Signal
int LastReading1;       //  Last Reading of the Signal for the Push Button
int LastReading2;       //  Last Reading of the Signal for the Limit Switch

// Counting Parameters
int i_winds = 0;      //  Number of Initial Winds
int s_winds = 0;        //  Number of Setup Winds
int c_winds = 0;        //  Number of Final Winds
int total = 0;        //  Number of Sets of Revolutions
int STOP = 0;
int t1 = 0;
int t2 = 0;
int t3 = 0;

const int I_WINDS = 1;    //  Target Number of Initial Winds
const int S_WINDS = 2;    //  Target Number of Setup Winds
const int C_WINDS = 20;    //  Target Number of Final Winds + 1
const int TOTAL = 5;      //  Target Number of Sets of Specimens


void setup() {

        pinMode(R1, OUTPUT);
        pinMode(R2, OUTPUT);
        pinMode(PullPin, OUTPUT);
        pinMode(DirPin, OUTPUT);
        pinMode(EnablePin, OUTPUT);
        pinMode(L1, INPUT_PULLUP);
        pinMode(L2, INPUT_PULLUP);

        Serial.begin(9600);

        digitalWrite(R1, LOW);    //  Angle Seat Valve is Closed
        digitalWrite(R2, LOW);    //  UV Light is Off
        digitalWrite(PullPin, LOW);
        digitalWrite(DirPin, HIGH);
        digitalWrite(EnablePin, HIGH);

}
```

```
void loop() {

	digitalWrite(R1, HIGH);
	digitalWrite(R2, HIGH);
	LastReading1 = Reading1;
	Reading1 = digitalRead(L1);
	total = 0;
	delay(100);

	if (Reading1 == LOW) {
		if (LastReading1 != LOW) {
			Serial.println("Initial Process Initiated");
			i_winds = 0;
			s_winds = 0;
			c_winds = 0;
			total = 0;
			STOP = 0;
			LastReading1 = Reading1;
			delay(10);

			while (total != TOTAL) {
				while (i_winds < I_WINDS) {
					LastReading1 = Reading1;
					LastReading2 = Reading2;
					Reading1 = digitalRead(L1);
					Reading2 = digitalRead(L2);

					digitalWrite(PullPin, HIGH);
					digitalWrite(PullPin, LOW);
					delay(1);

					if (Reading2 == LOW) {
						if (LastReading2 != LOW) {
							i_winds = i_winds + 1;
							Serial.print(i_winds);
							Serial.println(" - Initial Process");
							//LastReading2 = Reading2;
						}
					}

					if (Reading1 == LOW) {
						if (LastReading1 != LOW) {
							Serial.println("Initial Process Stopped");
							//LastReading1 = Reading1;
							STOP = 1;
							break;
						}
					}
				}

				if (STOP == 1) {
					break;
				}

				Serial.println("Initial Process Complete");
```

```
// Setup Process - Positions the filament just inside the UV Light Box

        Serial.println("Setup Process Initiated");
        digitalWrite(R1, LOW);    //  Resin is allowed to flow
        delay(1000);              //  Allow the resin to reach the block

        while (s_winds != S_WINDS) {
                LastReading1 = Reading1;
                LastReading2 = Reading2;
                Reading1 = digitalRead(L1);
                Reading2 = digitalRead(L2);

                digitalWrite(PullPin, HIGH);
                digitalWrite(PullPin, LOW);
                delay(1);

                if (Reading2 == LOW) {
                        if (LastReading2 != LOW) {
                                s_winds = s_winds + 1;
                                Serial.print(s_winds);
                                Serial.println(" - Setup Process");
                                //LastReading2 = Reading2;
                                delay(10);
                        }
                }

                if (Reading1 == LOW) {
                        if (LastReading1 != LOW) {
                                Serial.print("Setup Process Stopped at ");
                                Serial.println(s_winds + 1);
                                //LastReading1 = Reading1;
                                STOP = 1;
                                break;
                        }
                }
        }

        if (STOP == 1) {
                break;
        }


        Serial.println("Setup Process Complete");
```

```
                        Serial.println("Curing Process Initiated");

                        digitalWrite(R1, HIGH);     //  Resin is not allowed to flow to
                                                      build pressure within the pressure
                                                      pot
                        delay(5000);
                        digitalWrite(R1, LOW);      //  Resin is allowed to flow
                        digitalWrite(R2, LOW);      //  UV Light is turned ON

                        while (c_winds != C_WINDS) {
                                LastReading1 = Reading1;
                                LastReading2 = Reading2;
                                Reading1 = digitalRead(L1);
                                Reading2 = digitalRead(L2);

                                digitalWrite(PullPin, HIGH);
                                digitalWrite(PullPin, LOW);
                                delay(1);

                                if (Reading2 == LOW) {
                                        if (LastReading2 != LOW) {
                                                c_winds = c_winds + 1;
                                                Serial.print(c_winds);
                                                Serial.println(" - Cured");
                                                //LastReading2 = Reading2;
                                                delay(10);
                                        }
                                }

                                if (Reading1 == LOW) {
                                        if (LastReading1 != LOW) {
                                                Serial.print("Curing Process Stopped at ");
                                                Serial.println(c_winds + 1);
                                                c_winds = 0;
                                                //LastReading1 = Reading1;
                                                STOP = 1;
                                                break;
                                        }
                                }
                        }

                        digitalWrite(R1, HIGH);         // Stops the flow of resin

                        if (STOP == 1) {
                                break;
                        }

                        delay(20000);                    //  Allows the filament within the
UV Box to be cured fully
                        digitalWrite(R2, HIGH);         //  Turns the UV Light OFF
                        Serial.println("Curing Process Complete");
                        total = TOTAL;
                        Serial.println("Finished");
                }
        }
}

}
```

7.4 Appendix D: Front Page from M2VIP2016 Publication

3D Printing of Fibre Reinforced Honeycomb Structured Composite Materials

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Abstract*—The paper presents the work on manufacturing and preliminary characterisation of fibre reinforced composite honeycomb structured composites by 3D printing. The capabilities and limitations of the processing are discussed. The work aims to compare the effectiveness of reinforcement using specimens of similar dimensions produced on the same machine and characterise them. Initially, tensile performance of unprinted fibre and printed fibre has been evaluated. Challenges associated with the testing of the printed specimens are addressed. Bend testing will follow to assess the performance as a composite structure to assess the interaction between fibre, matrix and core. Continuing work is planned to compare the effect of other parameters such as fill pattern and fill density to assess their effect on the composite.

Keywords—3D printing; composites; continuous fibres; FRTP

I. Introduction

Currently, additive manufacturing (AM), otherwise known as rapid prototyping, is a production technique that is becoming increasingly popular in industry due to its ability to outperform conventional manufacturing techniques [1]. AM is capable of fabricating complex parts of various shapes and sizes with short development time and low wastage, especially when compared to subtractive manufacturing methodologies [1–3]. These along with the other benefits of utilising AM techniques can result in a reduction in production cost, which allows more room to create competitive advantages [1–4]. The current major industries that utilise additive manufacturing include aerospace [5], automotive [6] and medical [2]. Some of the other industries include dental [7] and education [8] but AM is being used in a wide array of industries. Despite the several advantages of using AM in production, AM is designed towards a certain type of market. AM cannot compete with the conventional production techniques as these have been designed for mass production of products. On the other hand, AM has generally been designed to create small quantities of complex products that cannot be achieved easily using conventional methods [4]. This inability to create large quantities of products makes it unlikely for AM to replace conventional production techniques but rather AM will have its own specialized market [9].

In AM, two main areas of research strive to expand the capabilities of AM. The first area of research is designed about reducing the production time for the creation of parts whilst retaining the quality of the products [1]. The ability to reduce the production time will in turn allow more parts to be made in a short period. The second area of research is in the development of new materials that can be utilised by AM techniques [2]. An example of this is in the development of an AM technique that is capable of creating fibre reinforced thermoplastic (FRTP) composite product, in particular carbon fibre reinforced thermoplastic (CFRTP) composite parts [10]. CFRTP composite parts are extremely desirable due to their high tensile strength and high strength-to-weight ratio compared to traditional materials [11]. The ability to create complex parts that utilise the strengths of carbon fibres and other fibres using AM techniques is very appealing for many products and it could be very lucrative as a result.

There are various forms of AM production techniques that are available, but research shows that the most commonly used AM production technique for creating CFRTP composites is fused deposition modelling (FDM). This can be attributed to the ease of which carbon fibre, in tow form, can be easily integrated into the filament material being used and the potential to create composite parts that have had the fibres orientated into a specific arrangement to handle a specific situation. FDM, like most AM production techniques, creates three-dimensional parts using files made using computer aided design (CAD) software. These files divide the three-dimensional parts into a series of two-dimensional cross-sections, which serve as individual layers [12].

The process that a FDM printer follows is based on the use of thermoplastic materials, such as Nylon or acrylonitrile butadiene styrene (ABS). These thermoplastic materials are in filament form and are fed into an extruder. The extruder heats the thermoplastic material to its glass transition temperature and feeds the heated material through a nozzle to be deposited onto to a print bed. Once the heated material is on the print bed, the material cools and solidifies. Depending on the FDM printer, either the extruder, the print bed or both are able to move. This movement combined with the depositing of heated material allows a printer to create a single layer of a three-dimensional part. After each layer is completed, the bed is lowered or the extruder is raised by a set amount, based on the thickness of the layers, and the next layer is deposited on top of the previous layer. This process is repeated until the three-dimensional parts have been created. Support material is used to support sections of a part which have no support directly below and can be made of a different material or a less dense amount of the same filament material.

7.5 Appendix E: Front Page from M2VIP2017 Publication

Analysing the Tensile Properties of 3D Printed Fibre Reinforced Thermoplastic Composite Specimens

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***Abstract*—The paper presents the work on the characterisation of fibre reinforced thermoplastic composite parts made using 3D printing. The Taguchi method is used to develop an orthogonal array of the minimum required combinations of variables to analyse the effect different variables have on the tensile properties of specimens. The aim of this research is to determine the optimal combination of three independent variables for yielding the specimen with the highest tensile strength and to determine the contribution the variables have on the tensile strength of specimens.**

***Keywords*—3D printing; Taguchi method; Continuous fibres;**

I. INTRODUCTION

Additive manufacturing (AM), otherwise known as 3D printing or rapid prototyping, is the manufacturing technology that creates three-dimensional objects through the process of adding layers of material on top of one another [1]. In the past, AM has been used for the generation of visualization models. More recently, AM has been used to produce end-use parts that are being used in a range of industries [2]. These industries include aerospace [3], automotive [4], medical [5, 6] dental [7, 8] and education [9].

AM is a popular manufacturing technology in industry due to AM providing certain advantages over conventional subtractive manufacturing methods in the production of parts with certain characteristics. AM is a manufacturing technology that is more suitable to produce complex parts that conventional manufacturing methods struggle to replicate [10]. Examples of the complex parts that AM is more suitable for producing are parts that have a constantly changing cross-section or parts that have complex internal cavities. Other advantages that AM has when compared to conventional manufacturing methods are that there is low wastage when producing parts and there is low development time for designing parts [11]. One of the limitations of AM is that it cannot produce the sheer volume of parts in the same amount of time and cost as mass manufacturing methods. AM is a manufacturing technology that is more suitable towards producing low volumes of highly complex parts [12].

In terms of research for 3D printing, there are two key areas of research. The first key area in research is in improving the print speed of current 3D printing methods and improving the quality of parts made using 3D printing methods [2, 13]. Improvements in this area increase the viability of using 3D printing as a manufacturing technology for a wider range of parts. This area of research includes developing new methods for 3D printing that either produce parts with a reduced print time or parts of better quality. The second key area of research is the development of new materials that can be incorporated into current AM methods [14]. By increasing the types of materials that can be used in 3D printing methods, this increases the viability of using 3D printing in industry. Currently, 3D printing methods can produce parts using a range of materials including thermoplastic polymers, ceramics, metals and composites. One of the materials that has been researched for 3D printing methods are fibre reinforced thermoplastic (FRTP) composite parts with an emphasis on carbon fibre reinforced thermoplastic (CFRTP) composite parts [15]. FRTP and CFRTP composite parts are desirable due to the mechanical properties that the fibres add to the matrix material. These mechanical properties the fibre impart on the composite parts include high tensile strength and a high strength-to- weight ratio when compared to traditional materials [16].

CFRTP composite parts can be made using the fused deposition modelling (FDM) 3D printing method by incorporating fibres within the filament material before making the part. The type of methods of incorporating fibres into the filaments are dependent on the length of the fibres. The most common method of incorporating carbon fibres into filament is to impregnate carbon fibre yarn into the filament before the filament is deposited onto the print bed. The carbon fibre yarn is impregnated into the filament material when the filament is heated above its glass transition temperature and is deposited as a composite filament onto the print bed through the same extruder. Examples of this are shown through research by Matsuzaki, et al [17]. There are other examples of incorporating short fibres into FDM 3D printers including work conducted by Ning, et al [15]. These methods often are based around creating a filament for a FDM 3D printer by impregnating short fibres within a thermoplastic polymer.

7.6 Appendix F: Front Page from M2VIP2017 Publication

3D Printed Carbon Fibre Composite Knee and Hip Replacements

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***Abstract* — This paper reviews current research on the design, processing and finite element analysis (FEA) of bone implants for the human body. The feasibility of producing carbon fibre composite implants, in particular knee and hip replacements which are common bone replacements by 3D printing, is discussed. The relationship between design and material requirements is elaborated.**

Keywords— 3D printing; bone implant; FEA analysis

I. INTRODUCTION

An increase in the number of hip and knee replacements has been the trend in the past decade. Around twenty to thirty years ago, the majority of hip and knee replacement patients were older than seventy years but now it is very common for patients to be as young as twenty-five years old. It is possible for hip replacement surgery to be undertaken by patients under 25. So, with the increase in the demand for bone replacements, the demand for the supply of replacement parts is also increasing.

Technology around the world is making great advances with 3D printing growing greatly since it was first introduced in the 1980's. Markforged, a 3D printing company, has made it possible to produce fibre reinforced composite parts using nylon as the matrix and a range of fibre materials for the fibre reinforcement. The composite parts that this printer can create maintain very good mechanical properties, such as high strength-to-weight ratio and high tensile strength. These mechanical properties make it suitable to be used for manufacturing bone prosthetics in the human body.

The possibility arises for an improvement on current bone implants by producing 3D printed nylon and carbon fibre composite bone implants. There is very large market for bone replacement, with around 773000 Americans having had hip or knee replacement in 2009 [1]. A commercial 3D printer capable of making carbon fibre composite parts is a very recent piece of technology and has only been around for the past couple of years. So, there is very little information on the mechanical properties of such a fibre composite material. The basis of this paper is to demonstrate the feasibility of using a 3D printed carbon fibre composite part in the human body. Different tests such as tensile strength and FEA analysis have been conducted to demonstrate the mechanical properties of the material and how it may be implemented. The Mark One 3D printer has certain fibre and nylon parameters which can change the structure of the part. The tests completed show the best possible combination of parameters to produce the strongest possible part. The strongest combination of parameters can then be implemented into the final bone replacement.

The bone is living and growing tissue [2] in the human body, mostly made of collagen. The bone isn't uniformly solid and instead consists of a rough matrix. This rough matrix makes up about 30% of the bone. The remaining 70% provides strength and is made of salts. The matrix is made from around 5% ground substance and between 90%- 95% collagen fibres. The ground substance is an amorphous gel- like substance surrounding the cells. The primary portion of the bone known as osseous tissue, is quite hard and lightweight. The matrix consists of mostly a composite material which involves the inorganic mineral calcium phosphate in the arrangement termed calcium hydroxyl apatite (this mineral gives bone its rigidity) and collagen, an elastic protein which improves fracture resistance [3]. When humans become older and older, their bones become less dense and the bone strength decreases. This indicates that they are more vulnerable to fracture in the later years of life. Therefore, it is more common that most types of bone replacement surgery occurs in the elderly. Table I shows Young's Modulus for various bone constituents.

TABLE I. – Young's Modulus of Bone [4]

Bone Material	Young's Modulus, E (GPa)
Collagen(dry)	6
Bone Mineral (Hydrooxyapatite)	80
Cortical bone, longitudinal	11-21
Cortical bone, transverse	5-13

Bones are subjected to bending moments during normal loading. These bending moments create both tensile and compressive stresses in different regions of the bone. Different bones have different functions, so there is a large variation in strength required for them to function. Table II shows the range of tensile and compressive strength values of bone in the human body.

In total hip arthroplasty or total hip replacement the damaged bone and cartilage is removed and replaced by an artificial component. The femoral head is taken out and

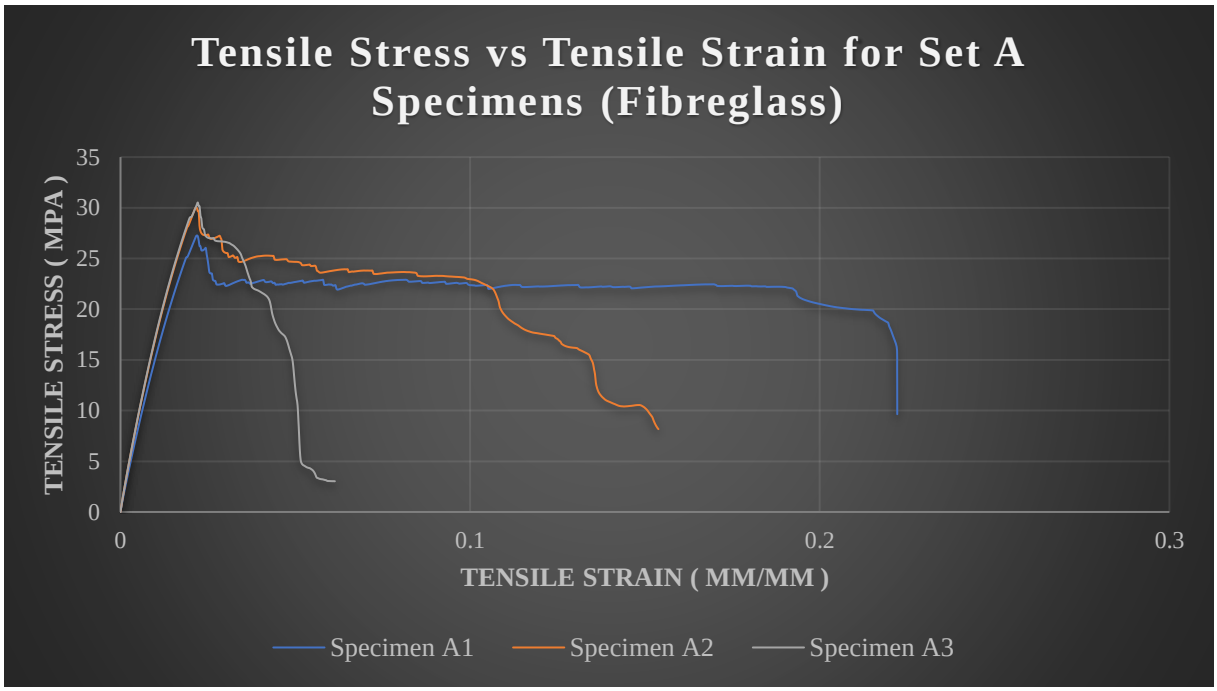
7.7 Appendix G: Mark One Material Properties for Fibre Reinforcement

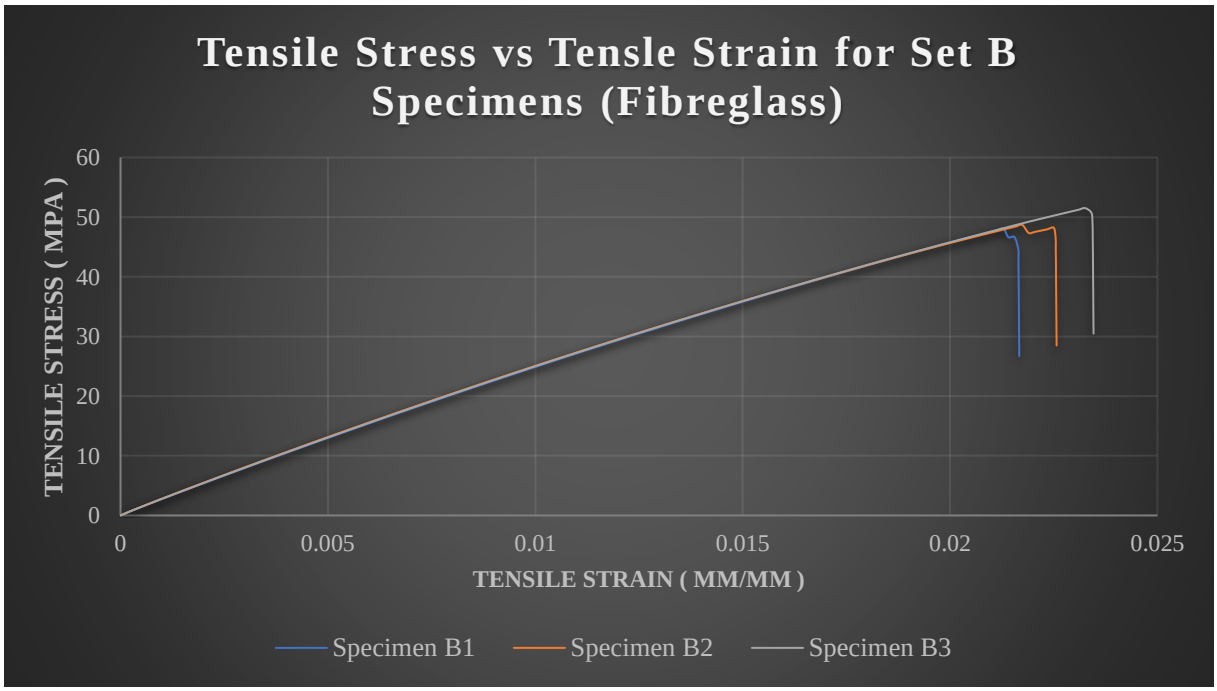
Property	Test Standard	Carbon Fibre	Kevlar	Fibreglass
Tensile Strength (MPa)	ASTM D3039	700	610	590
Tensile Modulus (GPa)	ASTM D3039	54	27	21
Tensile Strain at Break (%)	ASTM D3039	1.5	2.7	3.8
Flexural Strength (MPa)	ASTM D790	470	190	210
Flexural Modulus (GPa)	ASTM D790	51	26	22
Flexural Strain at Break (%)	ASTM D790	1.2	2.1	1.1
Compressive Strength (MPa)	ASTM D6641	320	97	140
Compressive Modulus (GPa)	ASTM D6641	54	28	21
Compressive Strain at Break (%)	ASTM D6641	0.7	1.5	n/a
Heat Deflection Temperature (°C)	ASTM D648 Method B	105	105	105
Izod Impact – Notched (J/m)	ASTM D256-10 Method A	958	1873	2603

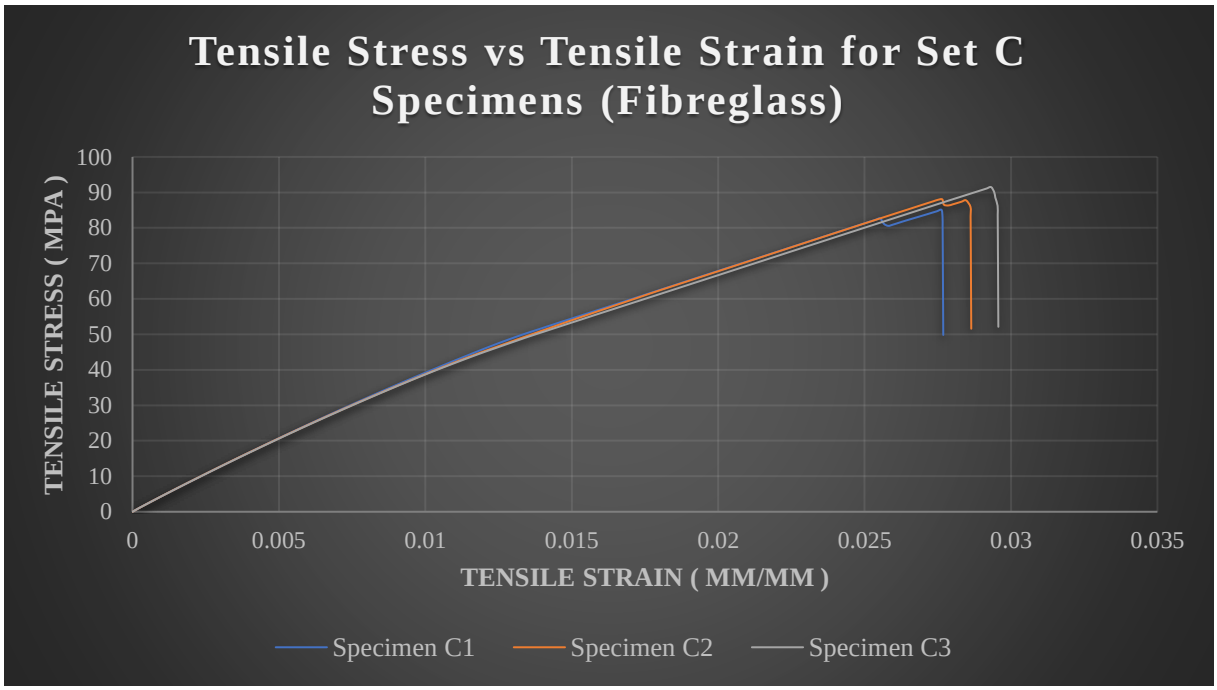
7.8 Appendix H: Mark One Material Properties for Nylon

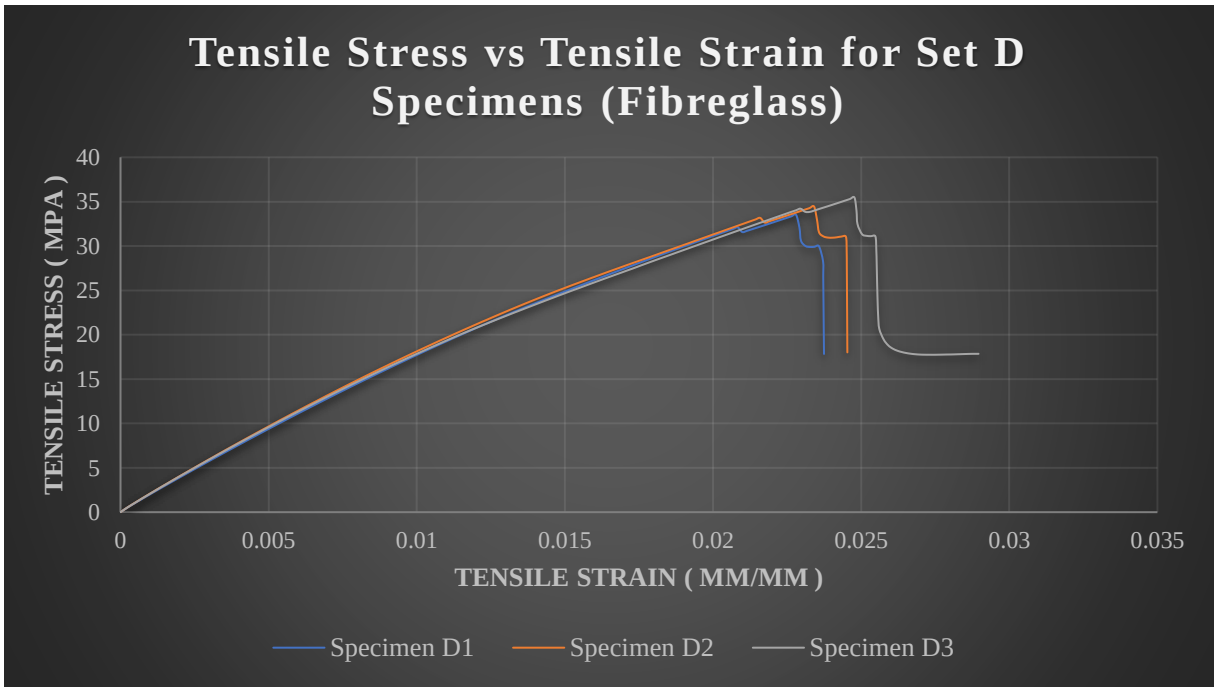
Property	Test Standard	Nylon
Tensile Modulus (GPa)	ASTM D638	0.94
Tensile Stress at Yield (MPa)	ASTM D638	31
Tensile Strain at Yield (%)	ASTM D638	27
Tensile Stress at Break (MPa)	ASTM D638	55
Tensile Stress at Break (%)	ASTM D638	260
Flexural Strength (MPa)	ASTM D790	32
Flexural Modulus (GPa)	ASTM D790	0.84
Flexural Strain at Break (%)	ASTM D790	n/a
Heat Deflection Temperature (°C)	ASTM D648 Method B	49 140
Izod Impact – Notched (J/m)	ASTM D256-10 Method A	1015

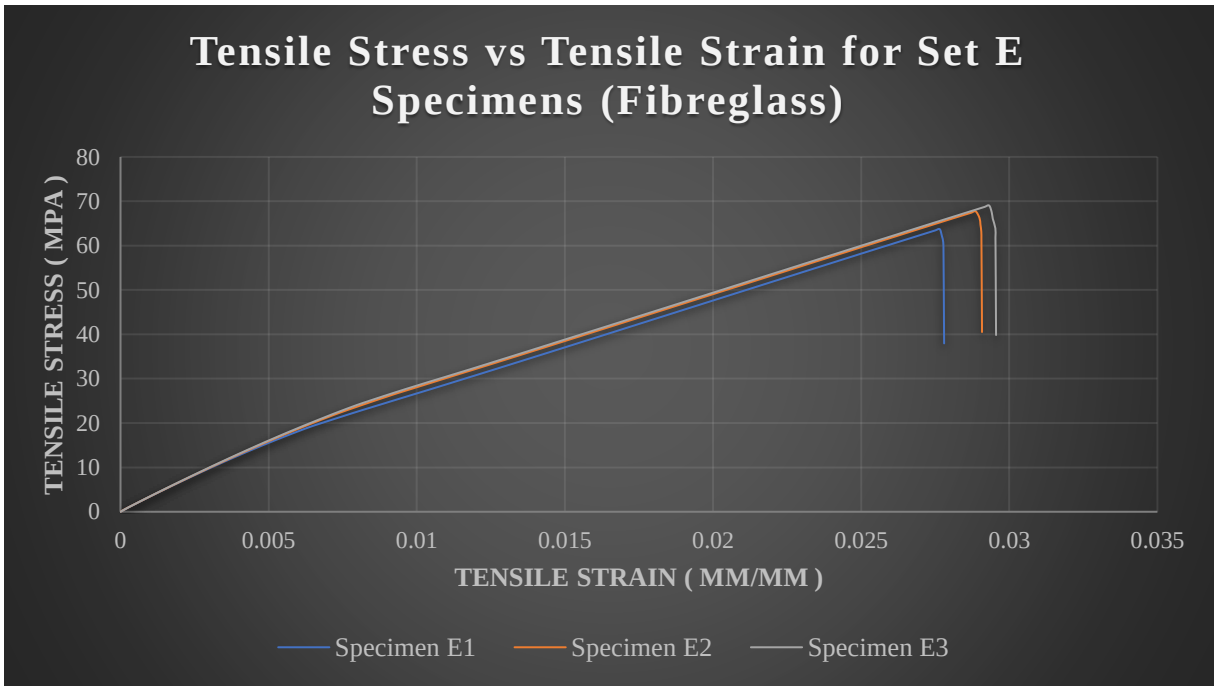
7.9 Appendix I: Fibreglass Tensile Stress vs Tensile Strain Graphs

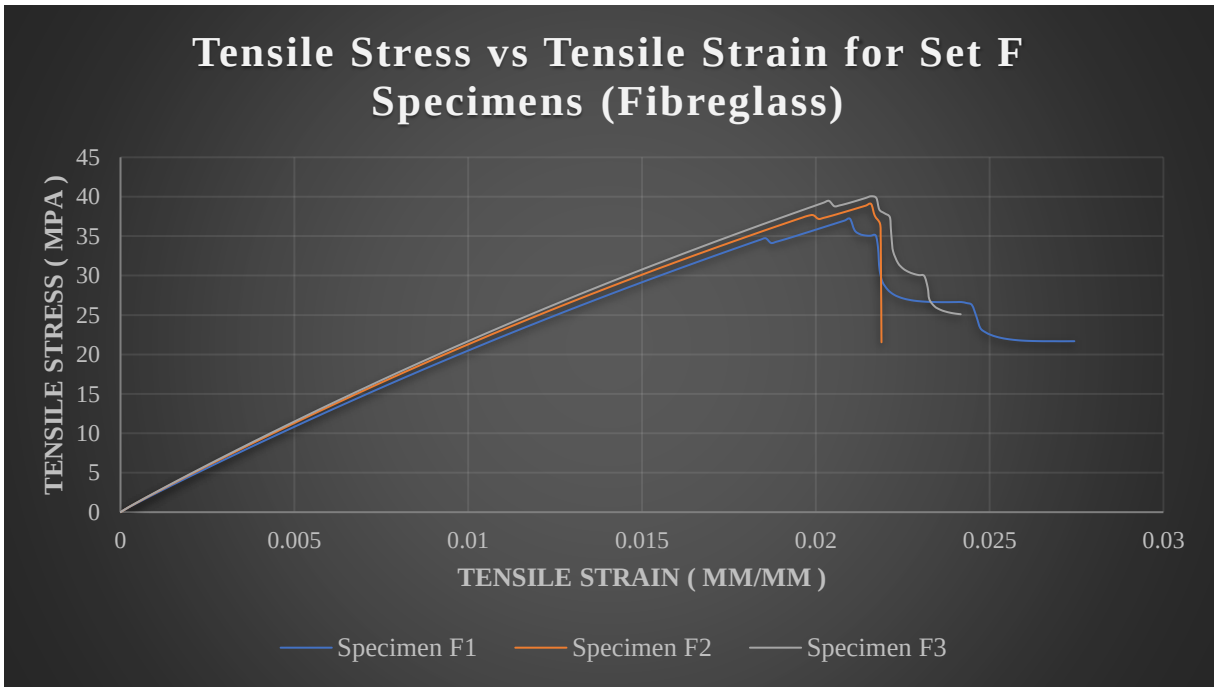


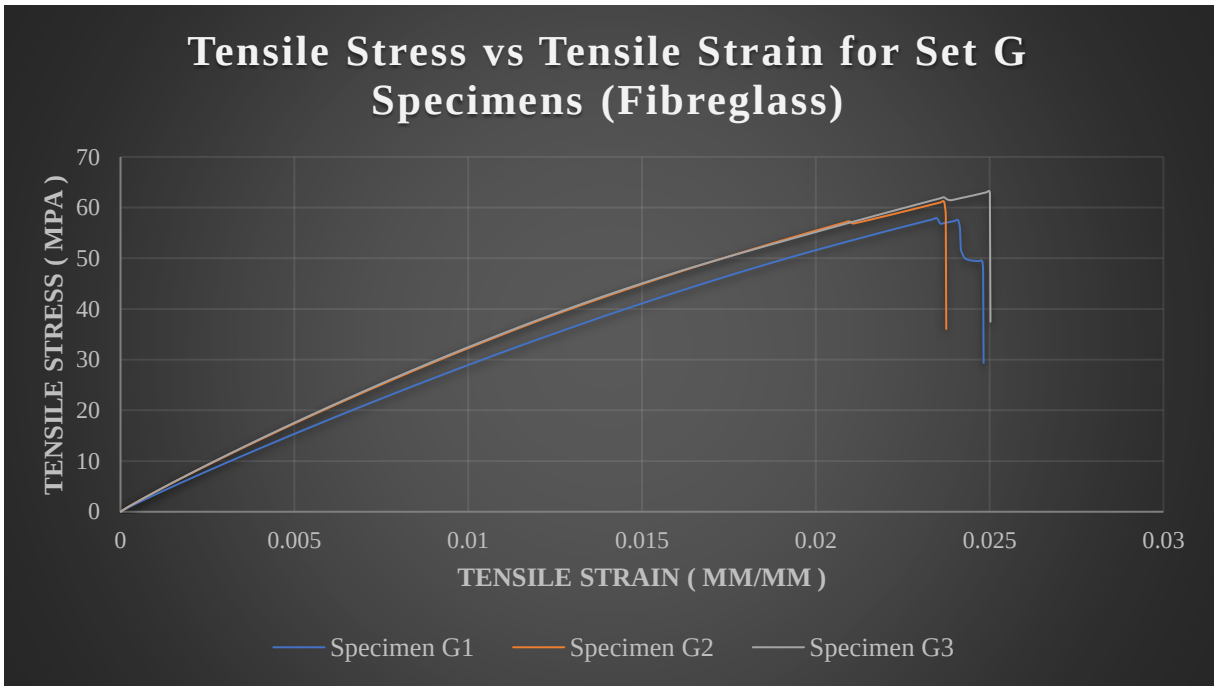


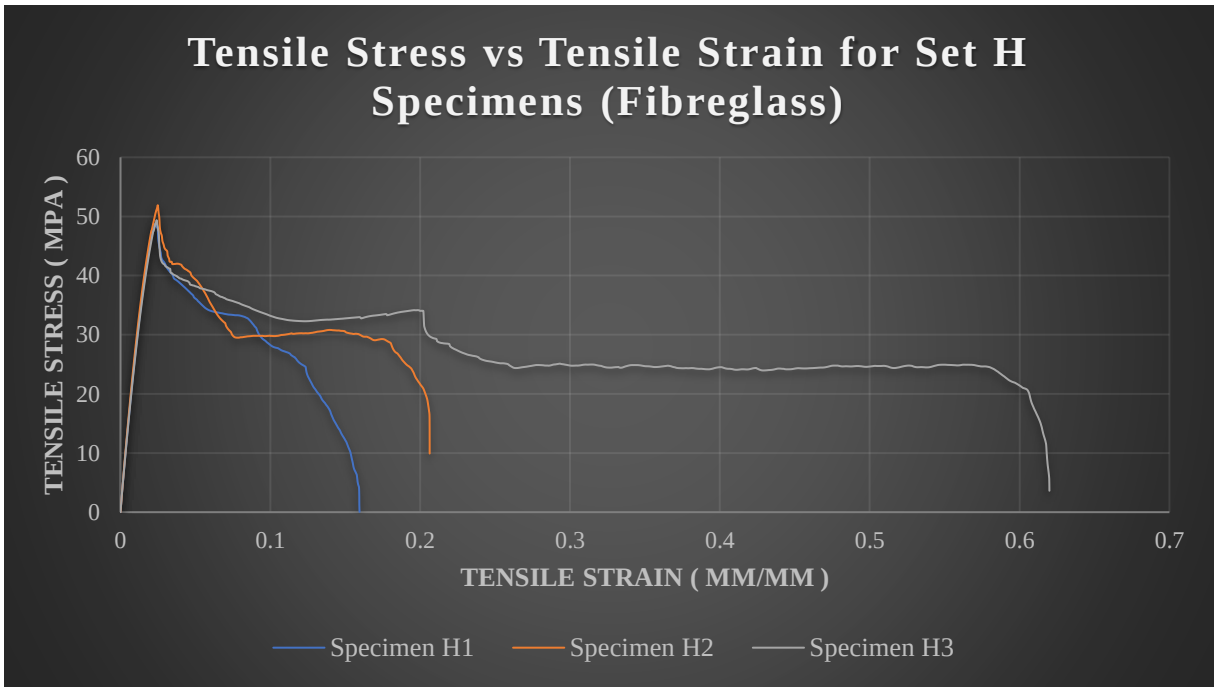

Tensile Stress vs Tensile Strain for Set C Specimens (Fibreglass)
TENSILE STRESS (MPA)
100
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
TENSILE STRAIN (MM/MM)
Specimen C1
Specimen C2
Specimen C3

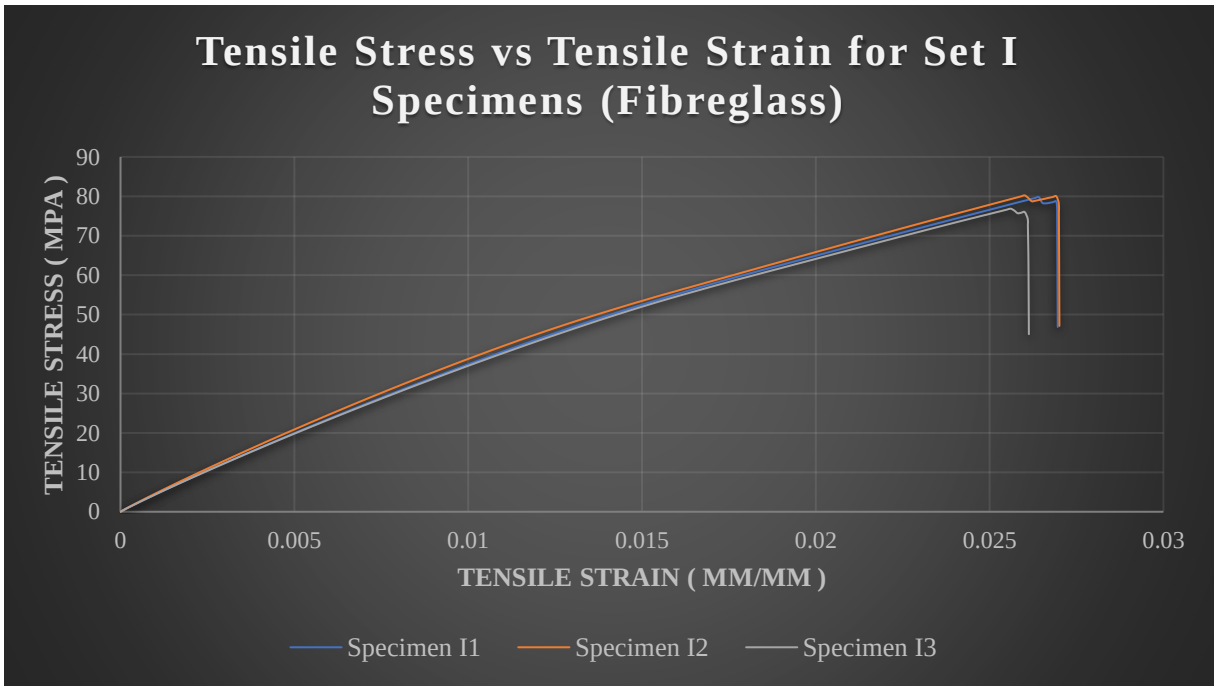

Tensile Stress vs Tensile Strain for Set D Specimens (Fibreglass)
TENSILE STRESS (MPA)
40
35
30
25
20
15
10
5
0
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
TENSILE STRAIN (MM/MM)
Specimen D1
Specimen D2
Specimen D3

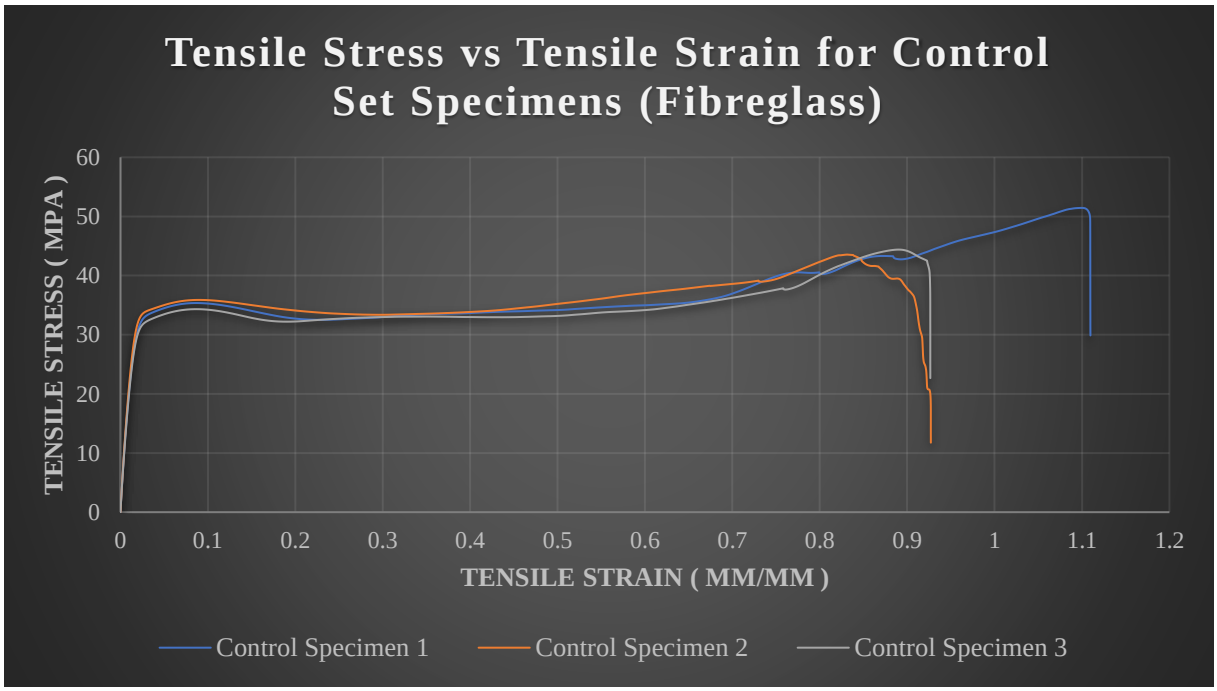

Tensile Stress vs Tensile Strain for Set E Specimens (Fibreglass)
TENSILE STRESS (MPA)
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
TENSILE STRAIN (MM/MM)
Specimen E1
Specimen E2
Specimen E3


Tensile Stress vs Tensile Strain for Set F Specimens (Fibreglass)
TENSILE STRESS (MPA)
45
40
35
30
25
20
15
10
5
0
0
0.005
0.01
0.015
0.02
0.025
0.03
TENSILE STRAIN (MM/MM)
Specimen F1
Specimen F2
Specimen F3

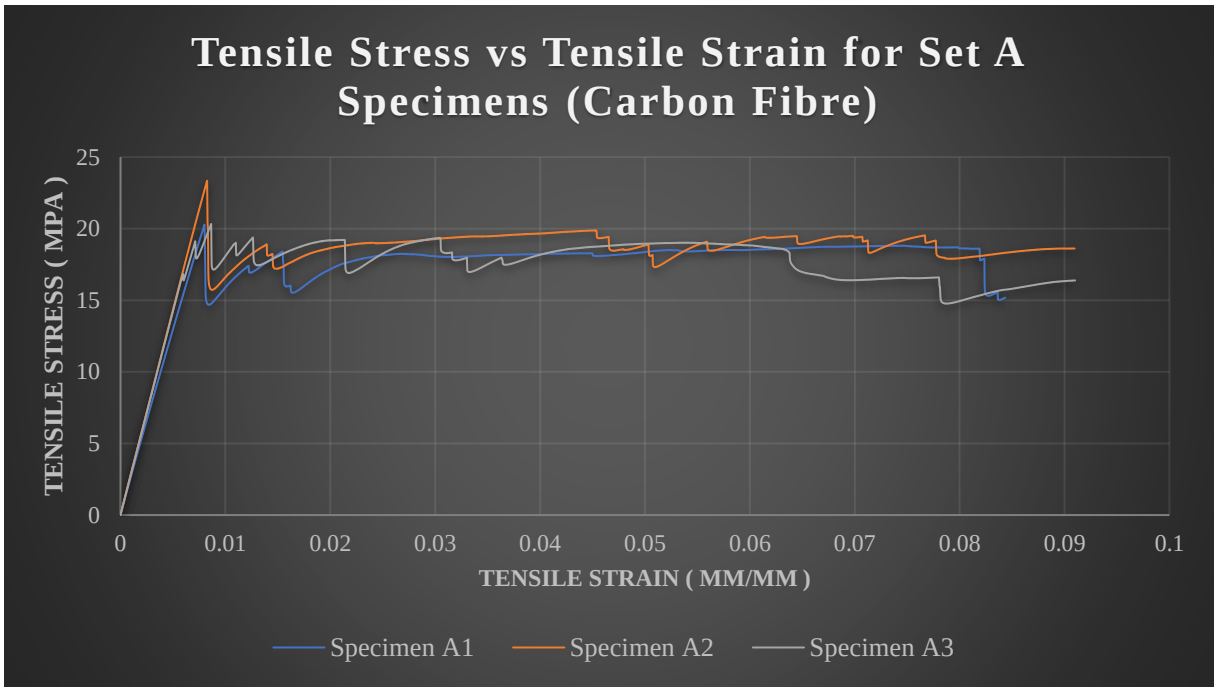

Tensile Stress vs Tensile Strain for Set G Specimens (Fibreglass)
TENSILE STRESS (MPA)
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
0.025
0.03
TENSILE STRAIN (MM/MM)
Specimen G1
Specimen G2
Specimen G3

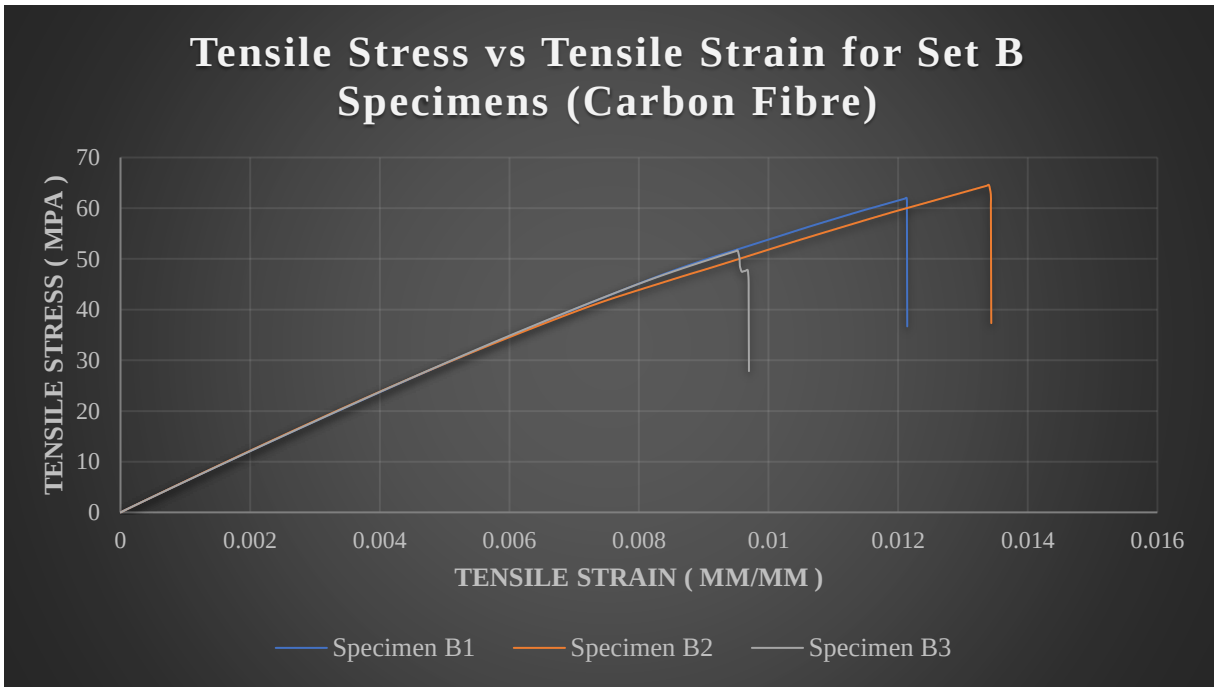

Tensile Stress vs Tensile Strain for Set H Specimens (Fibreglass)
TENSILE STRESS (MPA)
60
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
TENSILE STRAIN (MM/MM)
Specimen H1
Specimen H2
Specimen H3

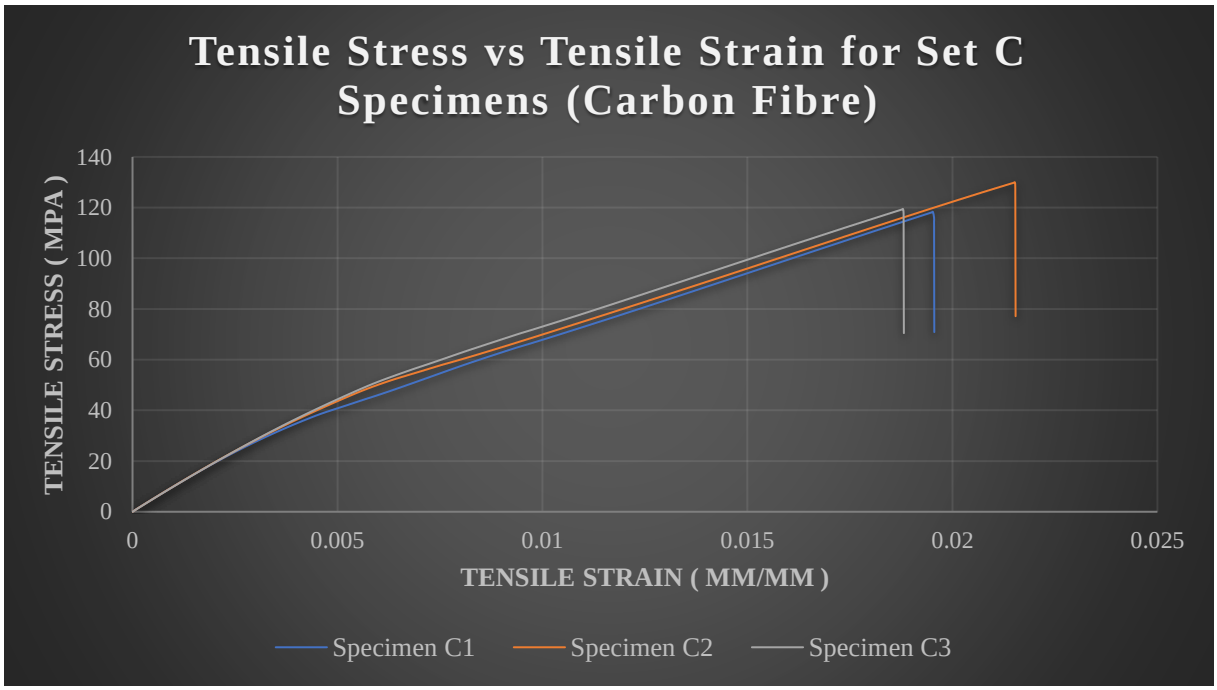

Tensile Stress vs Tensile Strain for Set I Specimens (Fibreglass)
TENSILE STRESS (MPA)
90
80
70
60
50
40
30
20
10
0
0
0.005
0.01
0.015
0.02
0.025
0.03
TENSILE STRAIN (MM/MM)
Specimen I1
Specimen I2
Specimen I3

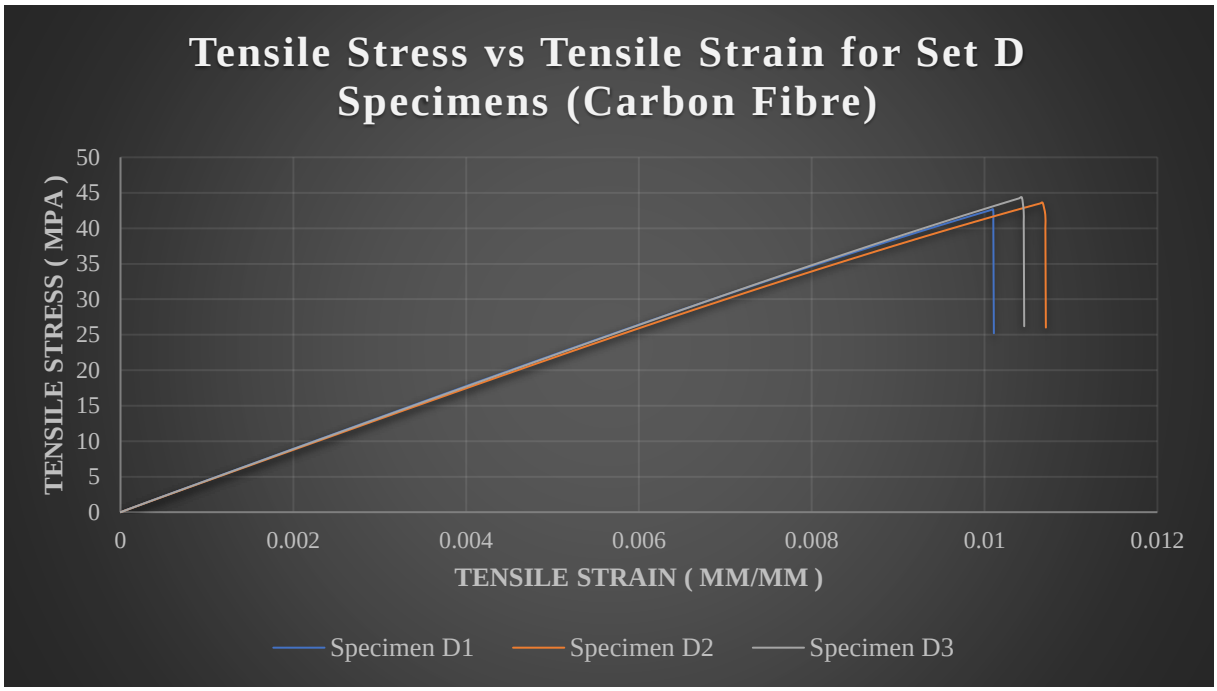

Tensile Stress vs Tensile Strain for Control Set Specimens (Fibreglass)
TENSILE STRESS (MPA)
60
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
TENSILE STRAIN (MM/MM)
Control Specimen 1
Control Specimen 2
Control Specimen 3

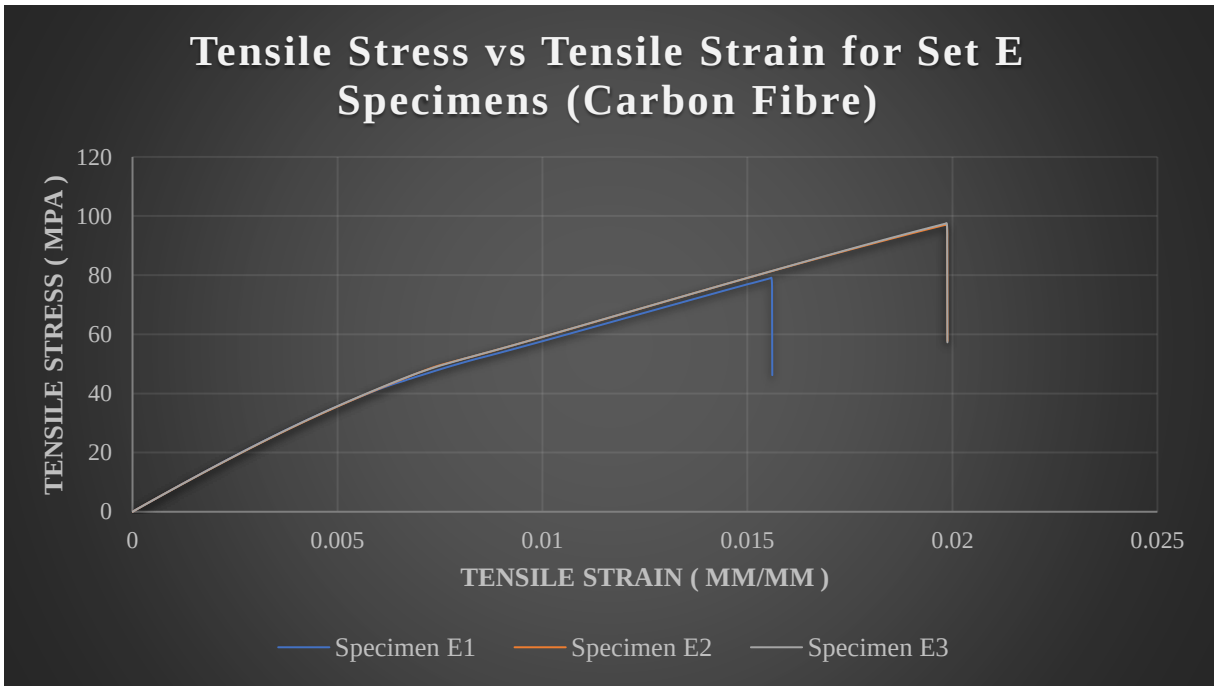
7.10 Appendix J: Carbon Fibre Tensile Stress vs Tensile Strain Graphs

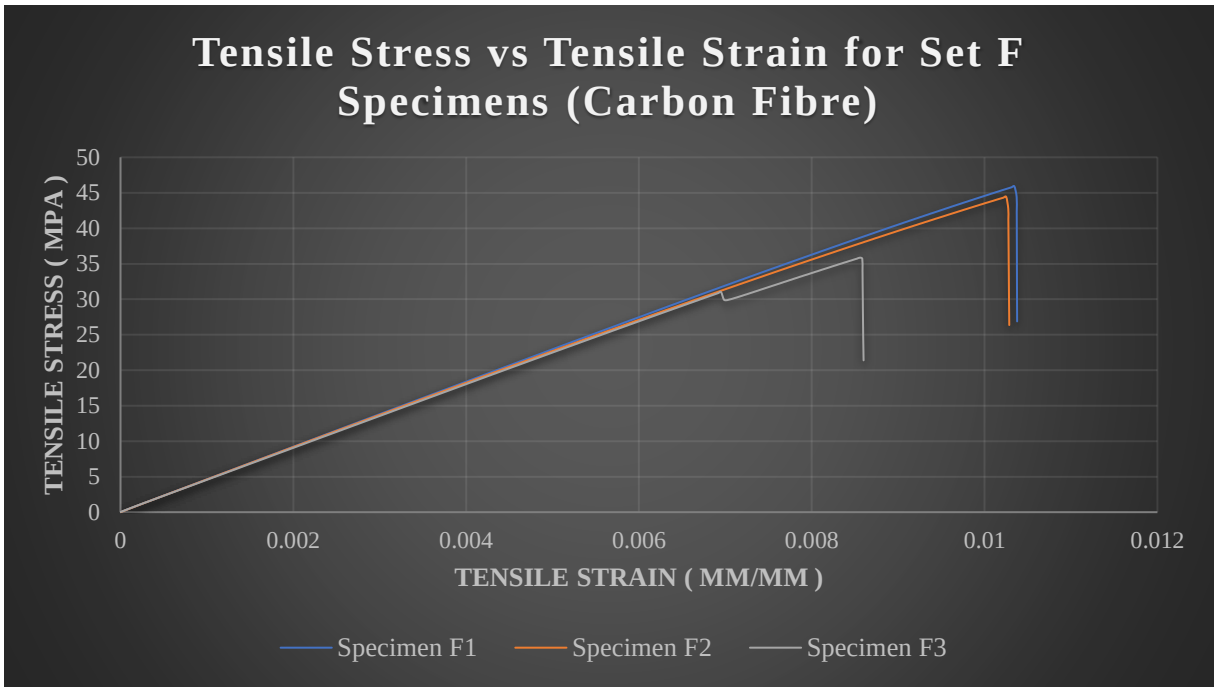


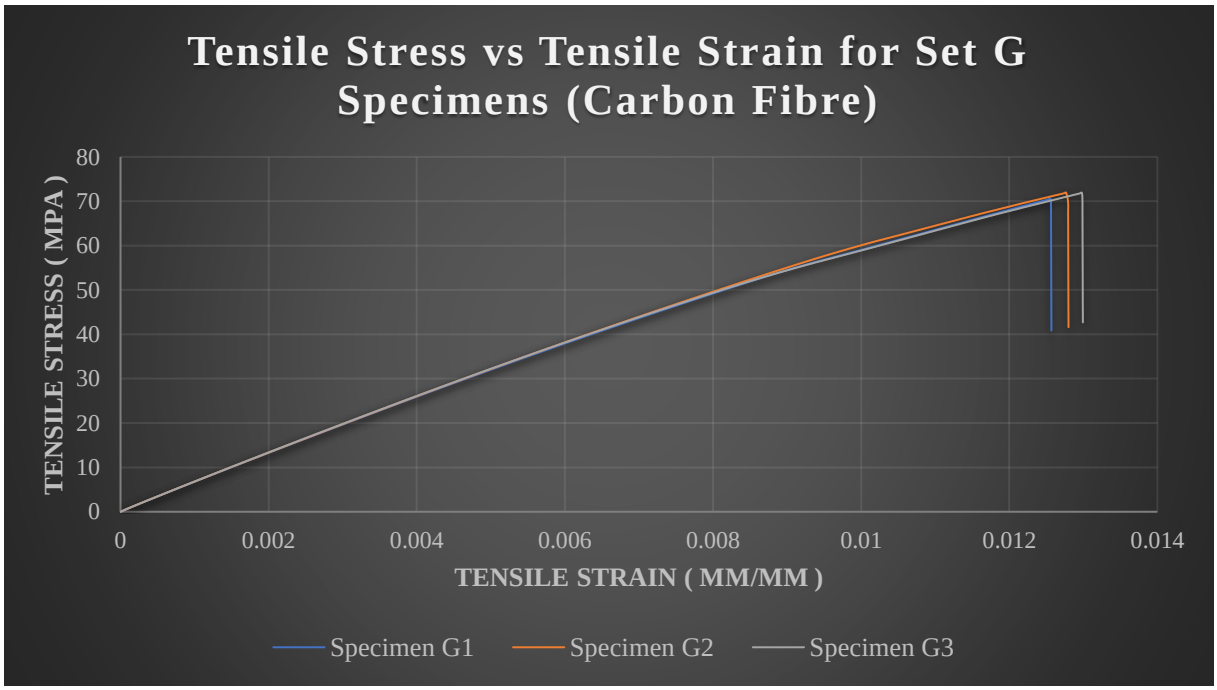


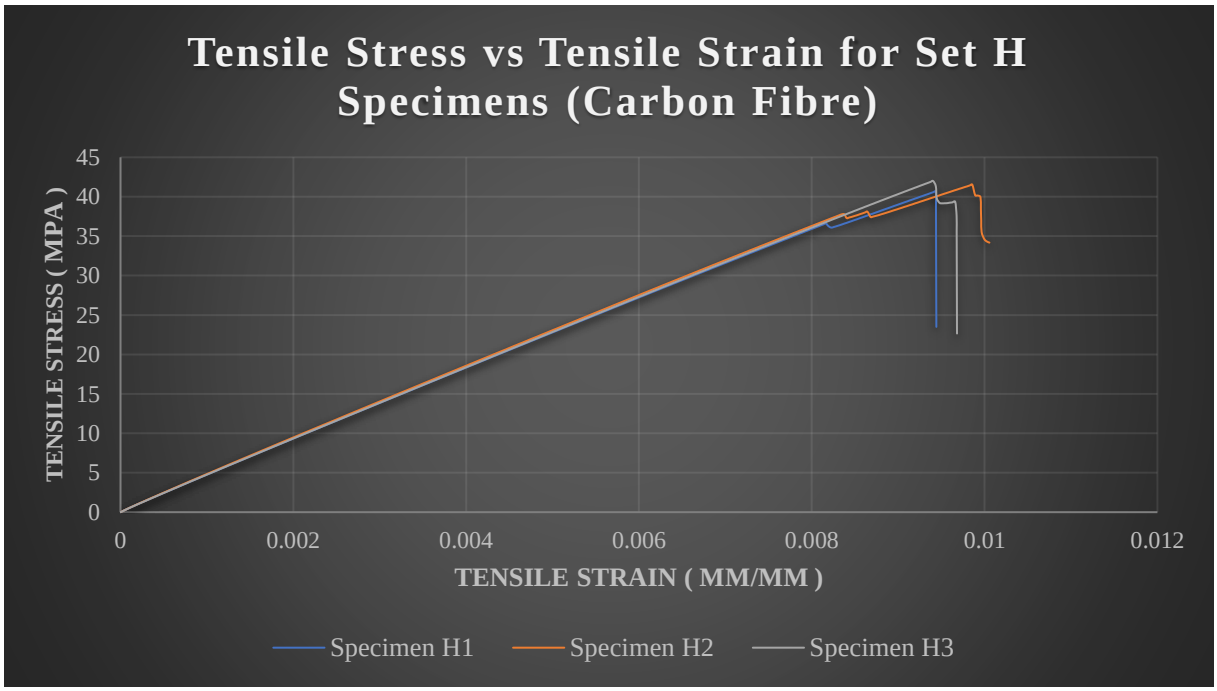

Tensile Stress vs Tensile Strain for Set C Specimens (Carbon Fibre)
TENSILE STRESS (MPA)
140
120
100
80
60
40
20
0
0
0.005
0.01
0.015
0.02
0.025
TENSILE STRAIN (MM/MM)
Specimen C1
Specimen C2
Specimen C3

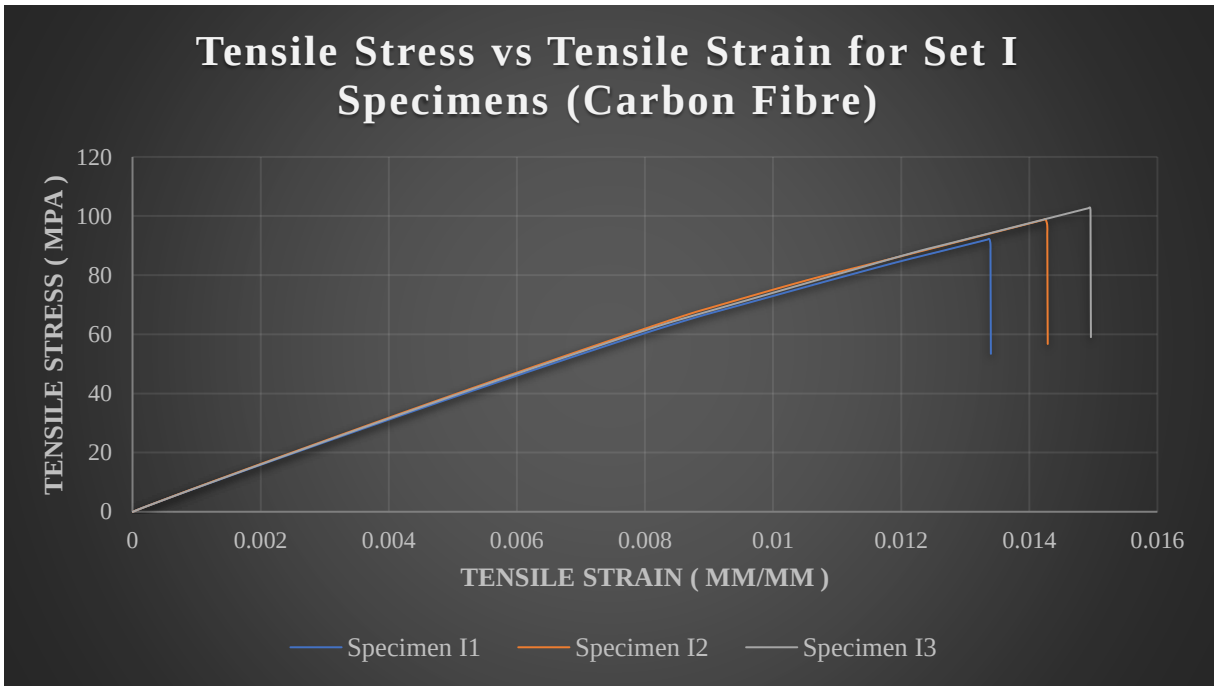

Tensile Stress vs Tensile Strain for Set D Specimens (Carbon Fibre)
TENSILE STRESS (MPA)
50
45
40
35
30
25
20
15
10
5
0
0
0.002
0.004
0.006
0.008
0.01
0.012
TENSILE STRAIN (MM/MM)
Specimen D1
Specimen D2
Specimen D3

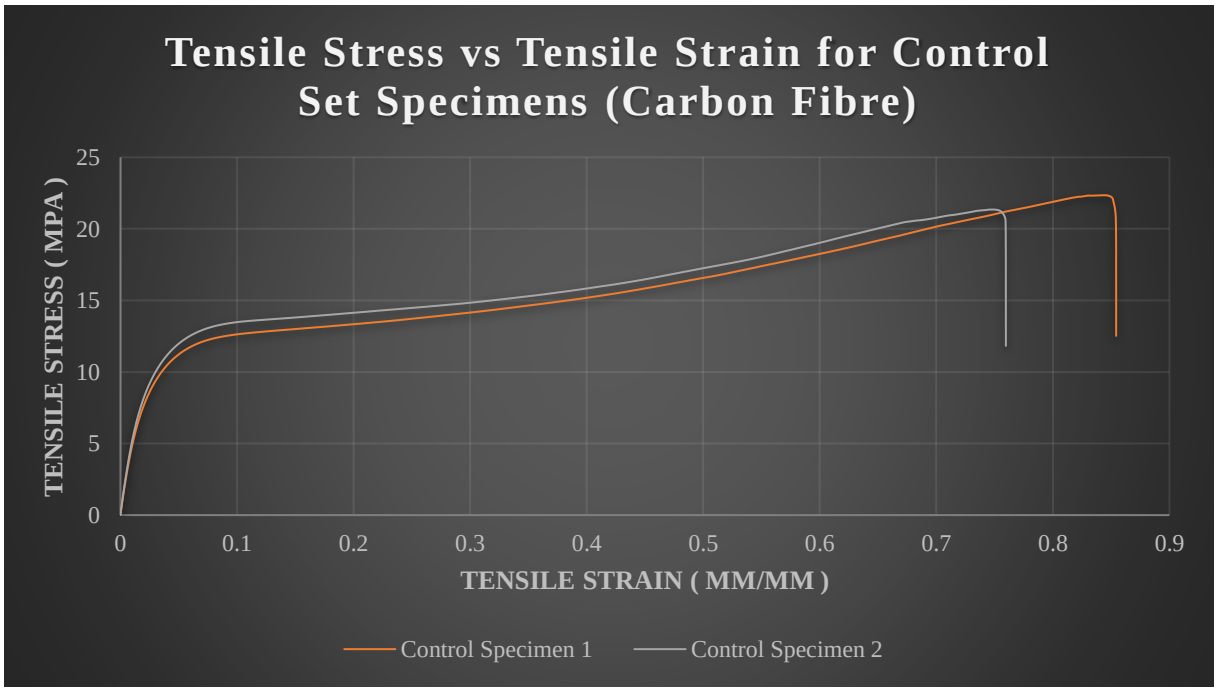

Tensile Stress vs Tensile Strain for Set E Specimens (Carbon Fibre)
TENSILE STRESS (MPA)
120
100
80
60
40
20
0
0
0.005
0.01
0.015
0.02
0.025
TENSILE STRAIN (MM/MM)
Specimen E1
Specimen E2
Specimen E3


Tensile Stress vs Tensile Strain for Set F Specimens (Carbon Fibre)
TENSILE STRESS (MPA)
50
45
40
35
30
25
20
15
10
5
0
0
0.002
0.004
0.006
0.008
0.01
0.012
TENSILE STRAIN (MM/MM)
Specimen F1
Specimen F2
Specimen F3


Tensile Stress vs Tensile Strain for Set G Specimens (Carbon Fibre)
TENSILE STRESS (MPA)
80
70
60
50
40
30
20
10
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
TENSILE STRAIN (MM/MM)
Specimen G1
Specimen G2
Specimen G3


Tensile Stress vs Tensile Strain for Set H Specimens (Carbon Fibre)
TENSILE STRESS (MPA)
45
40
35
30
25
20
15
10
5
0
0
0.002
0.004
0.006
0.008
0.01
0.012
TENSILE STRAIN (MM/MM)
Specimen H1
Specimen H2
Specimen H3


Tensile Stress vs Tensile Strain for Set I Specimens (Carbon Fibre)
TENSILE STRESS (MPA)
120
100
80
60
40
20
0
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
TENSILE STRAIN (MM/MM)
Specimen I1
Specimen I2
Specimen I3


Tensile Stress vs Tensile Strain for Control Set Specimens (Carbon Fibre)
TENSILE STRESS (MPA)
25
20
15
10
5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
TENSILE STRAIN (MM/MM)
Control Specimen 1
Control Specimen 2