Fracture Properties of Thermoplastic Composites Manufactured Using Additive Manufacturing

by

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YOUNGSTOWN STATE UNIVERSITY

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Abstract

Additive manufacturing (AM) has been successfully applied to fabricate aerospace, automotive and biomedical components due to their reduced economical features, low cycle time and their ability to use a wide range of materials. Material Extrusion (ME) is the most popular technology used in the AM field to produce thermoplastic components. Due to the limited mechanical properties in the ME produced thermoplastic parts when compared to the conventional manufacturing processes, there is a critical need to add reinforcements to these plain thermoplastics.

In this study, the fracture properties of short carbon fiber reinforced thermoplastics manufactured via ME has been investigated under static and dynamic loading conditions. Firstly the printing process parameters have been found to print short carbon fiber reinforced thermoplastics and then their tensile and flexural properties have been determined experimentally. Similarly, their high and low impact velocity properties have been determined. Additionally, their high velocity impact properties have been modelled theoretically. In order to characterize their fracture properties, these materials have been examined under an optical microscope and a scanning electron microscope after conducting each of the mechanical tests.
Acknowledgments

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Chapter 1 Introduction

Fiber reinforced plastic composites have had a great success in the automotive and aerospace industries due to their light weight features and high specific mechanical properties [1]. For instance, the Boeing 787 (see Figure 1.1) has 50% of its parts constructed with fiber reinforced plastic composite materials [2]. The Mercedes Mclaren SLR carbon fiber composite body is a great example of a success story in the use of Fiber Reinforced Plastics (FRP’s) in the race car industry [3]. Indeed, the Ford GT’s inner hood deck based on a carbon fiber was another commercially successful product [4]. In the Sixth Annual Society of Plastics Engineers Automotive Conference, Nobuya Kawamura from Toyota Motor Corp outlined that the use of plastics in the automotive industry has increased from 3% in the 60’s to a 9% in the 2000’s (2007) [5]. He mentioned that there has been excellent light-weight parts made of plastics like fuel tanks, drive shafts and intake manifolds, just to name a few. He also claimed that the use of carbon fiber composites in the race car industry has greatly reduced the number of deaths on car accidents.

**Figure 1.1** Schematic of percentage of materials used in the Boeing 787 [6].
The market study has shown that the composite industry will produce 11 million tonnes of composite product by 2015 [7]. From this production 39% will be held by the North America region by itself, with an overall production volume of 3.8 tonnes by the end of 2015. Table 1.1 describes the general market production of polymeric composites by region.

Table 1.1: Global composite market by region, 2015 [7]

<table>
<thead>
<tr>
<th>Region</th>
<th>Production volume (Tonnes)</th>
<th>Production value (£bn)</th>
<th>Share by Volume (%)</th>
<th>Share by value (%)</th>
<th>Average Unit price (£/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>3.8</td>
<td>31</td>
<td>35</td>
<td>39</td>
<td>8.2</td>
</tr>
<tr>
<td>EMEA</td>
<td>3.1</td>
<td>26</td>
<td>28</td>
<td>32</td>
<td>8.4</td>
</tr>
<tr>
<td>Asia-Pacific/Rest of the world</td>
<td>4.1</td>
<td>23</td>
<td>37</td>
<td>29</td>
<td>5.5</td>
</tr>
<tr>
<td>Total</td>
<td>11.0</td>
<td>80</td>
<td>100</td>
<td>100</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Where £bn is the Billion of British pounds

While America has been a global leader on the manufacture of composite materials for aerospace and automotive applications, Europe has been the leading continent in wind energy composites [8]. Table 1.2 summarizes the applications of composite materials in the different parts of the world in various industries. The units are in $10^3$ tonnes and percentages, respectively.
Table 1.2: Application of polymeric composites across the world [7]

<table>
<thead>
<tr>
<th></th>
<th>North America ('000 t)</th>
<th>Europe ('000 t)</th>
<th>Asia ('000 t)</th>
<th>Global ('000 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>Aerospace</td>
<td>190</td>
<td>155</td>
<td>41</td>
<td>440</td>
</tr>
<tr>
<td>Wind energy</td>
<td>76</td>
<td>217</td>
<td>82</td>
<td>330</td>
</tr>
<tr>
<td>Consumer goods</td>
<td>304</td>
<td>248</td>
<td>410</td>
<td>990</td>
</tr>
<tr>
<td>Electrical and electronic</td>
<td>570</td>
<td>403</td>
<td>943</td>
<td>1,760</td>
</tr>
<tr>
<td>Building and construction</td>
<td>1,026</td>
<td>651</td>
<td>1,435</td>
<td>2,970</td>
</tr>
<tr>
<td>Pipe and tank</td>
<td>152</td>
<td>186</td>
<td>410</td>
<td>770</td>
</tr>
<tr>
<td>Transportation</td>
<td>1,178</td>
<td>992</td>
<td>738</td>
<td>3,080</td>
</tr>
<tr>
<td>Marine</td>
<td>304</td>
<td>248</td>
<td>41</td>
<td>660</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3,800</strong></td>
<td><strong>3,100</strong></td>
<td><strong>4,100</strong></td>
<td><strong>11,000</strong></td>
</tr>
</tbody>
</table>

Due to their superior properties in terms of corrosion resistance, high wear resistance, high strength to weight ratio and ease of processing, the use of fiber reinforced plastics across the globe is expected to increase on other industries as well [9].

1.2: Additive manufacturing

The additive manufacturing (AM) process started around the mid 80’s and has now diversified into various processes like 1) Stereolithography (SLA), 2) Material extrusion 3) Laminated Object manufacturing (LOM), 4) Selective Metal Sintering (SLS), and 5) Directed Energy
Deposition (DED). Additive manufacturing was initially used as a rapid prototyping tool, but nowadays has began to be used as a main production technology [10]. Wohler’s report indicated that the annual growth rate of all the additive manufacturing services was from 25.4 % to 46.3 % for personalized 3-D printers from 1980 to 2012. In the case of the industrial 3-D printers, there has been a growth of 19.3 % just over a span of 3 years (2010-2013) [11].

Currently, AM is being used in the fabrication of polymeric and metallic products mainly on aerospace, automotive and biomedical applications [12]. Indeed, due to their reduced cycle time, ability to print complex geometries with advanced materials and economical features, the AM process is being used to fabricate aerospace components [13]. For example, the BAE 146 regional jet uses a plastic window breather pipe (see figure 1.2) constructed via AM [14]. Also, Optomec uses an additive manufacturing process called Laser Engineered Net Shaping (LENS) to fabricate metal parts for satellites and jet engines [15]. In the field of medicine, AM has been used successfully for the last 15 years to fabricate living tissues and organs by printing live cells [16]. In contrast, in the automotive sector, AM has been used to manufacture small quantities of structural and functional components like drive shafts, gear box components among many others [12].

Although AM will not be able to completely replace the conventional manufacturing processes in the near future, AM can be used as an integration tool within the conventional manufacturing processes to benefit from its economical features and reduced recycling features. AM can also be used on specialized designs where the conventional subtracting manufacturing represents a production challenge rather than an advantage.
Figure 1.2 Additively manufactured window breather pipe for BAE 146 jetliner [17].

1.3 Material Extrusion (ME)

Material Extrusion (ME) is one of the most popular method amongst the additive manufacturing to produce plastic components. This is because it offers several advantages like low cost, minimal waste, ability to change materials easily, and minimal post processing [18]. Figure 1.3 shows a plain thermoplastic material manufactured using Material Extrusion.

Figure 1.4 describes the contribution of rapid prototyping to the global market, where it is observed that the automotive industry accounts for more than 30% of the AM process.
Figure 1.3 Picture of Carbon fiber reinforced ABS composite and Plain ABS composite manufactured by Makerbot Replicator 2X- A machine that used Material Extrusion technology.

Figure 1.4 Use of rapid prototyping in the global industries [19].
From the total AM services, material extrusion contributes about 45% of the global market share [19]. Due to a variety of thermoplastics used in the material extrusion processes, the aerospace industry uses material extrusion for producing functional prototypes, manufacturing tools and final end products. For instance, NASA uses printed parts manufactured by material extrusion in the Mars Rover project [20]. The major parts on Mars Rover include the printing of flame retardant vents, camera mounts, large pod doors built using ABS, PC-ABS and Polycarbonate materials. PIPER aircraft uses material extrusion for manufacturing Aluminum form tools which is used in the process of hydroforming to produce Aluminum parts [21]. Here, the ME printed polycarbonate part are able to withstand high pressures. There are many uses of ME in the automobile industries in terms of production tooling, visual and functional prototyping and customized parts [22]. Recently, Mclaren signed a 4 years partnership with Stratasys to implement additive manufacturing to formula one [23]. Team Indy also joined hand with Stratasys to bring in customized 3D printed parts to Nascar and Indy car racing [24]. Although, there is growing market of the Material extrusion technologies in different industrial sector; currently, plain thermoplastic filaments are mainly being used to manufacture parts using this process. The most commonly used materials have been acrylonitrile butadiene styrene (ABS), poly lactic acid (PLA), Polyamide (PA) nylon and their respective combinations [25]. The major disadvantage with the current ME process is that very often, these plain thermoplastic parts have limited mechanical properties as compared to the parts manufactured by conventional manufacturing techniques such as injection molding. Therefore, the use of 3D printed plastic part on structural applications is still limited [26].

In order to solve this limitation, there is a need to induce reinforcements like short glass, carbon or Kevlar fibers on the plain thermoplastic components to improve their mechanical properties.
Researches like Zhong et al [27] have worked on manufacturing short glass fiber reinforced ABS to improve its mechanical properties while Ning et al [28] have worked on manufacturing chopped carbon fiber reinforced ABS to improve the strength and stiffness properties. Likewise, Shofner et al [26] have been able to successfully develop nanofiber reinforced ABS via material extrusion. Indeed, there has been a large number of studies trying to investigate the mechanical properties of reinforced 3D printed plastics via ME by adding different kind of fillers. Most of these efforts have concentrated on ABS and PLA under quasi-static loading conditions. Recently 3-D printers like Markforged mark two has enabled users to print a continuous reinforced parts based on carbon fiber, glass fiber and Kevlar [29] (See figure 1.5). These continuous composites have superior properties than short fibers [30]. These can produce high strength parts can be used for industrial purposes. However, most of the 3-D printed on composites, has been based on short fiber reinforcement.

![Figure 1.5](image)

**Figure 1.5** Picture of Markforged Mark two which is used to print continuous reinforced carbon fibers, glass fibers and Kevlar [29].
1.4 Objective:

The main objective of this research work is to investigate the fracture properties of short carbon fiber reinforced thermoplastic composites manufactured via material extrusion. This research has concentrated on manufacturing ABS, nylon and PETG thermoplastic filaments and their respective composites. The printed materials have been investigated under static and dynamic loading conditions. The specific goals of the present work are:

1) Print short thermoplastic reinforced composites
2) Investigate their tensile and flexural properties.
3) Study their low velocity and high impact velocity impact properties.
4) Model the tensile and high velocity properties.
5) Establishing the structure property-process relationship on the 3D printed composite systems.

Organization:

The present thesis is organized in the following manner:

- Chapter 1 presents the purpose behind the study of this research work.
- Chapter 2 presents the literature review of composites, additive manufacturing processes and 3-D printed composites.
- Chapter 3 presents the experimental methods carried out in this research program.
- Chapter 4 presents the results and discussions.
- Chapter 5 shows the conclusion of this thesis work.
References:


Chapter 2 Literature review

2.1 Introduction to Composite materials

Composites materials are systems that are assembled using at least two constituent materials with unique physical and chemical properties with the purpose to produce components with superior qualities than individual materials (see figure 2.1) [1]. Composite materials have a wide range of applications ranging from the aerospace and transportation sector to the medical and sports field [2]. In most of the engineering applications, composites are designed to increase the strength, stiffness and to reduce weight of structural components [3]. Fibers usually contribute to the strength and stiffness of the composites, whereas the resins have excellent chemical resistant features, and contribute on reducing the weight of the overall material. Indeed, fiber reinforced composite are materials with high specific modulus and specific strength that makes them attractive systems for the transportation sector where strong and light-weight structures suggest more efficiency and energy savings. Composites are of high importance in engineering applications since their designs can be tailored for a particular use in order to cope with specific stresses and environmental conditions [4,5].
2.2 Resins

There are two major types of resins used in the fiber reinforced plastic composite industry.

2.2.1 Thermoplastics

Thermoplastics are high molecular weight materials that can be reshaped upon heating and cooling, since no crosslinking is present in these kinds of materials. Their mechanical properties depend on the type of monomers used and the degree of entanglement of their chains [6]. In the composite industry, engineering thermoplastic resins have a wide range of applications because they have a high glass transition temperature, the ability to be reshaped and repaired, low manufacturing costs, long prepreg stability and less processing time compared to thermoset resins [7]. One of the major disadvantages of thermoplastic matrices is under the influence of sustained loading, since they are susceptible to creep rupture [2, 8].

Figure 2.1 Schematic representation of the structure of composite material [1]
Examples of the thermoplastic matrices investigated in this work are: A) Acrylonitrile butadiene styrene (ABS), B) Poly Ethylene Terephthalate glycol(PETG) and, C) Nylon.

**ABS:**

ABS contains three polymers: Acrylonitrile, butadiene and styrene in different proportions [9]. ABS has superior mechanical properties than styrene because it can be compounded with superior hardness and flexibility. ABS has applications in systems such as telephones, cameras, gears, pump impellers, deflectors, pipes and pipe fittings among many other uses [10]. The mechanical properties of ABS can be further enhanced by adding glass fillers and carbon fibers. Figure 2.2 shows a pictorial representation of the ABS polymer used for certain applications.

*Figure 2.2* Picture of ABS engraving sheet used in the production of signboards, chest cards, data plates among many other uses [11].
**Nylon:**

Nylon is based on a linear polyamide structure that results from the condensation polymerization of a dibasic acid and diamine groups [12]. The most commercially available form of nylon, is Nylon 6,6; which is made by the condensation polymerization of hexamethylene diamine and adipic acid. Nylon has a high mechanical strength, abrasion resistance and low coefficient of friction. Common applications of nylon are in the textile industry; for instance, ropes, toothbrush bristles, sutures, gears and propellers. The mechanical properties of nylon matrices can be improved by reinforcing them with fibers [13]. Figure 2.3 shows a picture of a Nylon rope.

![Figure 2.3 A Picture of textile Nylon used for jump ropes][14]

**2.3 Thermoset resins:**

Thermoset are a strong-three dimensional network of polymeric chains that undergo irreversible solidification when curing by forming chemical crosslinks [2]. The strength and stiffness of
thermosets come from the length and density of the cross linking. The curing stage is the process where liquid resins are converted into hard brittle solids. Examples of thermoset resins used in the composite industry are epoxy and polyester resins [15]. Epoxy resins have higher application temperatures, strength, stiffness, lower thermal coefficient of expansion and a better interfacial adhesion within fibers than Polyester resins. However, polyester resins are more economical than epoxy resins. Figure 2.4 shows an epoxy resin used on flooring. Table 2.1 shows the comparison of the mechanical properties between two commonly used thermoset resins.

![Figure 2.4 Picture of an epoxy resins used in flooring [16].](image-url)
Table 2.1 Comparison of mechanical properties between epoxy resins and polyester resins [2].

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Epoxy Resins</th>
<th>Polyester Resins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>Mgm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>1.1-1.4</td>
<td>1.2-1.5</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>GNm&lt;sup&gt;-2&lt;/sup&gt;</td>
<td>3-6</td>
<td>2-4.5</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td></td>
<td>0.38-0.4</td>
<td>0.37-0.39</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MNm&lt;sup&gt;-2&lt;/sup&gt;</td>
<td>35-100</td>
<td>40-90</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>MNm&lt;sup&gt;-2&lt;/sup&gt;</td>
<td>100-200</td>
<td>90-250</td>
</tr>
<tr>
<td>Elongation to break (Tension)</td>
<td>%</td>
<td>1-6</td>
<td>2</td>
</tr>
</tbody>
</table>

2.2 Fibers:

Fibers are the load carrying phase in the composite systems, and typically occupy the largest volume fraction in a lamina. The most commercially used fibers are glass, carbon and Kevlar 49 (Aramid) [17].
**Aramid:**

According to the US federal trade commission, an aramid fiber is defined as “a manufactured fiber in which the fiber-forming substance is a long-chain synthetic polyamide in which at least 85% of the amide linkages are attached directly to two aromatic rings” [3]. The common trade name of aramid fibers is Kevlar. Kevlar exhibits high strength and stiffness due to the molecular alignment achieved by a solution spinning process [18]. Poly-P-phenylene Terephthalamide (PPTA), trade name of Kevlar is produced in liquid crystalline state in sulfuric acid at a polymer concentration around 20% [2,3,17,18]. However, one of the major disadvantages in aramid fibers is its poor fiber/matrix interfacial adhesion due to their inert chemical structure [19]. Aramid fibers have a wide range of applications in the aerospace, marine, automotive, rubber and sports industries [2,3].

**Glass Fiber:**

Glass fibers are commonly produced by combining silica with other additives such as oxides of calcium, boron, sodium, iron and aluminum. Continuous fiber glass strands are produced by melting the raw materials in a tank and subsequently passing them through a platinum bushing. Here, due to gravity, the glass flow down, and fine fibers are drawn mechanically downwards as the glass is expelled from the openings. The glass filaments are wound onto drums at rates of a few thousand meters every minute. An organic sizing solution like binders, lubricants, coupling and antistatic agents are applied before the fibers are drawn as packed strands. These agents also assist the fiber on having a better interfacial adhesion within the matrix [20]. Three types of glass fibers are commonly produced: E Glass and S glass. Due to low cost, high resistance towards chemical attack, high tension and flexural strengths, E-glass fiber reinforced composites have
been used frequently in dental applications to substitute metallic applications in dentures, endodontic posts, orthodontic posts [21]. Glass fiber reinforced resins are also being used in the construction industries, and due to its good durability and superior energy absorption properties [22], they are also used widely in the automotive industries. However, glass fiber, are prone to suffer static fatigue, a process where a material subjected to a constant load for a long period of time, tends to undergo a subcritical crack growth, a condition that can lead to failure over time [2, 23]. The table below compares the stress strain properties of between different glass epoxy systems.

**Carbon fiber:**

Carbon fibers are materials consisting on small graphite structures arranged in a hexagonal array. Here atoms in the layer are bonded in a covalent manner and van der Waal forces between each layer keep the fibers as a single material [2]. Due to this factor, carbon fibers are anisotropic in nature, which means that the mechanical properties of the material change with direction along the axes. The major method of production of carbon fibers are from a PAN based source, which produce fibers with tensile strengths up to 7 GPa. The process developed by Rolls Royce and the Royal Aircraft Establishment, uses PAN as the precursor material. Here the precursor is stretched to produce alignment of the molecular chains in the direction of the fiber axis, then the fibers are further heated to get oxidized, and finally reduced to give a carbon ring structure. This structure is then converted in the form of graphite by heating the fibers at a higher temperature [25]. Due to their high specific strength and modulus, carbon fibers are generally used as a reinforcement material on plastics; for example, carbon fiber reinforced plastics, carbon fiber
reinforced ceramics, carbon–carbon composites and carbon fiber reinforced metals [26]. Carbon fiber reinforced composites have a wide range of applications in the aerospace, sports and automobile industries [27, 28].

2.3 Fiber reinforced composites

Based on the fiber length, composites can be classified into continuous and short fiber reinforced composites.

2.3.1 Continuous reinforcement

There are three main types of orientations in continuously reinforced fibers. 1) Unidirectional, where the fibers are stacked parallel to each other. 2) Angle ply, where the alignment of fibers are at an angle, and 3) Cross-ply, where the fibers are stacked perpendicular to each other. The axial stiffness and strength of the composite is based on the alignment of the fibers. The maximum axial strength and stiffness in continuous reinforced composites are in the 0° alignment within a unidirectional fiber arrangement [29]. The stiffness and strength in continuous fibers can be modelled by using the rule of mixtures, considered the fibers to be infinitely long [30].

Due to their excellent mechanical, light weight features and high service-life, Continuous fiber reinforced composites are being used in a large number of applications in the aviation, automobile and civil fields just to mention a few of them [31-33].
2.3.2 Short fiber reinforcement:

Short fibers are chopped discontinuous fibers, which typically show inferior mechanical properties than continuous fibers, but due to their easy fabrication and lower cost than continuous fibers, have many commercial applications. For example, in the case of thermally sensitive electronic packaging materials, short fiber reinforced polymers are commonly desired because the combination of the reinforcement with a high thermal conductivity embedded in the low thermal conductivity resin matrix [34]. Garoushi et al [35] used short glass fiber reinforced semi interpenetrative composite resins to improve the mechanical properties of dental composite resins, whereas Rezaei et al [36] developed short carbon fiber reinforced polypropylene composites for car bonnet applications. They reported that by using 10% short carbon fiber reinforced polypropylene system, the specific mechanical properties of the car bonnet was comparable to typical metal based bonnet. Figure 2.5 shows a long carbon fiber and short carbon fiber thermoplastic system.

![Schematic representation of continuous reinforced fiber in a thermoplastic resin and a short/discontinuous fiber reinforced thermoplastic systems](image)

**Figure 2.5** Schematic representation of continuous reinforced fiber in a thermoplastic resin and a short/discontinuous fiber reinforced thermoplastic systems [37].

The strength of short fibers reinforced composites will depend on the length and alignment of the reinforcing fibers. It is safe to assume that the strength of the composite material is directly
dependent on the mechanical properties of the fiber. Once the material reaches the maximum fiber fracture strength, a complete fracture occurs in the system. Indeed, the maximum strength that can support the fiber on the composite depends on the length. Therefore, during the fabrication process it is important that each layer has an average length of each fiber greater than its critical length (length at which the matrix and fiber fail at the same strain).

Indeed, if the length of short fibers are sufficiently long, and considering their ease of processing and price, short fibers can be an alternative replacement to continuous fibers on non structural applications. This is because at the same fiber loading, the stiffness levels of the continuous fibers on the composite can be achieved with a short fiber system [24]. Table 2.2 highlights some of the mechanical properties of commonly used reinforcing fibers.

**Table 2.2 Mechanical properties of the reinforcing fibers [3]**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>High strength Carbon fiber</th>
<th>Kevlar 49</th>
<th>E Glass Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (μm)</td>
<td>7.6-8.6</td>
<td>12</td>
<td>8-14</td>
</tr>
<tr>
<td>Youngs Modulus (GPa)</td>
<td>250</td>
<td>125</td>
<td>70</td>
</tr>
<tr>
<td>Tensile strength (GPa)</td>
<td>2.7</td>
<td>2.8-3.5</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Strain at fracture (%)</td>
<td>1</td>
<td>2.2-2.8</td>
<td>1.8-3.2</td>
</tr>
<tr>
<td>Density (g cm⁻³)</td>
<td>1.75</td>
<td>1.45</td>
<td>2.55</td>
</tr>
</tbody>
</table>
2.4 Manufacturing Process

One of the first manufacturing method for fiber reinforced polymer composites was the hand lay up process [38]. Although it is a very reliable technique, it is slow and labor intensive. Here, the composite materials are made by impregnating fibers with resins using rollers. These hand lay-up composites can be arranged into a unidirectional, glass-ply or in woven form [39]. The hand layup method involves manipulating each layer by hand, and manually sticking them to the previous layer, making sure that there is no air gap between each layer.

This method can produce parts with complex designs; however the quality of the manufactured parts are affected due to human variation in terms of experience [28]. Also, the cost of a labour and materials can sometimes be high. Figure 2.6 represents the hand layup method where the reinforcement materials are placed by hand and then wetted with a resin.

![Hand Layup Process](image)

**Figure 2.6** Schematic representation of the hand lay up process in the composite industry. In this process, a fiber mat is layered up with a resin to form a composite [40].
**Film stacking**

This method involves deposition of a thermoplastic matrix containing fibers with low resin content, which are deposited or stacked in alternate layers within the polymer material [39]. The low resin-fiber content is complemented by the pure polymer matrix that impregnates the fibers to give the desired volume fraction in the composite. These composites are further strengthened by applying pressure and heat. An applied pressure of 6-12 Mpa and a temperature of 300-350°C is commonly used to make sure that there is a good flow of thermoplastic matrix between the layers.

**Compression Molding:**

Compression molding is a process in which a resin is preheated and is placed into an open mold cavity. Here, pressure is applied to force the material to distribute along all the areas of the mould. The pressure and temperature are maintained throughout the process until the polymer is consolidated. Advanced thermoplastic composite materials can be manufactured using this process [41, 42]. Figure 2.7 shows a picture of compression molding used in the manufacture of thermoplastic composite materials.
Figure 2.7 Schematic representation of compression molding of a thermoplastic [43]. Here, a plastic is placed in a mold, and pressure is applied until the polymer is fully consolidated.

**Injection molding**

Injection molding is the most commonly used process to manufacture plastic parts [44]. It has also used on the fiber reinforced plastics industry as well. A wide variety of parts with complex shapes, sizes and application can be produced using injection molding. In this process, a hot molten polymer is filled in a cold empty cavity shaped like the part. A high pressure is applied in this process until the material solidifies. This process can be classified into 3 stages: 1) Filling, 2) Post filling, and 3) Molding [45]. In these processes the polymer is under high temperature and pressure changes; thus, the quality of the part depends on post processing steps like removing the residual stresses. Figure 2.8 represents a conventional injection molding process used in the composite industry.
2.5 Applications

Due to the unique mechanical properties that polymeric composite material exhibit, they have been able to solve challenges of complex designs in modern aircrafts. Table 2.3 shows the use of fiber reinforced composite materials in the aerospace sector. Carbon fiber reinforced composites (CFRP) has been the most used system amongst the fiber reinforced plastics in the aerospace industry. CFRP can offer up to 25% weight saving if compared to metals like Aluminum or Titanium, especially in strength and stiffness in fighter planes [47]. Control surfaces, fuselage components, wings are the common parts produced using CFC in military aircraft applications [46].

Figure 2.8 A schematic figure of an injection molding machine used in the plastics manufacturing process [44].
Polymeric composites also have a large number of applications in the sport sector because of their light weight and good specific strength properties. For instances: table tennis, bats, golf shafts, fishing rods, sports cycle frames among many others. CFRP are also used in musical instruments like Violins and guitar frames due to their high sound quality; a feature associated to the presence of carbon fibers in the composite.

Formula 1 cars also use polymeric composites as part of their structure, due to their aforementioned light-weight features and good energy absorbance capabilities in crash situations like McLaren MP4 [48].

Indeed, qualities like high specific strength, stiffness, light weight, low thermal expansion coefficient has promoted the usage of fiber reinforced composite materials also in the communication satellite industry as well that is in Intelsat5, Exosat [49].
2.6 Additive Manufacturing

According to the ASTM definition, additive manufacturing is defined as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [50]. This manufacturing process is also commonly called 3D printing or rapid prototyping. There are seven methods of additive manufacturing, namely: Material Extrusion, Binder Jetting, Directed Energy Deposition, Material Jetting, Powder Based Fusion, Sheet Lamination and Vat Photo Polymerization [51]. Even though, each of the processes differ in their own ways, they all add up material in a layer by layer fashion based on a computer aided design software.

2.6.1 Basics steps involved in the AM process:

CAD modelling software is the first step in building an additive manufactured part. CAD models enables the surface of the additively manufactured to be completely enclosed and fully describes the external geometry. Any professional CAD modelling software can be used for this purpose. The slicing algorithm for every layer in the CAD object is achieved by converting the design into a STL file. STL stands for standard tessellation language, in which the 3D part is represented in terms of raw and unstructured triangles with unit normal and vertices represented in a Cartesian coordinate system [52]. Nowadays, nearly every CAD system can be converted to this STL format [53].

In this process, the STL file is transferred to the 3-D printing machine where the sizing, position and orientation are modified. In the machine, the part is built through a completely automated process. Once the printing stage is accomplished, the part is removed and followed by some post
processing if needed. A flow diagram describing the aforementioned AM process is shown in figure 2.9.

**Figure 2.9** Schematic representation of the building stages in the additive manufacturing process [54].
2.6.2 Types of Additive manufacturing

a) Vat Polymerization:

This process is based on solidification of a photopolymer using a UV or laser energy [54]. It is commonly called Stereolithography [SLA] process and consists of a movable build plate enclosed in a VAT or a tube, in which the polymer is cured or solidified using ultraviolet or laser energy. After deposition of each layer, the build plate moves down allowing more liquid to deposit over the solid.

The two basic approaches in vat polymerization are: 1) direct or laser writing, and 2) mask based writing. Both of these processes are single photon photo fabrication processes. Direct writing is a process in which the object is scanned at one point, whereas in mask based writing approach, a whole layer of the polymer is cured using the polymerization source [55].

The advantages of the VAT polymerization process include good build speed, smooth surfaces, economical process, the disadvantages include the need of support structures or scaffoldings to overhanging structures and the hazardous nature of the photopolymer resins [56]. Figure 2.10 shows the two common VAT polymerization processes used in SLA.
**Figure 2.10** Representation of the two VAT polymerization process [56]. The first technique (a) uses a layer scan approach to cure the whole layer by a UV lamp. The second technique (b) uses one single point of scanning.

**Sheet lamination:**

The Laminated Object Manufacturing (LOM) process, was one of the first forms of sheet lamination which was commercialized by Helysis in the 1980’s [57]. This type of manufacturing is based on bonding layers of sheets of different or same materials over each other. These layers are usually bonded by a thermaloplastic adhesive, and a laser then cuts through the cross section. This process is repeated until the final part is produced [58]. Figure 2.11 is the illustration of the sheet lamination process:
Figure 2.11 Pictorial representation of the components of the sheet lamination process [58].

Here the material is rolled by a laminated roller and a laser cuts through the material until the final part is manufactured.

The advantages of this process include fast building times, economical, large volume parts and there is no need of supports and rafts. Since the mechanical properties of the materials will depend on the adhesive that is used to bond the different layers, the manufactured structure might lead to anisotropic properties [59]. This process typically lead to a significant amount of scrap or waste [60].

Powder Bed fusion:

Powder bed fusion can be used to fabricate plastic, metals and ceramic parts [61]. This process was initially used to make plastic prototypes and it was called Selective Laser Sintering (SLS). It was developed by the University of Texas at Austin. In this manufacturing process, the growth of the powder bed fusion for metal production is growing exponentially, due to the broad materials and temperature ranges that are associated with the process [62]. The Figure 2.12 shows a representation of the powder bed fusion process.
Figure 2.12 Schematic representation of the powder bed fusion process, where the powder is delivered to the build plate using the piston and a laser source is selectively moved across the bed as specified in the CAD file to create the part.

In this process, the powder is spread over the building plate in a layer by layer fashion. According to the specification of the part geometry and dimensions in the CAD file, a laser is selectively moved across the bed containing the powder to create the solid object. The mechanical properties of the part depend on the process parameters such as layer thickness, laser power and travelling speed [63]. The main advantage of the powder bed fusion is its flexibility of using a wide range of materials. Also, no supports and rafts required, and it has the feature of
recycling the unused powder. However, the major disadvantages of this process are the poor surface finish kept on the printed parts, the presence of warping and the significant warm up time required before the build starts [59, 60].

**Directed energy deposition:**

According to the definition by ASTM, direct energy deposition is defined as any process that uses thermal energy to fuse materials together by melting them as they are simultaneously being deposited [50]. This is a powder based additive manufacturing method in which a part is built by melting consecutive layers of metal feed in a building plate. The energy source is a pre-programmed source of laser similar to powder bed fusion process. The material is delivered to the build plate by directing the spool or the powder continuously through the coaxial nozzles to the melt pool to produce a completely dense three dimensional part with complex geometries [64]. This system can have large building volumes. For instance: the Optomec LENS 850-R unit has a building volume greater than 1.2 m³ [65]. The figure 2.13 shows a schematic direct energy deposition process. One of the major advantages of this process is its ability to build parts of different geometries or compositions in the same machine, which can economize the manufacturing process by reducing the tooling costs [66]. Other advantages include its ability to use and repair worn out components. The disadvantages of this process include the need for supports and rafts, long build times, and a rough surface finishing.
Figure 2.13 Pictorial representation of the directed energy deposition process. Here, the feed and the laser is focused on a point, where it is melted and solidified to create a layer and the final part.

**Binder Jetting**

Binder jetting is defined as the process of using a liquid bonding agent to selectively deposit and join powder materials [50]. The feed powder is evenly spread in a building plate by a counter rotating roller. After the powder is evenly spread, the binder is deposited by the print head to stick the powders together as established by the CAD file. The building plate is then lowered along the Z axis according to the layer thickness, and then, the next layer is printed in the same fashion until the complete object is built. The binder is commonly cured as it prevents the part
from breaking. Kyle Myers et al [67] used binder jetting to manufacture Al/Al203 interpenetrating ceramic metal phase composites. They found that the process parameters such as particle size distribution, powder spread speed, layer thickness, binder saturation and sintering temperature played a crucial role in the final density of the part. Figure 2.14 illustrates the binder jetting process.

![Figure 2.14](image)

**Figure 2.14** Schematic representation of the binder jetting process [67]. Here, the powder feed is evenly deposited in the powder bed, and the binder bonds the powder together as specified in the CAD file.

### 2.7 Material Extrusion:

Material extrusion (ME), the ASTM term used for Fused deposition Modelling (FDM), is an important additive manufacturing method that was developed by Stratysis Inc [68]. The most common materials used in this type of prototyping process are ABS and PLA. The major advantage of the ME process is that it is an extremely simple to use. Here, a 3-D model of the part to be printed is first created using a computer aided design (CAD) software. The model is
then stored in Stereolithography (STL) format, and later exported to an slicing software (i.e. Quickslice). Then the physical properties like temperature, raster pattern, layer thickness, raster pattern and feeding velocity are assigned to the ME machine. The feeding source material is a polymer based filament which is fed through a hot nozzle for producing the parts. Figure 2.15 shows the representation of a ME machine.

**Figure 2.15** Schematic representation of a material extrusion process [69]. In this process, the polymer filament fed through the hot nozzle is melted and deposited in the building plate in a layer by layer fashion to produce the final part.

Ahn et al. [70] studied the anisotropic properties of printed ABS parts that they manufactured via ME. They investigated the mechanical properties of the printed ABS by varying the process parameters like raster orientation, air gap (space between the beads of the material), color of the
filament, type of loading and temperature. By using a design of Experiment (DOE) method, it was found that the two most significant parameters were air gap and raster pattern. The samples were prepared based on the modification of these two conditions. For instance ABS samples were manufactured based on different raster angle (0, 45, 90) and different airgaps.

The printed samples were tested under tensile and compressive conditions and the results were compared to these parts manufactured using an injection molding machine. The results showed that the samples printed with 0 degree raster angle, negative airgap, and axially loaded, had mechanical properties that were comparable to those samples manufacture via injection molding.

Tymrak et al [71] studied the mechanical properties of PLA and ABS by using Reprap, an open source 3-D printer and they reported an average tensile strength of 56.6 and 28.5 MPa, for the PLA and ABS respectively. These results indicate that Material Extrusion can replace conventional processing techniques like compression molding if a wide range of materials can be printed.

Although Material Extrusion is a very economical process it has several disadvantages. The major disadvantages are: 1) the use of ME machines are restricted to low temperature ranges, 2) printed material shows highly anisotropic features, 3) low stiffness and strength through the deposition axis. Additionally, few materials are currently used in the ME process, and fewer are explored as reinforced materials

Hence, in order to fully utilize the advantages of the Material extrusion process, it is important to print a wide range of materials and test its mechanical and fracture properties. Various researches have investigated the optimal ME processing conditions of short carbon fiber reinforced
thermoplastic materials [70-77]. These studies have been driven with the purpose to create composite structures with improved designs and light-weight features.

Tekinalp et al [74] have used ME techniques to print chopped carbon fiber reinforced ABS composites, and they compared the tensile strength and modulus of the printed specimens to these samples manufactured by compression molding for applications as load bearing components. Here, the nozzle temperature was maintained at 205°C, and the print bed at a temperature at 85°C with a layer- height set to 0.2mm. Tensile tests were performed on the printed samples, and it was shown that the printed composites had higher specific strength and elastic modulus than Aluminium 6061-0. In this work, the fibers in the printed composite were isolated using acetone to investigate the orientation and dispersion in the matrix, and it was observed that the fibers were well dispersed and more uniformly oriented than samples manufactured through compression molding. However, a considerable amount of porosity was observed in the samples, a feature that was associated to the heating and cooling stages of the printing process.

Zhong et al [77] used short glass fibers, as well as compatibilizers and plasticizers on ABS to improve its mechanical properties. The samples were printed using ME. The 3-D printer used in this work was a MEM-250, which was a multifunctional 3-D printer used for both ME and Laminated object manufacturing (LOM) process. They investigated two types of samples, which were based on their orientation with respect to XYZ planes. One printed sample was parallel to the XY plane and the other set was parallel to Z axis. ABS was investigated due to its good thermo-physical properties like low thermal coefficient of expansion, low viscosity and low melting point, a feature that leads to parts with high dimensional accuracy. The work showed
that reinforcing ABS with short glass fibers and modifiers, significantly improved the strength and flexibility of the composite.

Fuda Ning et al [75] also investigated the mechanical properties of carbon fiber reinforced ABS manufactured via ME. The mechanical properties under investigation were the tensile and the flexural properties. They also investigated the ABS with different weight percentages of carbon fibers ranging from 0 to 15%. The carbon fiber reinforced ABS was prepared by blending plastic pellets and carbon fibers. Carbon fiber reinforced ABS samples were prepared with average fiber lengths of 150 µm and 100 µm. The filaments were fabricated in a way that the carbon fiber content was uniformly across it. The process parameters for printing these samples were nozzle temperature of 230°C, layer thickness OF 0.2mm, and an infill density of 100%. From the tensile and flexural testing results, it was observed that the highest value of tensile and flexural strength was based on composites with 5 wt% of carbon fiber (42 MPa) whereas the tensile strength of composites based on 10% weight display the lowest value (34 MPa). From the SEM investigations, it was observed that the samples containing 10 wt% had the highest value of porosity. It was also reported that the CFRP samples based on the fiber length of 150 µm displayed higher values of tensile strengths than the ones with 100 µm fiber length. This was because the fiber length exceeded the critical length comfortably, so it could bear more load. Analysis from the SEM showed that the fibers were ruptured during the testing, suggesting that the load transfer from the matrix to fiber was effective, an indicator of good load bearing capabilities.

Fuda Ning et al [78] also discussed the effect of the printing process parameters affecting the mechanical properties of CFRP parts. They performed tensile tests on the printed samples and the fracture interfaces were observed in a SEM to analyze the modes of failure. They investigated
the raster angle, infill speed, nozzle temperature and layer thickness, on the tensile strength of the printed material. It was reported that the values of tensile strength and the yield strength were higher in the samples with raster angle of 0, 90 than those based on -45, 45. From SEM analysis, they inferred that the interface of the 0,90 raster angle was subjected to complete rupture of the fibers, a condition associated to a load transfer between the matrix and the fiber. The specimens were also tested at different infill speeds ranging from 15 mm/sec to 35 mm/sec. It was observed that the tensile properties showed their highest values at 15mm/sec. At higher infill speeds, the deposition time caused low interlayer bonding. From the SEM micrographs, it was observed that there has been raster breakages occurring at higher speeds. In contrast at 15mm/sec, there were less number of voids and the rasters had better interaction between each other. The samples were also tested at different nozzle temperatures ranging from 220°C to 240°C. They reported that the highest tensile strength of the printed samples were obtained at the nozzle temperature of 220°C. SEM analysis showed that at this temperature, there were less pores and the merging of the interlayers was superior. The final parameter considered in this work was the layer thickness. Samples were printed in different layer thicknesses ranging from 0.15mm to 0.35mm. The results showed that the highest tensile strength was achieved on the 0.15 mm layer thickness. This was due to the deposition of the layers being more tightly squeezed, which led to large bonding strength. Also it was observed that at this layer thickness each raster was deformed within each other, reducing the porosity of the specimens by filling the voids.
References:


11) “1.3mm 600*1200mm Laser Engraving Sheet For Abs Double Color Sheet - Buy Abs Double Color Sheet,Abs Plastic Sheet,Laser Engraving Sheet Product on Alibaba.com.”


27) Fitzer E. PAN-based carbon fibers – present state and trend of the technology from the viewpoint of possibilities and limits to influence and to control the fiber properties by the process parameters. Carbon 1989;27(4):621–45.


Laser Enclosure Cooling Head Deposition Head Delivery Powder Ar Carrier Gas Cr 2.


71) “The effects of PLA color on material properties of 3-D printed components” ScienceDirect.” [Online]. Available:


Chapter 3  Experimental Methods

The main purpose of this research work is to study the fracture properties of additive manufactured short carbon fiber reinforced thermoplastic composite materials. The type of additive manufacturing technology used in this research work was the Material Extrusion. Once the plain thermoplastics and carbon reinforced composites were manufactured, the samples were tested to investigate their mechanical properties. Here, the materials were also characterized by microscopy techniques. The experimental methods are described in detail in the following section:

3.1 Material Extrusion of thermoplastics and thermoplastic composites:

Six thermoplastic filaments purchased from 3DXTECH were investigated: 1) ABS, 2) Carbon fiber reinforced ABS, 3) Nylon, 4) Carbon reinforced Nylon, 5) PETG 6) Carbon fiber reinforced PETG. The diameter of all these materials were 1.75mm, and with the exception of ABS, which was blue in color, all the other five materials were black in color. The averaged length and diameter of the short carbon fiber in the matrix, was found by investigating their surface in an optical and SEM microscope. Figure 3.1 shows an illustration of the average length of the short fibers on ABS. The mass fraction (%) data was given by the manufacturers. Table 3.1 displays the length diameter and the fiber mass fraction of each of the thermoplastic composites investigated in this research work.
Table 3.1 Experimental investigation of the length, diameter and the volume fraction of the short carbon fiber thermoplastic composites

<table>
<thead>
<tr>
<th>Material</th>
<th>Length (+-) S.D (Microns)</th>
<th>Diameter (+-) S.D (Microns)</th>
<th>Mass fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF-ABS</td>
<td>43 (+-) 14</td>
<td>10 (+-) 1</td>
<td>15</td>
</tr>
<tr>
<td>CF-Nylon</td>
<td>105 (+-) 32</td>
<td>11 (+-) 0.372</td>
<td>15</td>
</tr>
<tr>
<td>CF-PETG</td>
<td>142 (+-) 40</td>
<td>10 (+-) 0.86</td>
<td>15</td>
</tr>
</tbody>
</table>

Figure 3.1 Illustration of an optical microscopy sample of CF-ABS composites to find the averaged length of the fiber. Included in the figure are the pixel length of sampled fibers, that converted to Microns using a calibrated scale.
**Printer specifications:**

In this work, a Makerbot Replicator 2X printer was used for manufacturing the samples. This printer has the building dimensions of 24.6 x16.3 x 15.5cm (9.7x6.4x6.1 in.) which correspond to the width, length and height, respectively. The printer also has a layer height setting in the range of 0.0039 to 0.0118in and uses a brass nozzle with a printing orifice diameter of 0.4mm (0.015 in). Figure 3.1 shows a schematic representation of the Makerbot printer unit.

![Figure 3.1 Schematic representation of the Makerbot printer unit.](image)

**Figure 3.2** Image of the Makerbot Replicator 2X [1].

FDM printers are commonly used to make solid 3-dimenisonal objects by melting the filament that passes through the heating nozzle. Once the 3-D file is programmed in the software, the secure digital (SD) card reads the instruction from the program, which is in a STL format, and the nozzle oozes out the material in a heated building plate in a layer by layer fashion. Figure 3.2 shows a micrograph of manufactured dog bone shape of a carbon reinforced ABS printed part.
Figure 3.3 3D printed carbon fiber reinforced ABS part using a ME unit.

3.2 CAD file and processing parameters:

The CAD files that were converted to the .STL format were made in the SolidWorks CAD software (see figure 3.4). Here, shapes like dogbones, rectangles and squares were printed in the Makerbot replicator 2X system.
Figure 3.4 CAD files of tensile and flexural testing used in this work a) Dog bone shape for tensile testing and b) Rectangular sample for flexural testing. The thickness of the specimens were 4mm and 5mm, for the tensile and flexural samples, respectively.

Although in this work, no major post processing stages were required. The rafts and supports on the samples were removed after the printing process since these sections did not contribute to the mechanical properties of the final structure.

The process parameters in the Material extrusion system depends on the following 1) infill density, 2) speed of extrusion, 3) Temperature of the extruder, 4) Layer height, 5) Raster angle. From these process parameters, this work investigated the infill densities and speed of extrusion as the optimization process variables because these were the most variable parameters that could be modified in the Makerbot software.

The process parameters for printing the fiber reinforced plastics, specifically the carbon fiber reinforced ABS was optimized based on their tensile strength.

Initially, in order to manufacture carbon fiber reinforced thermoplastics, samples of CF reinforced ABS with 90% and 100% infill density with speed of extrusion of 90 mm/sec, 40
mm/sec and 10 mm/sec were printed (See Table 3.2). The printing temperature used for these systems were 230°C.

Here, the samples were printed based on the ASTM D638-10 configuration [2]. Plain ABS was also printed at these conditions, in order to compare its mechanical properties against its composite counterpart. For both systems, the raster angle was also kept constant on the printing process at [0, 90]. The raster angle was kept at a [0, 90] because it was not possible to modify the G-Codes in the Makerbot software and this is the default pattern configuration.

<table>
<thead>
<tr>
<th>Material</th>
<th>Infill density(%)</th>
<th>Speed of extrusion(mm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure ABS</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>Pure ABS</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>Pure ABS</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>CF/ABS</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>CF/ABS</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>CF/ABS</td>
<td>100</td>
<td>10</td>
</tr>
</tbody>
</table>

Once the printing process was optimized based on the tensile strength of the system, Nylon, PETG and their corresponding composites were printed and mechanically tested under flexural...
and impact conditions. Here, the Nylon and PETG systems were printed at a temperature of 260°C and 265°C, for the Nylon and PETG, respectively.

### 3.3 Mechanical properties

#### 3.3.1 Tensile Testing

The tensile samples were manufactured following the ASTM D638. The tensile testing was performed on a Universal Instron machine (see figure 3.5), at a loading rate of 2 mm/min at room temperature. The Blue Hill 3 software was used to export all the raw data from the testing. From the raw data the stress-strain curves were plot and the tensile strength was calculated using the following equations:

\[
\sigma = \frac{F}{A} \quad (3.1)
\]

\[
e = \frac{\Delta L}{\Delta L_0} \quad (3.2)
\]

Where \(\sigma\) is the stress, \(F\) the applied force, \(A\) the cross-sectional area, \(e\) the engineering strain, \(\Delta L\) the elongation, and \(\Delta L_0\) the original length of the testing sample.
Similar to the tensile testing, the flexural testing was also performed in an Universal instron machine (see figure 3.6). Here, the samples were based on rectangular shape according to the ASTM D3039 [3]. The loading rate at which the samples were tested was 2mm/min. Also, similar to the tensile testing, the raw data was stored and exported from the Bluehill 3 software. The force and displacements from the exported raw data was used to find the flexural stress and the flexural strain of the samples using the following equations:
\[ \sigma = \frac{3FL}{2bd^2} \quad (3.4) \]

\[ E = 6\Delta L \frac{d}{Lo^2} \quad (3.5) \]

Where \( F \), is the load acting on the sample, \( b \), the width of the sample, \( d \), the thickness of the sample, \( L \), the length of the span, and \( \Delta L \) the elongation.

**Figure 3.6** a) Schematic representation of the flexural testing b) 3 point bending Instron machine
3.3.3 Low Velocity impact testing:

The low velocity impact test consisted on a free fall impact tower assisted with a polycarbonate impactor weighing 4.04 Kg (see figure 3.7). Here, square samples with length and width of 4 Inches (101.6 mm) and thickness of around 2mm were printed and tested. The potential energy of the samples were calculated by varying the height at which the impactor was dropped. The equation here used was:

\[ E = m \cdot g \cdot h \]  \hspace{1cm} (3.6)

Where \( E \) is the low velocity impact energy, \( m \), the mass of the impactor, \( h \), the height at which the impactor was dropped, and \( g \), the gravity.

Low velocity impact using an impact tower has also been studied by a number of authors [4-7]. For instance, Kostopolus et al [6] investigated the impact behavior of carbon fiber reinforced composites and carbon nanotubes using a drop impact tower and found out that there was not a significant difference in the delamination area or the energy absorbed per unit delamination area by adding carbon nanotubes. Cantwel [7] et al also studied the low velocity impact properties of carbon fiber reinforced composites and found out that this kind of technique simulates the impact event of heavy drop tools at low velocities on laminated systems.
Figure 3.7 Micrograph of a low velocity impact tower. Samples are placed at the center of the platform and impacted with a heavy weight.

3.3.4 High velocity impact test:

This test investigates the impact performance of materials when subjected to high impact velocities. The high impact velocity impact test consisted of a gas gun apparatus (see figure 3.8) where, a compressed nitrogen gas expelled the impactor. The gas gun was assisted with a chronograph, which was used to measure the velocity of the projectile passing through the system. The printed and tested sample had a thickness around 4 mm for each material studied, and the impact velocities of the projectile were adjusted by varying the pressure of the gas. Here,
the impactor had a weight of 0.2g, and was placed in a sabot for aiming to the printed samples. The gas gun has a sabot catcher, where the sabot is trapped and just the projectile is released to make the impact on the sample. The final impact energy was calculated by applying the following equation.

\[ E = \frac{1}{2} mv^2 \]  

(3.7)

Where \( m \) is the mass of the projectile, \( v \) is the velocity at which the projectile travels.

The gas gun system has been used by a number of researchers [7-10]. For instance, Villanueva et al [10] used a gas gun to evaluate the impact properties of sandwiches and composites and they found out that these systems had a good impact energy absorbing capabilities. Cantwell [7] also studied the high velocity response of carbon fiber reinforced composite materials using a gas gun apparatus. He reported that the structural integrity of the composites has a higher damage than at the low velocity impact conditions.
The high velocity impact energy was modelled by using the theoretical approach established by the Reid and Wen’s perforation model [13].

$$V_b = \frac{\pi \tau \rho_t \sigma_e D^2 T}{4m} \left[ 1 + \sqrt{\frac{1+8m}{\pi \tau \rho_t D^2 T}} \right]$$  \hspace{1cm} (3.8)

Where $V_b$ is the theoretical velocity, $\tau$ is 1.5 for hemispherical ended projectile, $\rho_t$ the density of the sample, $\sigma_e$, the compressive elastic limit, $D$, the diameter of the projectile, $T$, the thickness of the target and $m$, the mass of the projectile.

### 3.4: Optical microscopy

The fractured samples used in this work were investigated under the optical microscope. A Nikon SMZ 800 compound light microscope was used to investigate the microstructure of the
fractured specimens. The pictures were taken using a PixeLink CCD camera. The purpose of this optical microscopy was to find the fracture mechanism of the tested samples. This analysis was also performed to investigate the nature of binding between each printed layer, as well as the fiber/matrix adhesion on the printed samples.

3.5: Scanning electron Microscopy

The fractured samples were analyzed using a SEM, JEOL JIB 4500 multibeam system, with a voltage of 15 KeV (see figure 3.9). Here, the samples were placed in a sample holder by using a carbon tape. A copper tape was incorporated between the sample and the holder in order to improve the conductivity of the sample. The samples were coated with palladium-gold in a sputter apparatus for 3 minutes.

![JEOL JIB-4500 Scanning electron microscope](image)

**Figure 3.9** Micrograph of the JEOL JIB-4500 Scanning electron microscope used in this work.
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pdf

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Chapter 4 Results and Discussion

This section presents the results and discussion of the experiments carried out on this research program. The main objective of this work was to manufacture short carbon fiber reinforced thermoplastic composite materials using Material Extrusion and study their mechanical properties under static and dynamic loading rate conditions.

4.1 Initial 3D printing parameter optimization – Tensile testing

Effects of the infill density and speed of extrusion on 3-D printed plain ABS and carbon fiber reinforced ABS parts were initially investigated. Figure 4.1 shows the stress-strain plots of plain printed ABS under three different manufacturing parameters: 1) 90% infill and 10 mm/sec speed of extrusion, 2) 100% infill and 40 mm/sec speed of extrusion, and 3) 100% infill and 10 mm/sec speed of extrusion. The samples were printed at 230°C with a raster angle of [0, 90].

Figure 4.1 Stress strain curve of plain ABS printed at different infill densities and extrusion velocities.
Figure 4.1 shows that the plain printed ABS samples display a relatively linear profile up to their yield point followed by a limited ductility region before reaching their fracture point. Also from figure 4.1, it is observed that the nominal strain reaches a value between 6 to 11 %, suggesting that ABS systems has a brittle performance. Similar results have been found by Cantrell et al [1], where the samples printed along the 0,90 raster angle had a failure strain of 7.14%. A micrograph of the tensile fractured printed ABS samples is shown in figure 4.2. The figure shows that the sample do not exhibit signs of plasticity, a feature that seems to corroborate the stress-strain plot shown in figure 4.1.

Cantrell et al [1] also reported a tensile strength for the printed plain ABS of about 33.5 MPa a value, which is close to the average tensile strength of the ABS samples printed in this work.

Figure 4.2 Micrograph of the fractured surface of ABS printed at 100% Infill and 40 mm/sec extruding speed.
Figure 4.3 shows the results of the averaged tensile strength of ABS printed at different percentage of infill and speed of extrusion conditions. From figure 4.3, it is observed that the lowest tensile strength was from samples based on a 90% infill density and 10 mm/sec printing speed (27.5 MPa), whereas the samples printed with a infill density of 100% and 40mm/sec and 100% infill and 10mm/sec have tensile strengths in the range of 33 to 34 MPa, a value which is 23.3% higher than the 90% infill and 10 mm/sec printing speed. However, based on the overlapping standard deviation shown on figure 4.3, it can be inferred that no statistical difference is present on the tensile strength of the samples printed at 100% in fill density and 10 and 40 mm/sec extrusion speed. Additionally, a t-test was performed at 95% confidence level within each groups. The two tailed P value within the groups printed at a 100 % infill density and 40 mm/sec speed of extrusion and the samples printed at 90 % infill density and 10 mm/sec speed of extrusion was found to be 0.0471, which was considered to be statistically significant.

**Figure 4.3** Averaged tensile strength of 3D printed plain ABS. The labels of the X axis shows the printing conditions, where the first digit indicates the percentage of infill, and the second, the printing speed.
4.1.1 Tensile testing of Carbon Fiber reinforced ABS

Similar to the printed ABS samples, effects of the infill density and printing speed were investigated on the carbon fiber reinforced ABS parts. Here, the processing printing parameters were the same as those used on the plain ABS. Figure 4.4 shows the stress-strain profile of the printed ABS composites, where it is observed a marked non-linear elastic response on the samples. This behavior can be associated to the contribution between a linear elastic carbon fiber and the non-linear elastic ABS matrix. The figure also shows a flatter region around 4 MPa, a zone related to the initial stage of adjustment of the specimens to the grips.

![Stress-Strain Curve](image)

**Figure 4.4** Tensile strength of short carbon-fiber-ABS composites manufactured under different conditions.

Figure 4.4 shows the averaged tensile strength of the printed composites based on the different infill and printed speed processing parameters. It is observed that the samples manufactured with 100% infill and 10 mm/sec printing speed displays the highest tensile strength; although its
standard deviation overlaps with that of the 100% and 40 mm/sec samples. The figure shows that the specimen based on 90% and 10 mm/sec displays the lowest tensile strength. These tensile strength results are similar to those reported by Ning et al [2]. They reported that at low printing speeds there is a reduced inter-bonding between the printed rasters than at high printed speeds.

**Figure 4.5** Tensile strength comparison of ABS and CF-ABS at different printing parameters. The first digit indicated the percentage of infill, whereas the second digit the speed of extrusion.

Included in figure 4.5, is the tensile strength of the plain printed ABS, where it can be observed that although the averaged strength of the composite specimens printed with 100% infill and 10
and 40 mm/sec are higher than the plain ABS, the standard deviation of the plain ABS appear to overlap the tensile strength of their corresponding composite counterparts. Here, a t-test resulted in two tailed P-values of 0.1242, 0.1789 and 0.0561 for the comparison between the strength of the ABS and its composite manufactured at the 100/10, 100/40 and 90/10 % infill/printing speed conditions respectively. These results suggest that none of the comparison were statistically significant at a 95% confidence level implying that the presence of short fiber on ABS does not seem to enhance the tensile strength of the polymer. Figure 4.6 shows a SEM image of the fractured CF-ABS sample, and it can be observed that a large degree of porosity is present on the sample. This presence of porosity appears to have resulted in a low tensile strength. Figure 4.7 shows an optical image of the ABS and CF-ABS where it can be clearly observed the porosity across the printed composite, mainly in the inter-laminar regions. In contrast, the plain ABS sample did not show signs of porosity. Ning et al [3] also observed the presence of high degree of porosity in the FDM printed ABS reinforced short carbon fiber composites. They attributed the porosity to the generation of gaps between each different individual layer during the FDM fabrication process. These printing flaws could limit the application of these composites in functional applications. Therefore, in the next phases of this work, the orifice of the nozzle tip was increased from 0.4 mm to 0.8 mm in order to enhance the flow of the printed filament and consequently to reduce the porosity on the final parts manufactured.
Figure 4.6 Scanning electron microscopy picture of a CF-ABS sample. The dashed lines represent the porosity of the sample.

Figure 4.7 Low magnification micrographs of the fractured surfaces of printed ABS, A) CF-ABS B) Plain ABS
4.1.2 Tensile testing of Nylon and PETG Systems:

Based on the initial tensile testing of the printed CF-ABS and plain ABS, the 100% infill and 10 mm/sec printed parameters were used to manufacture the printed Nylon and PETG systems.

Here, the plain Nylon and short carbon fiber reinforced Nylon (CFRN) samples were printed at 260°C due to the recommended temperature given by the manufacturer [4]. In contrast, the PETG and its composite counterpart were printed at 265°C. As in the case of the ABS systems, the Nylon and PETG were printed at a raster angle of [0,90].

Figure 4.8 shows the stress-strain profile of the Nylon and CF-Nylon composite. The figure shows that the inclusion of CF on the Nylon resin resulted in a stronger system. From the figure, it is observed that the average maximum stress achieved by the composite (50 MPa) is 66% higher than plain Nylon (30 MPa). This increase in strength is associated with the effective load bearing capabilities of the fibers in the Nylon composite. Similar results have been published by Tekinalp et al [5] where the inclusion of short carbon fiber on thermoplastic polymers enhances the tensile properties. Figure 4.8 shows that the stress-strain plot of the plain Nylon displays a non-linear elastic behavior, a feature that has also been observed by Shan et al [6] on Nylon samples tested at room temperature and at a cross head speed of 1mm/min. Figure 4.9 shows the fractured surface image of Nylon and carbon fiber Nylon.
**Figure 4.8** Stress strain curves of the plain Nylon and Carbon fiber reinforced Nylon.

**Figure 4.9** Fracture surface of Nylon samples printed at a 100% infill and 10 mm/sec extrusion speed. A) Plain Nylon and B) CF reinforced Nylon.

From the figure, it is observed that the printed plain Nylon sample displays a high degree of porosity. In contrast, the Nylon composites appears to have a good interfacial adhesion, less porosity and the rasters seem well coalesced. These features on the CF-Nylon samples resulted
on a superior tensile strength than that shown by its plain counterpart as well as that of the ABS composite. The presence of large porosity on the Nylon samples seems to have been associated to the absorption of humidity, which appears to have induced a irregular swelling on the filament-printed part.

The stress-strain profile of the plain PETG and its composite is shown in Figure 4.10. Here, as in the case of the Nylon system, the inclusion of carbon fiber seems to improve the strength of the system. Figure 4.10 shows that the inclusion of short carbon fiber to the PETG system enhances its tensile strength by 27%. The figure also shows that the strain at fracture for both PETG and CF-PETG is less than 10%, suggesting a limited plasticity in this material.

![Figure 4.10 Stress-strain profile of the plain PETG and CF-PETG composite.](image)

A summary of the tensile strength of the six different materials have investigated is shown in figure 4.11, where it can be observed that the highest strength is displayed by the PETG and its
composite counterpart. This agrees with the results reported by the manufacturers 3DXTECH [4]. In fact, they have reported a value of the PETG composite 26% higher than the ABS composite. A t-test analysis was performed on the Tensile strength between the Nylon and CF-Nylon as well as the PETG and CF-PETG. The obtained two tailed P-values resulted to be 0.0011 and 0.0496 for the Nylon and PETG system respectively. This suggests that the tensile strength between the plain polymer and the composite on these two systems have a statistical at a confidence level of 95%.

**Figure 4.11** Averaged tensile strengths of the six different materials here investigated

Figure 4.12 shows the percentage of nominal strain at failure of the six systems investigated. From this table, it is observed that though the addition of carbon fibers have led to an embrittlement of the systems by decreasing the plasticity of the plastics.
Figure 4.12 Averaged tensile nominal strain at failure of the six different systems investigated in this research work.

4.2 Flexural Testing:

Flexural testing was also performed for all the six materials investigated. Figure 4.13 shows the flexural strength graph of the ABS system. The printing parameters used to print these materials where the same as these used on the samples subjected to the tensile strength testing (100% infill, and 10 mm/sec printing speed).
4.2.1: Printed ABS and CF-ABS- Flexural strengths

From the figure 4.13, it can be observed that the flexural strength of the ABS composite exceeds that of the plain ABS by 14%. It is evident from the figure that the reinforcement effect in the plain ABS system creates a stiffer and a stronger system. The maximum flexural strength for 3-D printed ABS composite with a layer printing thickness (0.2mm) similar to that used in this work reported by Christiyan et al [7] was 43 MPa. The flexural strength seems to be in a close range to the reported work.
4.2.2 Flexural strengths of the printed Nylon and PETG systems

The flexural stress-strain profile of Nylon and CF-Nylon composite, as well as those of the PETG and CF-PETG was similar to that observed as ABS systems. It was inferred that the addition of short carbon fiber to the Nylon and PETG systems led to a stiffer system. It was observed that the flexural strength of the Nylon composite (83 MPa) exceeded the plain Nylon (42.12 MPa) by 97%. However, the inclusion of short carbon on Nylon has caused an embrittlement of the system since the percentage of strain at failure was considerably lower than the displayed by the plain Nylon. The flexural strength of carbon fiber reinforced Nylon composite reported by 3DXtech [4] is 78 MPa, a value which is in close range to the strength obtained in this research work.

In the case of the PETG, the composite appear to have exceed the strength of the plain PETG system (60 MPa) by 35%. Indeed, the flexural strengths of the PETG composite system reported by 3DXTECH is 80 MPa, which is in a close range to the strength reported in this research work (81 MPa). Figure 4.14 shows a comparison of flexural strengths of the materials here investigated.
Figure 4.14 Comparison of the average flexural strength of the six different materials investigated.

From the figure, it can be observed that the highest strength is displayed by the CF-Nylon and CF-PETG (83 and 81MPa) respectively. In contrast, the lowest strength is associated to the plain ABS (42 MPa). From these results, it is clear to observe, that the addition of the reinforcement increased the flexural strengths of the plain thermoplastic systems. A t-test on these results yielded the two tailed P values of 0.0439 on comparison of the ABS and its corresponding system, 0.0001 on the Nylon and its composite, and 0.0224 on the PETG and its composite systems with a confidence level of 95%. This suggest that the values of the averaged flexural strengths were statistically significant. These result seems to agree with Ning et al findings where they concluded that the average flexural stress of printed carbon fiber reinforced thermoplastic are superior than those of plain printed thermoplastic materials [8]. Figure 4.15 shows the nominal strain at failure in all the different materials here investigated. From the figure 4.15, it is interesting to note that the plain thermoplastic has displayed a higher percent of strain.
at failure than their composite counterparts. Here, Nylon showed the highest strain at failure by exceeding its composite counterpart by 109%. A t-test resulted in the two tailed P value of ABS and its composite of 0.0003, Nylon and its composite of 0.0011 and PETG and its composite of 0.0004 with a 95% confidence level. These values show that the strain at failure on each system were statistically significant. It is clear from the figure, that the inclusion of short fibers in the system has led to an embrittlement of the polymeric systems. This result seemed to corroborate the findings reported by Fu et al [9], where the inclusion of short carbon fiber on polypropylene reduced its strain at failure. They associated this reason to the matrix crack formation at the end of the fibers, where the final failure occurs across the weakest link in the sample above a critical level of cracking.

![Figure 4.15](image)

**Figure 4.15** Comparison of the average strain at failure of the six different materials investigated.

Optical micrographs of the fractured printed plain ABS and CF-ABS are shown in figure 4.16. The figure shows that whereas the CF-ABS has no signs of plasticity, the plain-ABS displays small areas of yielding; features that support the results shown in figure 4.15.
Figure 4.16 Low magnification images of the flexural fractured printed plain ABS (left) and its composite counterpart (right).

The flexural modulus has also been investigated and reported in figure 4.17. From the figure, it is observed that the inclusion of short carbon fiber in the plain thermoplastics produces a stiffer system. The highest flexural modulus is observed in the PETG composite (4221 MPa), which exceeds the plain PETG (1952 MPa) by 116%. Here, the plain Nylon system has displayed the lowest flexural modulus (1388 MPa) of all samples studied. The flexural Modulus of the plain ABS systems seems to be in a close range to the values reported by the manufacturer (1950 MPa) [4]. Also flexural modulus values of the plain Nylon specified by Stratysis [10] are similar to the values here reported. A t-test analysis resulted on the two tailed P values less than 0.0001 for the ABS and CF-ABS system. Similarly for the Nylon and CF-Nylon, the P value was 0.0011, PETG and for the CF-PETG 0.0004. These values were at a 95% confidence level suggesting that the results were statistically significant.
Based on the results shown in figure 4.14 and 4.17, it seems that the addition of short fibers to the plain thermoplastic systems appear to improve its flexural properties of the system by resulting in a stronger and stiffer parts.
4.3 Low velocity impact

In the low velocity impact testing, the samples were tested until complete perforation occurred. At their fracture points, their impact energies and specific impact energies were calculated. Here, the specific impact energy was calculated by normalizing the impact energy by its aerial density [11]. The thickness of the specimens were kept almost constant without much variation since it has been reported that the perforation resistances of fiber reinforced composites can increase by decreasing thickness due to a membrane effect [12]. Figure 4.18 and 4.19 show the perforation and the specific perforation energies of the plain thermoplastics and their composite counterparts respectively.

![Figure 4.18](image)

**Figure 4.18** Low impact perforation energies of the plain thermoplastics and their composite counterparts.

96
From Figure 4.18 and 4.19 it can be noted that the plain thermoplastic systems have significantly outplayed their composite counterparts with the exception of the PETG system. Caldeira et al [13] have observed similar results when they introduced vapor grown carbon fibers on a polycarbonate material due to the weak inter-bonding between the layers that led to a higher degree of inter-laminar delamination in the composites. Ziemian et al [14] have obtained a value of 2.5 J as the mean impact energy for ME printed ABS with a raster angle of [-45,45], which is a value in close range to the specific impact energy here reported by plain ABS (2.1 J m²/kg). These values are lower than the values reported on thermoplastics and thermoplastic composites manufactured via injection molding [15,16]. This could be due to interlayering features of the
printed parts and also probably because of the lack of thermal treatment before testing these materials to remove residual stresses. For instance, Akay et al [15] reported a low velocity impact strength of 6 KJ for injection molded ABS without heat treatment. However, with heat treatment and removal of residual stresses, it was possible to achieve a superior low velocity impact strength. Also, the lower impact energy of the composites can also be associated to the embrittlement of the plastic as can be observed in figure 4.15.

Figure 4.18 shows that the highest impact energies are associated to the plain ABS and Nylon systems. These materials have exceeded their composite counterparts by 70% and 55% respectively. A similar trend is observed in the figure 4.19 also. Tjong et al [16] have shown that the addition of 5% short glass fibers (SGF) to polyamide reduces its impact strength. This was because addition of SGF reduces the yielding of the matrix. Additionally, fiber de-bonding and weak matrix-fiber adhesions were also found out to be the mechanism that lowered the impact performance of their composite samples while examining under a SEM.

It is interesting to note that the trend of the low velocity impact do not agree with the flexural strength results. Here, the highest low velocity impact is associated to Nylon which exhibited a low flexural strength, but a high strain at failure. Okenwa et al [17] has observed that there is an interesting relationship between flexural energy and strain rate in short fiber reinforced plastics. They have found out that at higher strain rates, a change in the mode of failure occurs, where the greater part is played by the matrix in the fracture process. Thus, a higher percentage of strain at failure means a higher yielding occurring in the matrix. This supports the findings on the low velocity impact energy of the plain Nylon. Similar results were expected for the plain PETG, however this system displayed the lowest impact energy under low velocities, a performance that could be associated to the development of residual stresses on a printed larger sample, as well as
the incorporations of the out of plane displacement constrained by a holding frame during the testing. Figure 4.20 shows the optical pictures of all the systems investigated. From the figure, it is observed that most of the composites exhibited a brittle behavior. The figure also shows that the plain PETG displays no traces of plasticity, suggesting a brittle plastic.

**Figure 4.20** Micrographs of the low impact velocity fractured specimens A) ABS, B) CF-ABS, C) Nylon, D) CF-Nylon, E) PETG, and F) CF-PETG.
4.4 High Impact Velocity testing

Here, the samples were tested under high impact velocity conditions using a gas gun. The specific perforation was calculated by normalizing the impact energy by the aerial density. Figure 4.21 and 4.22 displays the perforation energy and the specific perforation energies of ABS, CF-ABS, and PETG respectively. No results are presented for the CF-PETG, Nylon, and CF-Nylon since these materials showed a brittle behavior and the gas-gun was not able to read low impact velocities (less than 200 m/sec).

Figure 4.21 Perforation energies of plain ABS, CF-ABS and PETG under high impact velocity conditions
From figure 4.21 and 4.22 it can be observed that CF-ABS has the highest impact energy (15 J) and the highest specific impact energy (3 J m$^2$/kg). From figure 4.24 it can be observed that the specific high velocity impact energy of the plain PETG appears to be 16% lower than the plain ABS. These results can be associated with a superior out-of-plane compressive stress, which is directly related to the impact energy of composites under high strain rate conditions [12].

Figure 4.23 shows the low magnification pictures of the plain ABS, CF-ABS and the plain PETG systems tested under similar approximately similar velocities (~240 m/s). From the figure, it can be observed, as in the case of low velocity impact tests, the printed PETG samples show a brittle behavior.
**Figure 4.23** Low magnification micrographs of the plain ABS, CF-ABS and plain PETG samples tested under a high impact velocity loading condition.
Figure 4.24 shows the SEM picture of the fractured plain PETG sample, where it can be observed that the material seems to display a lack of ductility. This feature seems to result in a low impact energy, as reported in figure 4.21.

Figure 4.24 SEM examination of the fractured plain PETG sample loaded under a high impact velocity condition.

4.5 High velocity theoretical modelling

In this work, the high velocity impact properties were modelled using the Reid and Wen’s perforation model [18]. As stated in section 3.4, the elastic compressive strength was initially measured in order to calculate the maximum velocity that the measured samples can be subjected to. This velocity was compared to that experimentally measured. Table 4.1 shows the elastic compressive stress of the investigated samples. From the table, it is observed that the ABS and
CF-ABS showed the highest values of elastic compressive strength. It can also be observed that the PETG shows a lower compressive strength, a property that can be associated to the lower impact energy here recorded.

Table 4.1 The elastic compressive strengths of the six samples under investigation

<table>
<thead>
<tr>
<th>Materials</th>
<th>Out of plane elastic compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>80</td>
</tr>
<tr>
<td>CF-ABS</td>
<td>86</td>
</tr>
<tr>
<td>Nylon</td>
<td>52.5</td>
</tr>
<tr>
<td>CF-Nylon</td>
<td>55</td>
</tr>
<tr>
<td>PETG</td>
<td>77</td>
</tr>
<tr>
<td>CF-PETG</td>
<td>45</td>
</tr>
</tbody>
</table>

Figure 4.25, shows the experimental and the modelled impact energy of the systems investigated. From the figure, it seems that the predicted perforation velocity matches the experimental values for the ABS, CF-ABS and PETG. Included in the figure, is the predicted perforation velocity of Nylon, CF-Nylon and CF-PETG. Here, it can be observed that the values are lower than the ABS system. Indeed, their predicted perforation velocity is below 200 m/s, which is the lowest velocity that the gas gun can provide.
It is interesting to note that the impact energy of the PETG under high impact velocities has a superior performance than at low velocity conditions. This could be associated to the different fracture mechanisms observed between the low and high velocity impact conditions. In the case of the high velocity impact conditions, the performance seems to be related to the compressive property, which in this work was higher than the Nylon system. In contrast, in the low velocity testing the performance is related to the out of plane displacement as an energy absorbing mechanism which in this work was constrained by holding the sample on a fixture during the testing.

![Graphical comparison of the experimental and the modelled impact energy of the six samples investigated.](image)

**Figure 4.25** Graphical comparison of the experimental and the modelled impact energy of the six samples investigated.

From figure 4.25, it is observed that the experimental values of the plain ABS system exceeded the theoretical values by 4.29%. Similarly the predicted perforation energy of the CF-ABS, and
plain PETG are 0.45% and 5.81% higher than their experimental values, respectively. These results suggest that the modelling here performed was accurate enough to calculate the perforation velocity of the plain thermoplastic and composite systems investigated in this work.
References:


4) https://www.3dxtech.com/


Chapter 5 Conclusions

In this study, short carbon fiber reinforced thermoplastic composites were manufactured using FDM and their mechanical properties were studied and compared to their plain thermoplastic counterparts under static and dynamic loading conditions. The materials used in this study were ABS, Nylon, PETG and their respective composites. The tensile, the flexural, and the low and high velocity impact properties of the aforementioned materials were investigated. This work showed that the incorporation of short carbon fibers on 3D printed thermoplastic matrices resulted in stronger specimens. It was observed that the CF-PETG displayed the highest tensile strength of the different materials here investigated, with a strength 27% higher than its unreinforced counterpart. Similarly, the carbon composites resulted in stiffer and stronger materials under flexural conditions. It was shown that whereas the carbon fiber reinforced Nylon displayed the highest flexural strength (83MPa), the plain ABS system exhibited the lowest strength (42MPa). In contrast, it was observed that the carbon fiber composites showed lower perforation energies than the unreinforced materials. Here, it seemed that the incorporation of short carbon fiber on the thermoplastic materials induced an embrittlement on the systems. In this work, the higher specific perforation energy was observed on the plain Nylon material (2.2 Jm²/kg). A reduced number of high velocity impact tests were performed due to the low impact velocities needed by the printed materials from the gas-gun here used. It was observed that the CF-ABS displayed the highest specific impact energy (3 Jm²/kg). In this work, a high velocity impact model was incorporated on the investigated systems, and it appeared that the analytical model predicted within 5% of error the perforation velocities of the tested specimens.