Investigation of the tensile properties in fibre-reinforced additive manufacturing and fused filament fabrication

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Abstract: This research project examines how fibre orientation affects the strength of a part produced by fibre-reinforced additive manufacturing (FRAM) process. Tensile specimens with varying fibre orientations were made using a 3D printer capable of printing with carbon fibre (CF), Kevlar (KV), and fibre glass (FG). Various tensile tests have been performed for different fibre orientation and materials. The strongest fibre orientations, in descending order, were two rings concentric with isotropic fill and five ring concentric fill. While fibre orientation and infill percentage could be specified for each layer, the fibre starting location was automatically determined which sometimes resulted in decreasing strength of the part by introducing stress concentration. Currently, industrial trends in the utilisation of fused filament fabrication (FFF) printers are mostly on PLA and ABS-based polymer materials. And, there is no comprehensive study available investigating the relations between these traditional FFF processes and continuous FRAM processes. The aim of this study is to provide an in-depth tensile property analysis showing the advantageous of FRAM compared to conventional FFF technologies.

Keywords: fibre-reinforced additive manufacturing; FRAM; tensile test; concentric; isotropic; fused filament fabrication; FFF.

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1 Introduction

AM is an advanced manufacturing technology commonly used in several industries and manufacturing processes (Gibson et al., 2010). AM is also interchangeably used with the layman's term, 3D printing. Fused filament fabrication (FFF) is one of the many types of AM processes. These processes use polymer filaments and create the parts layer by layer. This technology has found applications in many fields such as aerospace, motorsports, and education (Fidan et al., 2018). In Russell et al. (2017), a one-to-one Struthiomimus dinosaur is 3D printed. Also, 3D printed parts are used as patterns for casting (Fresques et al., 2015; Watson et al., 2017).

In general, there are many advantages of these processes:

- virtually no waste
- parts can be printed together as one assembly
- fast prototyping
- accelerated fabrication since tooling is not required
- designs are easily shared.

However, AM is not without disadvantages. Some include:

- large surface roughness due to limited resolution
- limited range of printable materials
- need for support structures
- long print times

- high energy consumption.

Also, as given in Krijnen (2016), due to the manufacturing process of FFF printers, the parts produced are weak perpendicular to the layers. When it comes to limited range of printable materials, the most commonly used materials for FFF are Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA) followed by PolyCarbonates (PC) (Dudek, 2013). Additively manufactured polymer parts suffer from inferior mechanical and thermal properties. Several studies for better mechanical and thermal properties resulted to be a drive in developing new materials or to reinforce the current materials. Brooks and Molony (2016) used a FFF printer to print a pulley housing made of PLA and ABS. Subsequently, continuous fibres were manually inserted into the pulley housings, which resulted in 'significant increases in part strength, toughness, elongation to failure, and stiffness.'

Currently, composites manufactured using conventional methods have higher stiffness to weight ratios than metals but are more expensive. Fibre-reinforced additive manufacturing (FRAM) can be much less expensive and retain the advantages conventional composites have over traditional materials as given in Page (2016).

Metal AM is one current competitor to FRAM. Presently, there is no AM technology for composites that is comparable to the best AM metal printer. At best, AM printed composites (CF with nylon) exceed the strength of machined aluminium (Chapiro, 2016). Nevertheless, there is potential for CF composite printing in certain industries when the proper investments are made. However, also composites are less expensive than some powders used in AM of metals and require less energy to make the parts (Chapiro, 2016). Matsuzaki et al. (2016) have shown that fibre-reinforced printing yields stronger parts than conventional PLA and ABS 3D printing. Also, parts printed with short fibres or fibre particles are mechanically inferior to continuous fibres. Moreover, Melenka et al. (2016) have evaluated the tensile properties of continuous AM printed parts and found that an increase in fibre volumetric fraction leads to an increase in elastic modulus. While continuous fibres are not as fragmented as short fibres, continuous fibre AM printed parts still contain fibre discontinuities in each layer. Der Klift et al. (2016) noted that their tensile specimens failed where the fibres discontinued. Furthermore, Dickson et al. (2017) did a study to evaluate AM fibre reinforced composites to find their mechanical properties. They performed tensile tests with continuous fibre reinforced specimens of varying material and found that failure occurred at the shoulder of the dog-bone specimens. They concluded that this was due to shear forces experienced by the offset fibre alignment. More studies in mechanical properties of FRAM has been conducted by Imeri (2017), Imeri et al. (2018a, 2018b), (Kuchipudi, 2017) and Mohammadizadeh et al. (2018) where tensile, fatigue, and creep properties have been evaluated at different fibre directions and fibre volumes.

Infill is the amount of the material added to the part. In AM, with the ability to make almost any shape, it is also possible to make hollow or solid parts. Setting the infill percentage determines how hollow or how solid the part will be. So, infill is another manufacturing parameter that affects the strength of 3D printed parts. Fernandez-Vicente et al. (2016) examined the effect of infill parameters on tensile mechanical behaviour. After testing ABS printed FFF specimens with various infill patterns and infill percentages, their tensile data shows that rectilinear 100% infill density had the highest tensile strength.

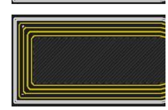
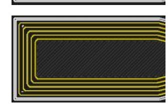
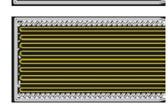
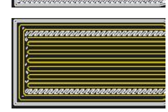
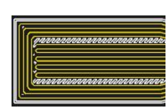
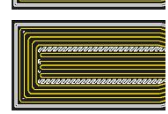
In this study, the effect of fibre orientation on tensile strength of a part produced with continuous FRAM technology was examined. Specimens with fibre at an angle of zero degrees with various number of rings were experimentally tested. The tensile strength of various fibre orientations and materials were compared. The data collected from the tensile tests were graphed, analysed, and presented.

2 Methodology

2.1 Materials

The filaments used were PLA, ABS, nylon, CF, FG, and KV. PLA and ABS filament was supplied by Esun (Esun 3d, 2018). Both had a diameter of 3.00 mm and a tolerance of +0.05 mm. The nylon used as matrix, CF, FG, and KV, which were used as fibre reinforcing materials, were supplied by Markforged. The FG and KV have a diameter of 0.3 mm. The CF had a diameter of 0.35 mm. The nylon has a diameter of 1.75 mm. The nylon was stored in a Pelican 1430 dry box to protect the filament from moisture.

Table 1 Fibre geometry orientation used in the research study (see online version for colours)

Fibre orientation	*Abbreviation*	*Description*	*Image*
2 ring concentric	CF/FG/KV-2RC	Two concentric rings of fibre in 42 out of 50 layers. Fibre volumetric fraction: $v_{CF} = 0.21$	
4 ring concentric	CF/FG/KV-4RC	Four concentric rings of fibre in 42 out of 50 layers. Fibre volumetric fraction: $v_{CF} = 0.39$	
5 ring concentric	CF/FG/KV-5RC	Five concentric rings of fibre. Fibre volumetric fraction: $v_{CF} = 0.47$, $v_{FG} = 0.50$, $v_{KV} = 0.47$	
0 ring isotropic	CF/FG/KV-0RI	All isotropic fill of fibre. Fibre volumetric fraction: $v_{CF} = 0.57$	
2 ring isotropic	CF/FG/KV-2RI	Two concentric rings and isotropic fill of fibre. Fibre volumetric fraction: $v_{CF} = 0.57$, $v_{FG} = 0.61$, $v_{KV} = 0.61$	
4 ring isotropic	CF/FG/KV-4RI	Four concentric rings and isotropic fill of fibre. Fibre volumetric fraction: $v_{CF} = 0.57$	
5 ring isotropic	CF/FG/KV-5RI	Five concentric rings and isotropic fill of fibre. Fibre volumetric fraction: $v_{CF} = 0.57$	

2.2 Nomenclature

Table 1 provides a list of fibre orientations and abbreviations used in this research project, images of the fibre orientation, and a short description. Materials used in FRAM processes are CF, FG, and KV. All fibre reinforced specimens were made with a nylon matrix. Nylon matrix is the base material which is reinforced with the continuous fibres. Filament fibre volumetric fraction on the specimen $(v_{(CF/FG/KV),f})$ mentioned in Table 1 is the ratio of fibre filament volume to the total volume in the specimen which can be shown as follows:

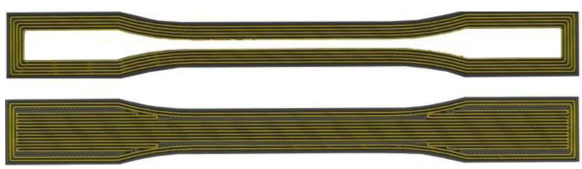
$$v_{(CF/FG/KV),f} = \text{fiber volume(CF / FG / KV) / total volume(nylon matrix and fiber)}$$

It should be noted that this is just theoretically calculated fibre volume fraction.

2.3 Fibre orientation and infill

The two fibre orientations that can be printed are ‘concentric’ and ‘isotropic’. Two cross-sections of the specimens with concentric (top) and isotropic (bottom) fibre orientations are shown in Figure 1. Concentric rings are along the boundary walls of the specimens, while isotropic fill add several continuous, unidirectional fibre filaments throughout the layer. The yellow lines represent the fibre reinforcing filament, while the black surface represents the matrix.

Figure 1 Cross-section of concentric (top) and isotropic (bottom) infills (see online version for colours)



The term isotropic does not refer to isotropic mechanical properties. All 3D printed parts have anisotropic mechanical properties. The term only refers to the way the printer lays down the material as shown at the bottom of Figure 1. Any further use of the term isotropic will refer to the way the filament is laid down, not the properties. For each layer the angle of the isotropic filled fibres can also be adjusted. In this study, the focus of the research is on zero-degree angles for isotropic fills with various number of rings. As given in Campbell (2010) for isotropic specimens, zero angle layers give better tensile properties. Furthermore, the goal is to find the strongest specimen in tensile strength, so the zero angle is used for all the specimens in each isotropic layer. For all composite 3D test specimens, a 75% rectilinear fill is used. Rectilinear fill is the geometric shape that is repeated each layer in the inside of the part. In Figure 2, rectilinear cross-section is shown with different infill percentage.

A 75% infill was chosen to make a strong nylon matrix and reduce print times. The print time increase from 75% to 100% was much higher compared to the increase from 25% to 50% or 50% to 75%. Der Klift et al. (2016) has shown that rectilinear infill has been proven to provide the strongest tensile results. For the PLA and ABS specimens, 25%, 50%, 75% and 100% rectilinear infills were used.

Figure 2 Rectilinear infill with (a) left – 25% infill (b) middle – 50% infill and (c) right – 75% (see online version for colours)

(a) (b) (c)

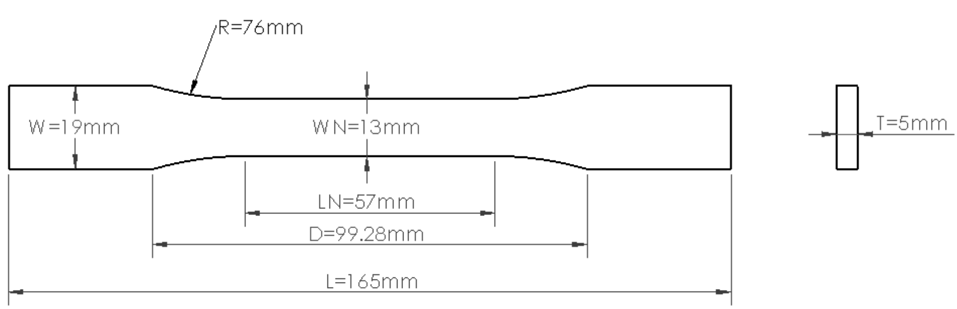
2.4 3D printers

The 3D printers used in this study were the Markforged Mark Two (MK) (Markforged, 2018), Ultimaker 2 Extended+ (UM) (Ultimaker, 2018), and Monoprice Maker Select V2 (MP) (Monoprice, 2018). The MK uses a dual extrusion nozzle and is able to print CF, FG, and KV with a nylon matrix. Additionally, MK can print two types of fibre orientations, 'concentric' and 'isotropic'. The UM and MP both are able to print PLA and ABS. Slicing software is used to convert an STL file into NC (numerical control) code that the AM machine reads. The fibre orientation, infill percentage, layer height, and other parameters can be set in the slicing software. The MK uses Eiger as its slicer, which is web-based. Cura is the UM's and MP's slicer.

2.5 Test models

ASTM International is a globally recognised leader in the development and delivery of international voluntary consensus standards. The standard design model for the tensile testing is D638-14 type I as shown in Figure 3 with a 5 mm thick cross section for tensile testing specimens. The ASTM specimens were modelled and converted to STL in SolidWorks 2016. The MK produced the CF, FG and KV with nylon specimens and the UM and MP produced the PLA and ABS specimens.

Figure 3 ASTM D638-14 type I model for tensile testing



Source: ASTM (2014)

3 Testing

Firstly, different geometries and infill patterns were generated as tabulated in Table 2. For each material, a different fibre orientation and infill combination was developed.

Table 2 Table of tensile specimens shown in Figure 4

Polymer material	*Fibre material*	*Fibre fill type*	*Rings*	*Infill type*	*Infill %*	*Machine*
Nylon	None	None	0	Rectangular	75	MK
Nylon	Carbon	Concentric	2	Rectangular	75	MK
Nylon	Carbon	Concentric	4	Rectangular	75	MK
Nylon	Carbon	Concentric	5	Rectangular	75	MK
Nylon	Carbon	Isotropic	0	Rectangular	75	MK
Nylon	Carbon	Isotropic	2	Rectangular	75	MK
Nylon	Carbon	Isotropic	4	Rectangular	75	MK
Nylon	Carbon	Isotropic	5	Rectangular	75	MK

However, testing the same geometries and infills for each material was costly and time consuming. Hence, CF reinforced specimens were tested for all the aforementioned geometries and infills. Then based on the best results, which gave the highest yield stress, the best fibre orientations were chosen and tested with FG and KV. Figure 4 shows the generated geometries and infill patterns for the specimens in Table 2 for CF and nylon. For each of the infill geometry and pattern, two specimens were printed and tested. Different number of rings results in different volumetric fractions. The number of rings was increased to understand their effect in mechanical properties. Insights collected from changes to the geometries of infill and reinforcement fibre reveal the effect each parameter has on tensile strength.

Figure 4 Tensile specimens printed with Markforged: (left to right) Nylon, CF2RC, CF4RC, CF5RC, CF0RI, CF2RI, CF4RI, CF5RI (see online version for colours)

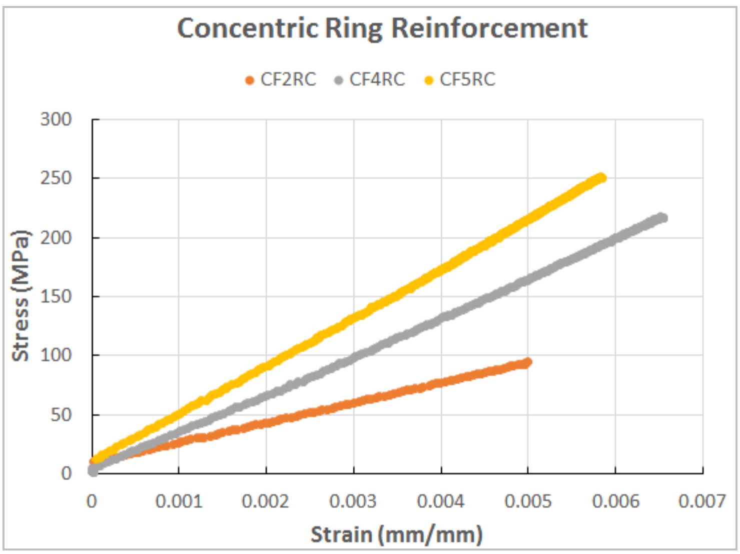
As for PLA and ABS tensile specimens were printed with infills of 25%, 50%, 75%, and 100%. Specimens were printed with both UM and MP. However, when printing with ABS material shielding was necessary so that ambient conditions would be warmer.

For tensile testing of the specimens the machine used was a MTS 810. The standard speed of testing was 5 mm/min, and nominal strain rate was 0.1 mm/mm min.

4 Results

As mentioned the infill of the specimens was divided into two categories: concentric and isotropic. Similar to the infill type and orientation graphing of the results was done for each type of specimens, two of them were tested. Since the differences between the measured values of both specimens were very small, only the best results were graphed. The variance of results was also smaller than the variance between different specimens. In Figure 5, the stress versus strain graph of CF with nylon matrix results are shown. The weakest of them happens to be the specimen with two concentric fibre rings. The strongest is the one that has five concentric fibre rings with a fracture stress of 250 MPa, which at the same has the highest fibre volumetric fraction.

Figure 5 Stress-strain of CF specimens with concentric fibre rings (see online version for colours)

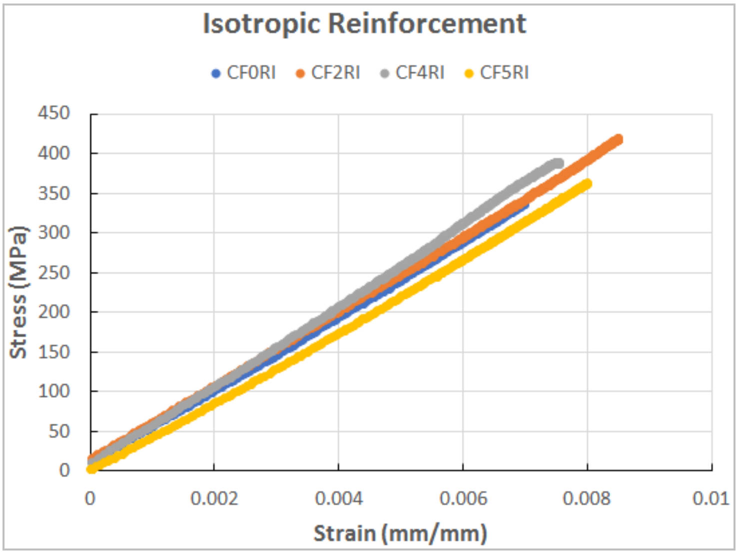


Note: Carbon fibre with 2, 4, and 5 concentric rings.

As for the isotropic infill type, Figure 6 shows the stress-strain graph for isotropic fill reinforced nylon. From the results the isotropic filled with two concentric rings gave the highest results with a 419 MPa fracture stress. The volumetric fibre fraction is almost constant for all of the specimens.

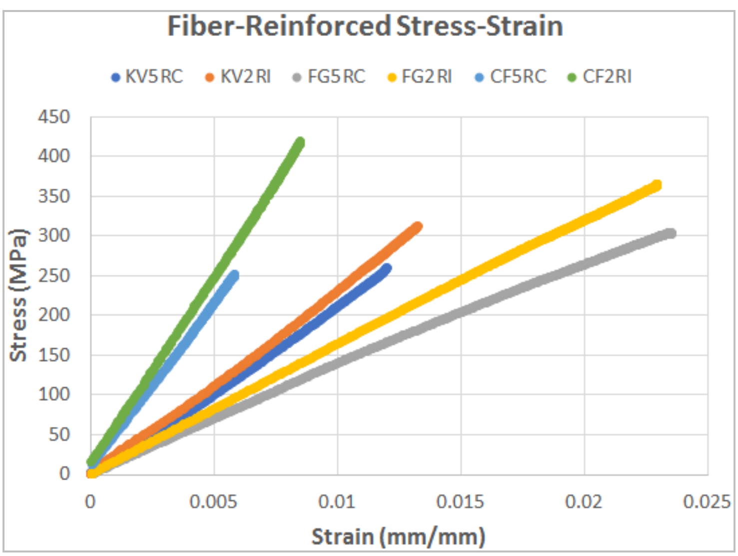
From the tensile data (Figures 5 and 6), the two ring isotropic and five ring concentric fibre orientations yielded the strongest parts. To conserve material and cost during testing, the two strongest fibre orientations were selected and specimens were printed with FG and KV as well. Compared to KV and FG, specimens made of CF had higher yield strength but less deformation resistance to fracture. Figure 7 shows the tensile stress-strain curves for all of the FRAM printed parts. FG is the most ductile, while KV is in between CF and FG in both stress and strain values.

Figure 6 Stress-strain of CF specimens with isotropic fill (see online version for colours)



Note: Carbon fibre with 0, 2, 4, and 5 rings isotropic infill.

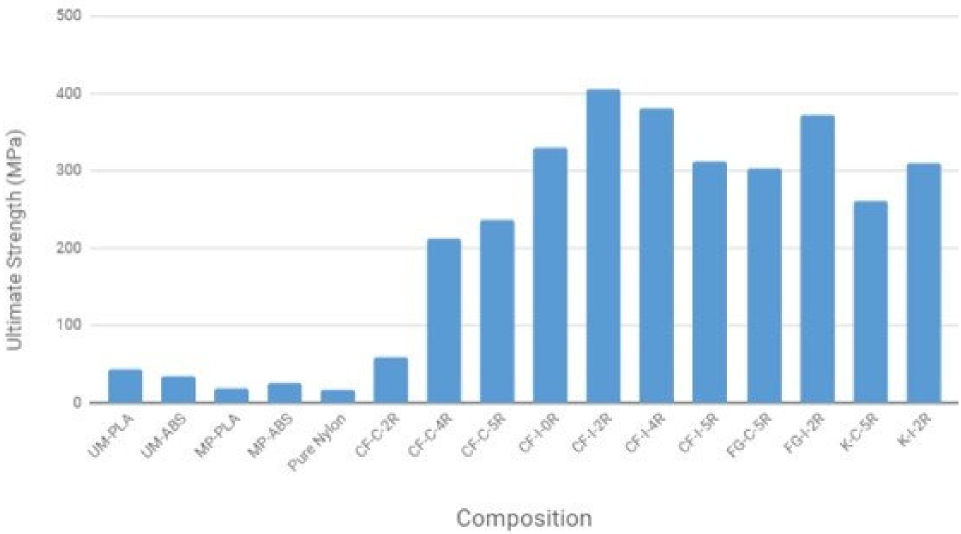
Figure 7 Tensile stress-strain graph of tensile specimens using the two best fibre orientations (see online version for colours)



Note: Kevlar, fibre glass, and carbon fibre with two rings isotropic and five rings concentric infills.

To have a general and thorough understanding of differences in stress between fibre reinforced specimens and plain PLA and ABS specimens, Figure 8 provides a benchmark of all specimens and materials. The effect of fibre reinforcement compared to other polymer specimens is obvious. Amongst fibre reinforced specimens, even between the same materials the specimens the two ring isotropic fill have higher yield strength than the other fibre orientation specimens.

Figure 8 Comparison of all variations of tensile specimens by ultimate tensile stress (see online version for colours)



Fibre reinforcement can be costly if it is used excessively in high volumetric fraction. It is necessary to know their strength to mass ratio so one could know how much strength is increased by while increasing the weight of the part. Depending on the application of the part, the decision of what infill and what amount of fibre reinforcement can be used.

Figure 9 shows the strength versus mass ratio chart for all the materials and specimens used in this research study. Same as for stress versus strain, CF has the highest result. Also, similar to stress versus strain data, the dominating pattern with highest strength versus mass ratio is the isotropic fill with two fibre rings specimen.

Figure 10 compares the yield strength to fibre volumetric fraction of the test specimens with concentric CF rings. It proves that increasing fibre volumetric fraction leads to increasing part strength. However, the increase in part strength is not linear. The amount of increase in strength decreases as fibre volumetric fraction increases. Figure 11 also compares yield strength to fibre volumetric fraction, but with test specimens made of isotropic CF fill. In Figure 11, the range of fibre volumetric fraction is almost constant varying from 0.566 to 0.574. The reason for this is that in isotropic fill the whole area is filled and when concentric rings are added again the area is filled with fibres but just in different orientations. Unlike the trend in Figure 10, the yield strength increases and then decreases as fibre volumetric fraction slightly increases. This could be due to the fact that isotropic fill is more impactful than concentric fill for approximately the same fibre volumetric fraction. The two, four, five ring isotropic specimens have concentric fibre rings around the isotropic fill. As the number of concentric rings increases, there is less area to place the isotropic fill.

Figure 9 Strength to weight comparison of tensile specimens (see online version for colours)

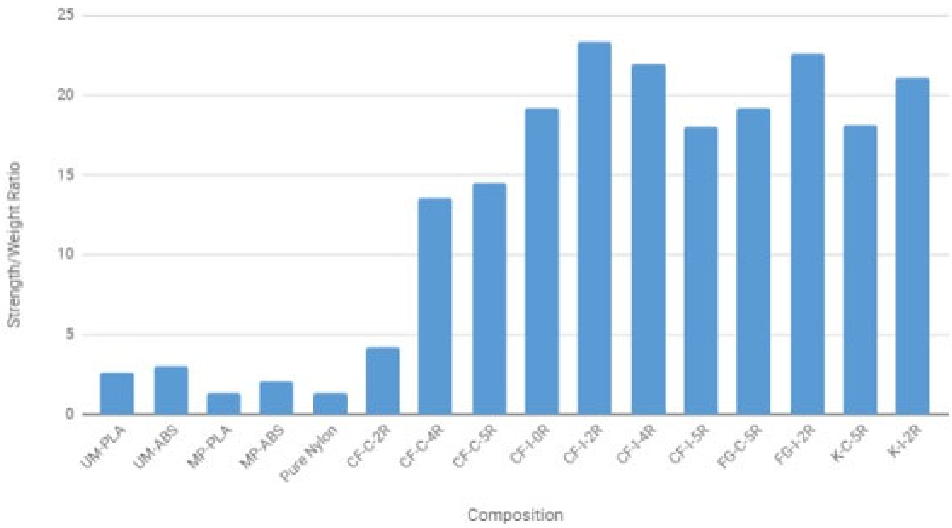


Figure 10 Strength to fibre volumetric fraction of CF specimens with concentric fills (see online version for colours)

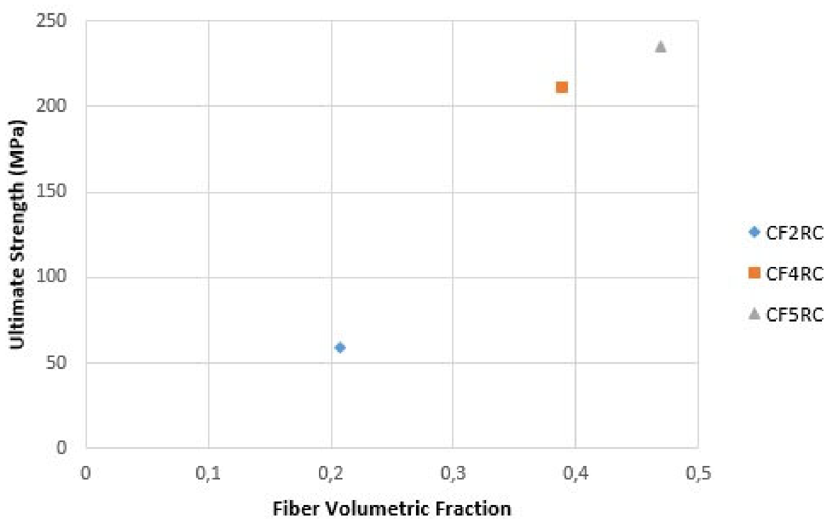


Figure 12 shows that price of filaments increase with increasing yield strength. FRAM is more expensive than PLA and ABS. Despite the better performance, isotropic fills cost more than concentric fills. If an extremely high yield strength is not required, a concentric fill is a good alternative.

Figure 11 Strength to fibre volumetric fraction of CF specimens with isotropic fills (see online version for colours)

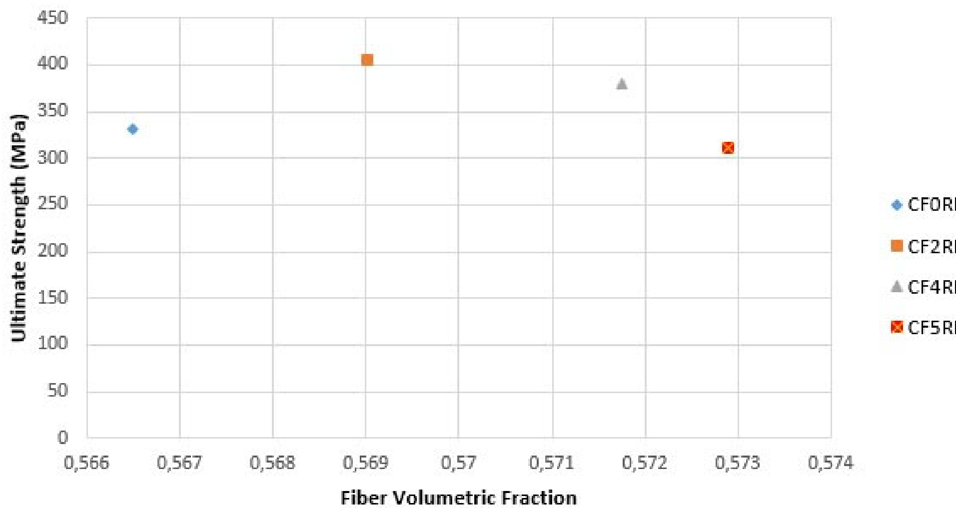
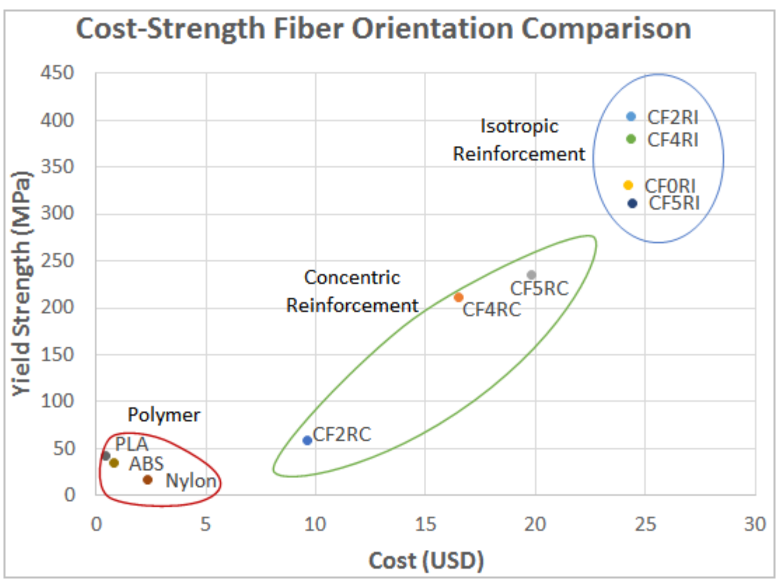


Figure 12 Yield strength vs. cost of tensile specimens (see online version for colours)

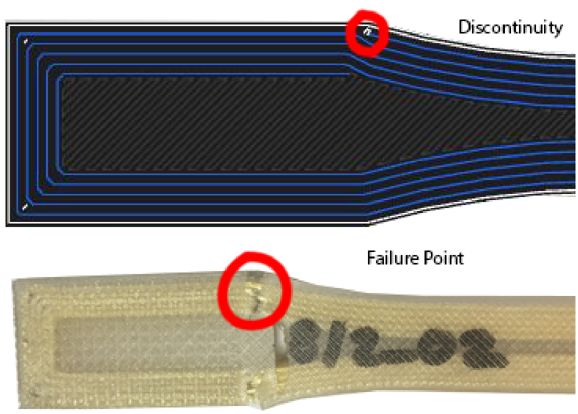


5 Discussion

Analysing concentric filled specimens, the five fibre rings show the highest strength. The reason for this is the higher fibre volumetric fraction which results in higher strength, the more fibre the stronger the specimen, which agrees with Figure 10. For the isotropic fill the volumetric is almost constant ranging 0.566 to 0.574, however the isotropic fill with two fibre rings is stronger than the other isotropic fibre orientations. Analysing the reason that two fibre rings is stronger than 4 or 5 fibre rings, a conclusion can be drawn that there is less area of the isotropic infill which decreases the strength. Isotropic infill seems to carry more load compared to concentric infill. Adding more rings adds the concentric infill area. delamination and poor bonding between fibres and nylon is a non-negligible effect that diminishes the mechanical properties of the additively manufactured parts. The bond is assumed to be perfect and the change in temperature is not considered. Also, without adding the concentric fibre rings, the isotropic fill fibre filaments slip or get pulled-out which results in lower strength. Hence adding the two fibre rings results to be the best combination for higher strength. Those concentric rings help to keep isotropic fill fibres from slipping past each other and from nylon matrix.

The failure point for most of the parts was at the shoulder of the ASTM specimen. The reason for this is the starting location of fibre laying down. There is a sharp corner that serves as stress concentration as well as misalignment of the fibres. Figure 13 shows the sharp point and the failure point.

Figure 13 Top – starting location of fibre laying down. Bottom – failure point of the specimen (see online version for colours)



One reason why two fibre rings isotropic was stronger than other isotropic fibre orientations was due to the amount of isotropic fill. When more concentric rings are added, there is less area to add isotropic fill.

Similarly to the results from the Dickson et al. the tensile specimens failed at the shoulder of the ASTM specimen instead of the narrower area at the body of the specimen. This was probably due to the fact that the MK began laying down the fibre at that point, resulting in a discontinuity in the fibre. Currently, there is not a way to specify where the 3D printer should begin laying down the continuous fibre.

Previous research has shown that PLA is stronger than ABS (Tymrak et al., 2014). However, our tensile specimens produced by MP had different results. The MP PLA specimens were weaker than the MP ABS specimens. This could be due to the difference in temperature conditions when printing the MP PLA and ABS specimens. The air conditioning unit in the room was blowing cold air at room temperature toward the MP. With the ABS MP specimens, a plastic bag and styrofoam were placed around the printer to shield it from the cold air. However, this shielding was not done for the MP PLA specimens. That said, PLA specimens were open to the air blown by air condition unit. A factor that is significant in the strength of the part is the change in temperature between the printhead and the room temperature, with the printer being open to the room conditions that could be a reason of this discrepancy in results between PLA and ABS. Another factor could be the room moisture. AM machines print better in dry conditions due to the filament not getting wet. Additionally, the MP machines are ten times cheaper than the UM.

6 Case study

The material and manufacturing parameters of the ASTM specimens with the best tensile properties selected were used for designing and prototyping a unique medical boot. A child size medical boot was printed since an adult size medical boot print would exceed the dimensional limitations of the AM machines used.

The prototype medical boot has overall dimensions of 70 mm × 160 mm × 155 mm and a weight of 200 g. The parts of the medical boot are connected to each other using a snap-fit design. The toe portion was made in a creative way that enables it to be used with either the left or right foot boot. The heel portion was made of KV and nylon with isotropic and concentric fibre layers. Top and bottom of the heel portion have a two fibre rings isotropic fill due to the maximum load being applied in there while the rest is five fibre rings concentric fill. For high loads from the tensile data, 2 fibre rings isotropic fill was shown to be the strongest. The amount of strength for a child's weight is not much as to use maximum amount of fibre reinforcement throughout the part. The calf portion was made of nylon with a 100% infill. The toe and shin portion was made of PLA with a 25% infill.

Compared to other medical boots, the prototype medical boot generated by the research team is significantly cheaper to produce. It has much less bulk and is lighter. Also, it is designed to be a custom fit for the user. The newly designed and prototyped medical brace was developed in conjunction with the technical support of the Whitson-Hester School of Nursing. One unique aspect of this design is that it can be assembled compared to most medical braces which are available as one solid piece. The brace was developed to assist children with disabilities of developmental difficulties. The feedback received was positive and compels future work in this area.

7 Conclusions

In the search for stronger, lighter, and custom-made parts, the fibre-reinforced parts outperform their FFF polymer printed competitors. Even within the fibre-reinforced parts, by varying the fibre orientation, infill percentage, and other parameters one can get stronger parts. This research study reported that the strongest fibre orientation turned out to be the two fibre rings isotropic fill. This pattern was prevalent for any of the fibre materials. Also, for concentric infill fibre orientation the five fibre rings resulted to be the strongest, however, still weaker than the two fibre rings isotropic fill by about 170 MPa. For concentric fill it can also be concluded that increasing the fibre volumetric ratio will not have a linear increase in strength. Depending on the application, one can choose the infill and fibre orientations to use for each layer of the part. Applications of FRAM machined parts find place in many fields, with one of them being the case study that was done in assistive devices in which the research team developed a medical boot for children.

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