CHARACTERISTICS STUDY OF CARBON FIBRE MATERIAL FOR BIOAPPS ROMICP® FOOT PROSTHESIS

SHEN WENHUI

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2021

CHARACTERISTICS STUDY OF CARBON FIBRE MATERIAL FOR BIOAPPS ROMICP® FOOT PROSTHESIS

SHEN WENHUI

RESEARCH PROJECT SUBMITTED IN THE FACULTY OF ENGINEERING UNIVERSITY OF MALAYA, PARTIAL FULFILMENT OF THE REQUIREMNETS FOR THE DEGREE OF BIOMEDICAL ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2021

UNIVERSITY OF MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: SHEN WENHUI

Name of Degree: Master of Biomedical Engineering

Title of Research Project:

Characteristics Study of Carbon Fibre Material for BioApps RoMicP® Foot Prosthesis

Field of Study: Biomedical Engineering

I do solemnly and sincerely declare that:

(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every rights in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature Date:

Subscribed and solemnly declared before,

Witness's Signature Date:

Name:

Designation:

CHARACTERISTICS STUDY OF CARBON FIBRE MATERIAL FOR BIOAPPS ROMICP® FOOT PROSTHESIS

ABSTRACT

In this research project, to study the characteristics of materials used in BioApps RoMicP® Foot Prosthesis and improve its performance in different parts which are in different positions and can withstand different types of forces. The material studied is the composite including Onyx and Carbon Fiber(CF) which were utilized in Markforged Mark-Two 3-D printer to produce a light foot prosthesis with high performance and low cost. To investigate the mechanical properties, samples with different CF contribution way and with different components of carbon fiber were produced. Three types of mechanical tests involving tensile test, compression test and 3-point bending test were conducted. Then, through calculation and analysis of the yield strength, yield modulus respectively to get the most excellent design of each part. In tensile test, the testing sample with 80% Onyx and 20% carbon fiber embedded in the middle behaves best, its yield strength is 117.1 MPa and yield modulus is 2.065 GPa. In compression test, the specimen with 10% carbon fiber printed in the middle showed the best performance, its yield strength is 5.03 MPa and yield modulus is 23.0 MPa. In 3-point bending test, the results of testing sample with 20% carbon fiber distributed at the both ends is most excellent, its flexural strength is 81.68 MPa and flexural modulus is 4.464 GPa. Therefore, according to the above results, we can design and print different parts in foot prosthesis to optimize their performance.

Keywords: carbon fiber, Onyx, mechanical property, 3-D printer, prosthesis

KAJIAN CIRI BAHAN CARBON FIBRE UNTUK BIOAPPS ROMICP® PROSTESIS KAKI

ABSTRAK

Projek penyelidikan ini untuk mengkaji ciri-ciri bahan yang digunakan dalam BioApps RoMicP® Prostesis Kaki dan meningkatkan prestasinya di bahagian yang berbeza seperti berada dalam kedudukan yang berbeza dan menahan pelbagai jenis daya. Bahan yang dikaji adalah gabungan Onyx dan Carbon Fiber (CF) yang digunakan dalam pencetak Markforged Mark-Two 3-D untuk menghasilkan prostesis kaki ringan dengan prestasi tinggi dan kos rendah. Untuk menyiasat sifat mekanik, sampel dengan cara sumbangan CF yang berbeza dan dengan komponen serat karbon yang berbeza dihasilkan. Tiga jenis ujian mekanikal yang melibatkan ujian tegangan, ujian pemampatan dan ujian lenturan 3 titik telah dijalankan. Kemudian, melalui pengiraan dan analisis kekuatan hasil, setiap modulus hasil untuk mendapatkan reka bentuk yang paling baik dari setiap bahagian. Dalam ujian tegangan, sampel ujian dengan 80% Onyx dan 20% serat karbon yang tertanam di tengah menunjukkan prestasi terbaik dengan kekuatan hasilnya adalah 117.1 MPa dan modulus hasil ialah 2.065 GPa. Dalam ujian mampatan, spesimen dengan serat karbon 10% dicetak di tengah menunjukkan prestasi terbaik, kekuatan hasilnya adalah 5.03 MPa dan modulus hasil adalah 23.0 MPa. Dalam ujian lenturan 3 titik, hasil sampel ujian dengan 20% serat karbon yang diedarkan di kedua ujungnya adalah paling terbaik dengan kekuatan lenturannya adalah 81.68 MPa dan modulus lenturan adalah 4.464 GPa. Oleh itu, berdasarkan hasil di atas, kita dapat merancang dan mencetak bahagian yang berbeza dalam prostesis kaki untuk mengoptimumkan prestasinya.

Kata kunci: serat karbon, Onyx, sifat mekanik, pencetak 3-D, prostesis

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisor Professor IR. Dr. Noor Azuan Bin Abu Osman who enlightened me how to choose a suitable research direction and led me to the right direction when I was confused.

I also want to show my deep appreciation to my senior PhD. Mouaz Kouzbary for his persistent guidance and help. Moreover, he taught me a spirit of adventure which inspired me to learn more new knowledge continuously.

Finally, I would like to appreciate my family and my friend-Ahmad Zulkhairi Bin Zulkefli for their encouragement and inspiration during this Covid-19 pandemic period.

TABLE OF CONTENTS

Abstract.......... iii

Abstrak.......... iv

Acknowledgement.......... v

Table of Contents.......... vi

List of Figures.......... x

List of Tables.......... xii

List of Symbols and Abbreviations.......... xiii

LIST OF APPENDICES.......... xiv

CHAPTER 1: INTRODUCTION.......... 1

1.1 IMPORTANCE OF FOOT PROSTHESIS.......... 1

1.2 IMPORTANCE OF MATERIAL SELECTION.......... 1

1.3 PROBLEM STATEMENT.......... 2

1.4 AIM AND OBJECTIVE.......... 3

CHAPTER 2: LITERATURE REVIEW.......... 5

2.1 INTRODUCTION OF CARBON FIBRE.......... 5

2.1.1 Definition and Structure of Carbon Fibre.......... 5

2.1.2 Property of Carbon Fibre.......... 6

2.1.3 Initial Application of Carbon Fibre.......... 6

2.1.4 Manufacturing of Carbon Fibre.......... 7

2.2 RELATIONSHIP BETWEEN STRUCTURE AND PROPERTIES OF CARBON FIBRE AND RELATED ANALYSIS METHODS.......... 8

2.2.1 Defects of Carbon Fibre.......... 8

2.2.2 Other Parameters of Carbon Fibre.......... 9

2.3 ANKLE-FOOT PROSTHESIS AND OTHER APPLICATION............................. 10

2.3.1 The History of Prosthesis.. 10

2.3.2 Manufacturing of Prosthesis...10

2.3.3 Insufficient Prosthesis in Energy Consuming.. 12

2.3.4 Insufficient Prosthesis due to Materials Selection...13

2.3.5 Carbon Fibre applying in Foot Prosthesis... 13

2.3.6 Application of Carbon Fibre in other prosthesis fields......................................14

2.4 THE SAMPLE WE DESIGNED IN THIS RESEARCH.. 15

2.4.1 Thermoplastics and Thermosetting Plastics.. 15

2.4.2 Onyx and Carbon Fibre... 15

2.4.3 Previous Tests on CF for Prosthesis.. 16

2.5 THE 3-D PRINTING TECHNOLOGY... 17

2.5.1 Fuse Filament Fabrication... 17

2.5.2 The Deficiency of 3-D Printing.. 17

2.5.3 Ways of Filling.. 18

2.5.4 The Advantage of Carbon Fibre in Composite..18

2.5.5 The Improvement of MarkTwo... 18

2.5.6 The Advantage and Optimization of 3-D Printing.. 19

CHAPTER 3: METHODOLOGY... 21

3.1 SELECTION OF METHODS...21

3.2 SAMPLE PREPARATION WITH 3-D PRINTER..23

3.3 TENSILE TEST.. 25

3.3.1 The Function of Tensile Test...25

3.3.2 The Factors in Testing... 26

3.3.3 Steps of Testing... 27

3.3.4 Precautions...28

3.3.5 Machine selection...28

3.3.6 Data collection...29

3.3.7 Strain Measurement...30

3.4 COMPRESSION TEST...30

3.4.1 Selection of Method...30

3.4.2 Factors in Testing...31

3.4.3 Steps, Machine and Data Collection...32

3.4.4 Precautions...32

3.5 3-POINT BENDING TEST...33

3.5.1 Selection of Method...33

3.5.2 Machine Selection and Data Collection...34

CHAPTER 4: RESULTS AND DISCUSSION...35

4.1 TENSILE TEST...35

4.1.1 Data processing...35

4.1.2 Data analysis...35

4.1.3 Discussion...42

4.2 COMPRESSION TEST...42

4.2.1 Data processing...42

4.2.2 Data analysis...43

4.2.3 Discussion...46

4.3 3-POINT BENDING TEST...47

4.3.1 Data processing...47

4.3.2 Data analysis...48

4.3.3 Discussion...52

CHAPTER 5: CONCLUSION...53

REFERENCES... 55

APPENDIX... 58

LIST OF FIGURES

Figure 1.1 The flex foot from Össur, Reykjakiv, Iceland....2

Figure 1.2 BioApps RoMicP® Foot Prosthesis....3

Figure 2.1 The basic structure of carbon fibre-turbostratic layers....5

Figure 2.2 The process of manufacturing precursor and carbon fibre 8

Figure 2.3 The Markforged Mark-Two 3-D printer.... 20

Figure 3.1 BioApps RoMicP® Foot Prosthesis....22

Figure 3.2 The content of methodology part.... 22

Figure 3.3 The loads with associated deformations of composite materials.... 23

Figure 3.4 Carbon fibre printed in the middle of specimen....24

Figure 3.5 Carbon fibre printed at the both ends of specimen....24

Figure 3.6 Dog bone-shape without carbon fiber used for tensile test.... 25

Figure 3.7 Rectangular sample used for compression test.... 25

Figure 3.8 Rectangular sample used for 3-point bending test.... 25

Figure 3.9 The Universal Testing Machine used for tensile test from MS INSTRUMENTS (SEA) SDN.BHD....29

Figure 3.10 Universal testing machine used for compression test from MS INSTRUMENTS (SEA) SDN.BHD....32

Figure 3.11 Universal testing machine used for bending test from SHIMADZU....34

Figure 4.1 The strain-stress graph of the sample with pure Onyx....35

Figure 4.2 The typical strain-stress curve of ductile materials....36

Figure 4.3 The strain-stress graphs of samples with 5%, 10%, 15% and 20% carbon fibre in the middle....37

Figure 4.4 The comparison among specimens in which the carbon fiber layers in the middle.... 38

Figure 4.5 The strain-stress graphs of samples with 5%, 10%, 15% and 20% carbon fibre at the both ends 39

Figure 4.6 The comparison among specimens where the carbon fiber layers at the both ends.. 39

Figure 4.7 Comparison between two different distribution of CF layers...................... 40

Figure 4.8 The strain-stress graph of pure Onyx... 41

Figure 4.9 The strain-stress curve of 20% carbon fiber which in the middle................41

Figure 4.10 The strain-stress graphs of samples with 43

Figure 4.11 The comparison among specimens in which the CF layers in the middle.. 44

Figure 4.12 The strain-stress graphs of samples with 5%, 10%, 15%, 15%R and 20% CF at the both ends.. 45

Figure 4.13 The comparison among specimens where the CF layers at the both ends.. 45

Figure 4.14 The comparison between two different distribution of CF layers..............46

Figure 4.15 The strain-stress graph of pure Onyx in 3-point bending test.................... 48

Figure 4.16 The strain-stress graphs of samples with 5%, 10%, 15% and 20% CF in the middle 49

Figure 4.17 The comparison among samples with 0%, 5%, 10%, 15% and 20% CF in the middle 50

Figure 4.18 The stain-stress graphs of samples with 5%, 10%, 15% and 20% carbon fibre at the both ends 50

Figure 4.19 The comparison among samples with 0%, 5%, 10%, 15% and 20% CF at the both ends 51

Figure 4.20 The comparison between two samples with different CF distribution 52

LIST OF TABLES

Table 2.1 Type of carbon fibre.. 6

Table 2.2 Mechanical characteristic of Onyx.. 16

Table 4.1 Yield properties of Onyx-Carbon fiber composites when CF in the middle.. 37

Table 4.2 Yield properties of Onyx-Carbon fiber composites when CF at the both ends39

Table 4.3 The 2nd yield property results of Pure Onyx 41

Table 4.4 The 2nd yield property results of 20% carbon fiber which in the middle....... 41

Table 4.5 Compression property result of Onyx-CF composites when CF in the middle43

Table 4.6 Yield property result of Onyx-CF composites when CF at the both ends......45

Table 4.7 Flexural property result of Onyx-CF composites when CF in the middle..... 49

Table 4.8 Flexural property result of Onyx-CF composites when CF at the both ends. 50

LIST OF SYMBOLS AND ABBREVIATIONS

NANDA	:	North American Nursing Diagnosis Association
SACH	:	solid-ankle cushion heel
CF	:	carbon fiber
3-D	:	three-dimensional
MATLAB	:	Matrix Laboratory
OpenCV	:	Open Source Computer Vision Library
UHM	:	ultrahigh modulus
HM	:	high modulus
IM	:	intermediate modulus
HT	:	high tensile strength
CT	:	computed tomography
ABS	:	acrylonitrile butadiene styrene
PP	:	polypropylene
PAN	:	polyacrylonitrile
CTE	:	coefficient of thermal expansion
PEEK	:	polyether ether ketone
MRI	:	magnetic resonance imaging
FFF	:	fuse filament fabrication
ROI	:	return of investment
AM	:	additive manufacturing
PMMA	:	poly methyl methacrylate
SR	:	silicon rubber
UTS	:	ultimate tensile stress

LIST OF APPENDICES

Appendix A: Basic information of machine in tensile test and compression test..... 58

Appendix B: Basic information of machine used for 3-point bending test.............. 59

CHAPTER 1: INTRODUCTION

1.1 Importance of foot prosthesis

There are many reasons causing lower limb disabilities, for example, the congenital disability, injury (amputation) and diseases (cerebral palsy and muscular dystrophy). There are also many kinds of assistant devices like wheelchairs, prosthesis, cane and crutch which can be used for assisting disabled persons to obtain basic mobility. This kind of physical impairment which may be temporary or even permanent can limit the basic mobility and movement of a person. In fact, apart from the accident injuries and congenital disability, many common diseases can directly or indirectly cause immobility nowadays. For instance, stroke and obesity. North American Nursing Diagnosis Association (NANDA) reported that American people will have higher risk of suffering from disability and mobility impairment with a longer life expectancy. Moreover, the problem of an aging population all over the world increases the number of people who have physical mobility impairment, which is mainly associated with loss of muscle strength, stiff joints and abnormal gait. No matter for young kids or old people, mobility is the basic demand and vital prerequisites in daily life. The feet and ankles serve an important role in human motion as they need to absorb shock reacting to load(Noroozi et al., 2013), provide stability responding to weight-bearing(Stark, 2005). Therefore, there are a lot of researchers studying the foot and ankle prosthesis.

1.2 Importance of material selection

In many developing countries, the durability of foot prosthesis is the most noteworthy issue(Cummings, 1996). The applied materials in prosthesis are closely related to durability. Additionally, the comfort when people are equipped with prosthesis is also another important factor which can affect the movement. The lightweight materials can reduce the burden when disabled people walk or even run, which can save energy and increase the comfort. In this case, the materials researched in the lab and used in practical applications should be chosen carefully according to the needs of the users.

In the late 1950s, the Solid-Ankle Cushion-Heel(SACH) foot was invented. After that there were nearly no changes in the products design and selection of materials until in the early 1980s. The presence of carbon fiber in prosthesis greatly reduces the limitation of disabled athletes. The difference between this "new" ankle-foot prosthesis with the previous one is that it can be compressed by the human weight and store the energy simultaneously during movement. When the force is removed in one foot, the compressed material is able to return to the original shape and function, and release the stored energy at the same time. This "new" invention from Össur is called flex foot(Fig 1.1) which can offer the effective push produced in normal human motion.

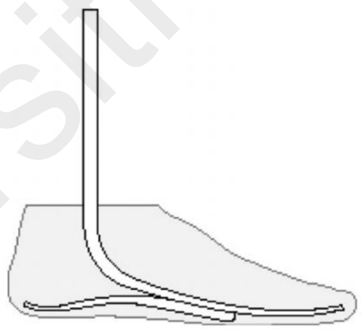


Figure 1.1 The flex foot from Össur, Reykjakiv, Iceland

1.3 Problem Statement

In recent years, there are various kinds of composite materials utilized in the manufacture of prosthesis, which can reduce the weight of auxiliary devices and provide the expected mechanical properties. As for the performance of composites, it depends on several factors such as the material compositions, its structure and processing methods. These factors will influence the mechanical behavior in application. Onyx is a kind of new material used specifically in 3-D printers. Due to the use of new material and 3-D printing technology, there are some unknown issues. There are two problems in this research project:

1. There is no test conducted before to examine the mechanical properties of Onyx-CF composites which are made by 3-D printers.

2. There is a need to improve the performance of current BioApps RoMicP® foot prosthesis design through optimizing the mechanical properties of parts.

1.4 Aim and Objective

In this project, the main aim is to study how components of carbon fibre and structure of Onyx-CF composites affect the mechanical characteristics of different parts in BioApps RoMicP® foot prosthesis. These parts which are similar to the human body part mimic the function and size of patients' feet. Then according to the kinds of forces they withstand, to optimize the design of each part in prosthesis through selecting the most suitable component of CF and structure of composite.

Figure 1.2 BioApps RoMicP® Foot Prosthesis

In this project, it mainly focuses on the material which is embedded with carbon fibre(CF) for BioApps RoMicP® foot prosthesis(Fig 1.2). This foot prosthesis uses an original continuous hierarchical control structure, and it is produced by 3D-printing technology. 3D-printing technique can allow the users to customize suitable size and this design embedded with carbon fibre is able to stand up to 1.2 ton load. Furthermore, the material used is printed by a three-dimensional (3-D) printer(Markforged Mark-Two 3-D printer) with two materials-Onyx and carbon fibre, it is printed layer by layer so the number of layers of CF just means its composition of the testing specimens and products. On the other hand, the position of carbon fibre layers which can mainly determine the structure of specimens can be adjusted before printing through SolidWorks software. Therefore, there are two main parameters in the manufacturing procedure we can study, the first one is the number of CF layers and another one is the distribution of CF layers. In this case, the design of specimens mainly includes different composition and different positioning of CF layers. The experiments conducted to test the mechanical properties of carbon fibre-reinforced composite conducted in this research involve tensile test, compression test and three-point bending test. After testing, the data from the experiment are analyzed through Matrix Laboratory (MATLAB). In the second part, the results from these samples with different composition and structure distribution will be compared to find the best selection for different parts in foot prosthesis.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction of carbon fibre

2.1.1 Definition and Structure of Carbon Fibre

Normally the carbon fibre(CF) is the composite whose component of carbon occupies 92%-100% in fibre. Once the components of graphite in CF are above 99%, it can be defined as graphite fibre. There are many similarities between the atomic structure of CF and graphite. They are both made up of layers of carbon atom which are arranged in the regular hexagonal way. However, for the majority of the CF, the basic structure is made up of a stack of turbostratic layers(Fig 2.1). This kind of structure is inhomogeneous(Park & Lee, 2015).

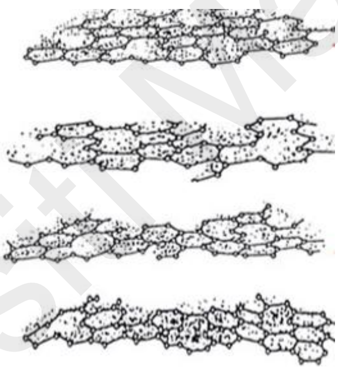


Figure 2.1 The basic structure of carbon fibre-turbostratic layers

According to the previous definition, the heat-treated temperature of carbon fibers is between 1000-1500℃, while the graphite fibers are above 2000℃(Fitzer, 1990). In addition, the carbon whisker (or call it as graphite whisker) is the single crystal in which the rolled up carbon layer looks like a scroll. Due to the natural properties of single crystal, the carbon whiskers nearly do not have defects, so they have very high strength. However, the shortcoming of it is the low productivity of carbon whisker(Bacon, 1960). According to the structure of fibre and the degree of crystalline orientation, in Table 2.1, we can divide the CF into five types-ultrahigh modulus(UHM), high modulus(HM), intermediate modulus(IM), high tensile strength(HT) and isotropic CF(Park & Lee, 2015).

Table 2.1 Type of carbon fibre

Type	Heat treatment Temperature/°C	Crystalline orientation	Long-distance order	
High modulus	>2,000	Mainly parallel to fibre axis	High	UHM/HM
High strength	≈1,500	Mainly parallel to fibre axis	Low	IM/HT
Isotropic	<1,000	Random	Very low	Isotropic

2.1.2 Property of Carbon Fibre

About the properties of carbon fibre, it has superior tensile strength, light weight, exceptional electrical and thermal conductivity, good creep resistance, and it can also show excellent chemical and thermal stability when there is no oxidant. The characteristic of materials is closely related to their structure. There are some relationships between the structure and characteristics of composite materials that are still poorly understood such as mechanical behavior and functional behavior. Even though the development of CF has been improved a lot in recent years, the defects of products in the manufacturing process still occur. Therefore, the detection of structure of CF is essential, from which we can study some potential links between the structure and properties of carbon fibre-reinforced composites. There are some common instruments and methods used to explore the structure of CF, like optical microscope, electron microscope, wide-angle, small-angle X-ray diffraction, transmission(Diaz, Guizar-Sicairos, Poeppel, Menzel, & Bunk, 2014). The valuable information about the structure of CF can include the size of pores, width and height of stack, orientation and size of crystalline(Morales & Ogale, 2013). For example, AG Stamopoulos combined X-ray computed tomography(CT) and mechanical testing to explore the influence of porosity of carbon fiber-reinforced composite on its mechanical characteristics(Stamopoulos, Tserpes, Prucha, & Vavrik, 2015).

2.1.3 Initial Application of Carbon Fibre

At first, Thomas Alva Edison developed the CF as the filament material in light bulbs(Park & Lee, 2015), but the service life of it is very short. Therefore, the use of CF in electrical light was soon substituted by tungsten wire. Later, people knew more about CF, especially its high strength, currently. Now it is expected to be applied in thermal and electrical insulation, building construction, transportation which means it can even replace glass fibre in the future.

2.1.4 Manufacturing of Carbon Fibre

Even though the high strength of CF is attractive to many researchers, the low productivity and high cost would discourage investors. So the users will not use the pure CF in the actual situation which can cause the excessive expenditure. The composites including CF can be considered as the ideal material since they can show the excellent characteristic in some specific field. CF can be used to combine with other materials to make various composites which can enhance the performance. The manufacturing process of these composites includes compression molding, liquid molding, injection molding, filament winding, tape winding and so on. In addition, it is important to investigate the influence of CF on the performance of these composites. Normally, the matrices for carbon fiber composites can be from thermosetting resins, such as vinyl ester resins, epoxy resins and polyester resins, can also from thermoplastic resins, like acrylonitrile butadiene styrene (ABS) resin, polyamide resins and polypropylene (PP) resins. In addition, the characteristics of materials can directly affect the application and use in daily life. In D.D.L. Chung's review paper which involves the properties of carbon fibre, such as mechanical, thermal conductivity, viscoelastic, dielectric, thermoelectric, etc(Chung, 2017). The capability of bearing load is greatly relative to the strength and modulus of the materials. Therefore, it is appropriate for CF to be applied in sporting goods due to its excellent strength and modulus.

The synthetic fibre which can be also called precursor fibre can be processed as CF through the means of heating treatment and stretching.(Akpan, 2019a) The characteristics and behaviors of CF are greatly affected by the precursor materials(Frank, Hermanutz, & Buchmeiser, 2012). The fabrication process of CF will be different with various precursors(Park & Heo, 2015), however, the main steps and features are the same(Akpan, 2019b), which can be seen in Fig 2.2 as below. Polyacrylonitrile (PAN), pitch, and rayon are three common precursors, and polyvinyl alcohol, polyamides, and polyesters can also be used to produce CF(Qiao et al., 2006).

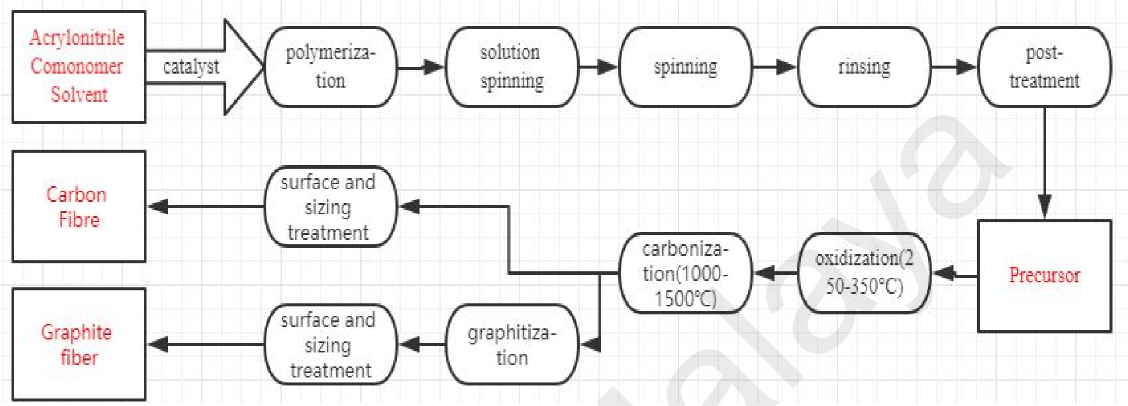


Figure 2.2 The process of manufacturing precursor and carbon fibre

2.2 Relationship between structure and properties of Carbon Fibre and related analysis methods

2.2.1 Defects of Carbon Fibre

The critical factors which can determine the characteristics of carbon fibre can be mainly divided into two types, the first one is basic structure of CF and another one is the structure defects. The basic structure of carbon fibre like crystal orientation, crystalline content and homogeneity can be changed and adjusted in the process of precursor fabrication.

On the other hand, the structure defects can be classified as interior defects (like void, impurity, heterogeneity and chemical change) and surface flaws (cracks and adhesion). These two defects are mainly caused in the stabilization and carbonization process, such as the extent of applied tension and stabilization rate, rate of temperature rise and atmosphere of processing. Normally, the surface flaws are treated as the main factor to be studied, which can be observed through s microscope.

2.2.2 Other Parameters of Carbon Fibre

Other factors affecting the properties of CF include the number of reinforcement layers and the type of reinforcement method in the production process. From Greg Gibbons's research, he proposed that the most important influence is the number of reinforcement layers, the second important one is the reinforcement type. Similarly, for the flexural modulus, they obtained the same results(Dantas & Gibbons, 2020).

There is a paper measuring the mechanical properties of several Onyx-based composites which have different density and shape of fill. The result shows that the layer height of materials just affects the mechanical characteristic slightly. The parity of layer numbers can also influence the mechanical properties, even numbers have better performance than the odd one. As for the infill density of samples, higher infill density can get a greater tensile load(Bárnik, Vaško, Handrik, Dorčiak, & Majko, 2019).

For the surface characterization technique, the most common method is X-ray photo-electron spectroscopy(Castle, 1984). From this method, we can obtain a lot of information about chemical analysis, and it can be applied in many kinds of specimens. When putting the specimen in an environment with high vacuum, the low energy X-ray is used to scan it. The photo-emission occurs when the binding energy of every element is lower than the frequency of the excitation X-rays(Eberhart, 1991).

Apart from the structure defect of raw materials, there are several other factors that can also affect the characteristics of materials. In the paper written by Dorčiak, it mainly focused on the influence of size and shape on the mechanical properties of composite material Onyx which was printed by 3-D printers. The analysis method was to use the finite element method through software ADINA. The conclusion is that the stress of samples will increase when the size of materials increases, and mechanical characteristics can be improved with the increase of volume. In addition, square is the best shape for this sample(Dorčiak, Vaško, Handrik, Bárnik, & Majko, 2019).

Cococcetta's paper proposed that through changing the parameters of processing and condition of lubricating the machinability of 3-D printed CF reinforced polymer can vary with different matrix arrangement. Then they found that the better quality of the surface finish of the CF reinforced polymer can be obtained with the post-processing. To decrease the burr formation, it used a minimum quantity lubrication method(Cococcetta, Pearl, Jahan, & Ma, 2020).

2.3 Ankle-foot prosthesis and other application

2.3.1 The History of Prosthesis

The history of prosthesis and orthotic stems from the era of Ancient Egypt in which the orthosis was fabricated by wood and later was made from leather and metal. But these materials used in supporting and replacing human body parts are too bulky and heavy, which can make the patients uncomfortable. After the mid-19th centuries, new materials like plastics and carbon-reinforced composites began to be widely applied in producing commercial prosthesis and orthotic devices, because they can form various shapes and are cheap. Furthermore, the carbon-reinforced materials have a high ratio of strength to weight. Pure plastics are cheaper than carbon composites, but its relatively low strength limits the uses in some fields. For example, the ideal ankle-foot prosthesis should occupy around 2.5% of human mass("Mechanical Work, Energy, and Power," 2009), therefore, the light carbon fibre can allow the prosthesis to bring higher comfort and less burden to people who use these assisting devices.

2.3.2 Manufacturing of Prosthesis

The prosthetic apparatus can be made according to the individual demand or standard size. The conventional method of manufacturing the prosthetic device is to make the positive mold of the part of the body first. For example, a common way is to cast the part of the body with the plaster of paris, from which the negative model is available. Dam the cast off and fill it with the slurry mixture of plaster of paris. Once it is hardened, the cast can be removed and get the plaster edition which is the positive model. The common materials used to produce prosthesis can be divided into three types, thermosetting composites, thermoplastic resin materials, and thermoplastic composites. Every kind of material has their own advantages and drawbacks in specific applications. Thermosetting composites are normally strong and rigid enough. The fibre layers can be impregnated by the thermosetting adhesive in the construction of prosthesis devices. Therefore, the strength of the prosthesis can be enhanced through different kinds of fibre. However, the need of much labor and time with the use of thermosetting composites increases the cost because every fibre layer needs to be sized alone and be covered on the positive mold. Moreover, the heavy weight of this kind of composite can also cause inconvenience. Unlike the thermosetting composites, thermoplastic resin is more easily used in constructing the device. Due to the flexibility of thermoplastic resin, it can be directly vacuum thermoformed on the given positive mold, which can simplify the manufacturing. The disadvantage of thermoplastic resin also results from flexibility which means it lacks enough strength and rigidity in prosthesis.

There are several thermoplastic composites that have been developed and applied in prosthetic devices. Typically, the core of thermoplastic composite is covered by fibre materials which are impregnated with the same kind of thermoplastic composite. The use of thermoplastic composites in prosthesis can reduce the negative effect caused by pure thermosetting materials or pure thermoplastics. Compared with the thermosetting composite, the thermoplastic composite can easily construct the products through a vacuum thermoforming process like the pure thermoplastics. At the same time, the combination of fibre layers in thermoplastic composites improves the prosthesis' rigidity and strength. In some condition and application, however, the customers do not need such high-strength materials. Thus, the additional fibre material can increase the weight, time and cost. In conclusion, the demand of patients and customers is the most important factor, and we designers need to select the most cost-effective materials and techniques.

2.3.3 Insufficient Prosthesis in Energy Consuming

The design and manufacturing of lower limb prosthetics is still a complicated issue as the function and performance of it is required to be completely the same as the human limb. Normally, the amputees with prosthesis will consume 10%-60% more energy than intact people during walking, and the actual energy consuming is determined by level of amputation, the type of prosthesis, the speed of walking and so on(Kang et al., 2017). Moreover, the walking speed of amputees is around 11%-40% slower than intact persons(Koh et al., 2019). The current commercial prosthesis can be equipped with spring structure which can keep elastic energy and release them later in every walking gait cycle. Due to the passive property of them, this type of prosthesis is not able to release more energy than storage. By contrast, the ankle part can act as a positive net work.

The reasons why amputees will consume more metabolic energy can be from two parts. The first one is that the muscle co-contraction may cause higher energy consumption, which was hypothesized by Winter and Sienko(Winter & Sienko, 1988). The transtibial amputees, for example, can make up for the drawback in energy consuming through utilizing hamstring muscles to positively extend the hip at an early stage(Winter & Sienko, 1988). But the excessive activity of this group of muscle can lead to more flexor moments around the knee. In this case, the excessive moment can only be canceled through knee extensor co-contraction. The second one can be resulted from the insufficient positive net work provided by prosthesis at a later period, which cannot reduce the heel strike loss of another leg. Even though the presence of actuator technology, it is still a challenge to invent an excellent ankle-foot prosthesis which can function like a normal human limb not only in size but also in weight and function.

2.3.4 Insufficient Prosthesis due to Materials Selection

There are some foot prostheses using inappropriate material which cause bad performance and short lifetime. For instance, there are two main types of construction materials-polyurethane foam and vulcanized rubber used in SACH. The vulcanized rubber has better durability, but it is heavier(Steen Jensen, Nilsen, Zeffer, Fisk, & Hartz, 2006). Furthermore, there are some other challenges in the use of rubber which are popular and common in prosthetic devices especially in the developing world. In the tests, several artificial feet devices made of vulcanized rubber which normally present the light foam construction occur rot and even cause structural failure(Jensen & Raab, 2007). The keel penetration may occur due to the excessive wear in the sole. Additionally, the foam layers can be delaminated under repeated loading(Steen Jensen et al., 2006), the long-term sunlight can deteriorate the materials(Jensen & Treichl, 2007). In fact, these issues and challenges are not only found in rubber. In most researches, the low cost, better performance in biomechanics and durability are still the unfinished goals. The appropriate materials in different applications and parts can make up for some deficiency.

2.3.5 Carbon Fibre applying in Foot Prosthesis

There are three common kinds of structural fibers, glass fibre, carbon fibre and aramid fibre. The tensile strength of CF is much greater than its compressive strength. The tensile strain at failure of glass and Kevlar fibre is much higher than CF. At the same time, the strain at failure of these three fibers is less than steel.(Table 1) The advantages of CF are lower coefficient of thermal expansion (CTE) and higher tensile modulus. The thermal expansion phenomenon mainly results from the temperature and the micro-structure of materials. The amplitude of the thermal vibration is greater with temperature increases. The extent of inside and outside vibration of the atoms is not symmetric, which can lead to the change of average bond distance with the increased temperature and then cause thermal expansion. Moreover, the carbon fiber shows better performance in electrical and thermal conductivity, the resistance of chemical materials and high temperature. Therefore, the combination of CF with high strength and low density and additive manufacturing (3-D printing) technique, the complicated shape of foot prosthesis can be easily obtained quickly compared to the conventional process.

2.3.6 Application of Carbon Fibre in other prosthesis fields

Apart from the application in the foot prosthesis, there are several other aspects which use the CF. For instance, the CF-reinforced poly ether ether ketone (PEEK) can be used in orthopedic implants in total knee arthroplasty which is not only because of its high strength, light weight, but it can also be resistant to fatigue strain, and reduce wear. The elastic modulus of this kind of CF-involved composites can be modified according to different demands of customers to mimic the cortical bone(Salernitano & Migliaresi, 2003). The CF can also be applied in other orthopedic medicine, like the potential use of CF in the hip and cranial surgical implants(Garcia-Gonzalez, Rodriguez-Millan, Rusinek, & Arias, 2015).

In addition, the conventional technique is to use the alloys in the manufacture of dental prosthesis. However, there are several deficiencies caused by the use of alloys, such as it can cause allergy, toxicity, corrosion and even have negative effects on the magnetic resonance imaging (MRI)(Malquarti, Berruet, & Bois, 1990). In this article finished by Christel P, it introduces the fabrication of hip prosthesis stems which is made of CF reinforced carbon composites. To test the performance of this prosthesis, the researchers conducted implantation into cadaver femurs, finite element analysis and fatigue testing(Foster et al., 2020). It concludes that this CF-reinforced prosthesis can show a better stress transfer than the metal one, and without fatigue damage(Christel, 1985). In Jesus Hernandez's paper, it shows that the myoelectric hand prosthesis printed by 3-D printer is relatively cheaper, and it is easier to operate it. Therefore, it decreases the cost and makes robotic prosthesis closer to our daily life(Purushothaman, 2016).

2.4 The sample we designed in this research

2.4.1 Thermoplastics and Thermosetting Plastics

There are two types of plastics, thermoplastics and thermosetting plastics. Thermoplastics which consist of long-chain macromolecules or polymers can have mobility and even form various shapes with heat. More importantly, it can be recycled, which can reduce the plastic waste. On the other hand, the thermosetting plastics which cannot change the geometry with catalysts or heat, consist of polymers. In this case, the application of thermosetting plastics is more suitable in high pressure and high temperature environments than thermoplastics. The melting process can accelerate the shaping of composite. Short fibre-composites are more versatile in shaping procedure compared with continuous one. The fabrication of thermoplastic composites needs less time than thermosetting one(Chung, 2017).

2.4.2 Onyx and Carbon Fibre

Onyx, a thermoplastic matrix used in the Markforged Mark-Two 3-D printer, can be used as printed material alone and can also be combined with carbon fibre to improve the strength of products. The temperature of heat deflection of Onyx is 145℃. The components of Onyx include chopped carbon fibre and nylon. The chopped CF has characteristic such as high strength and high stiffness. By contrast, the continuous CF can be applied in long-strand printing and the composite material involving it can show much stiffer and stronger than pure Onyx. The advantages of chopped CF in Onyx can include: a) improvement of surface finish; b) the ability to improve the stiffness of the samples; c) offer the reinforcement of micro-carbon. In this case, the strength of Onyx is around twice as ABS. At the same time, the role of nylon is also very important, it makes the wear resistance and the engineering toughness are comparable.

The types of fibers, orientation of angle, techniques in the fabrication process can greatly determine the stiffness of composites. For example, the carbon fibre made through conventional methods whose elastic modulus along 0 degree can be up to 1000GPa, however, its transverse modulus is only around 35GPa. This phenomenon in which the materials have different properties in different directions is called anisotropic. In addition, the fiber with high modulus normally has the low strain to be a failure.

Table 2.2 Mechanical characteristic of Onyx

Mechanical properties	Value
Young's modulus/GPa	1.4
Yield stress/MPa	36
Ultimate stress/MPa	30
Flexural strength/MPa	81
Flexural modulus/GPa	2.9
Density/g·cm^3	1.2

2.4.3 Previous Tests on CF for Prosthesis

Christel P et al(Christel, Meunier, Leclercq, Bouquet, & Buttazzoni, 1987) introduced the application of CF-reinforced carbon material in the hip prosthesis stem. In this project, the biomechanical properties of this carbon material used in hip stems were tested via fatigue tests and finite element analysis. The conclusion was that there was no fatigue damage and this prosthesis presented a better stress transfer than the metal prosthesis with the same design.

Hadi AN and Oleiwi JK(Oleiwi, 2015) proposed that in order to improve tensile strength, adding carbon fiber into the polymer involves poly methyl methacrylate(PMMA) and silicon rubber(SR) which was used in foot prosthesis. To produce the testing specimen, adding 5%-15% CF into polymer blends PMMA-SR which includes(PMMA:SR) 90:10, 80:20, 70:30, 60:40, 50:50 these five groups. Through tensile tests, it concluded that CF can show the improvement on the tensile strength of foot prosthesis material. And with the increase of CF, both tensile strength and modulus increase.

2.5 The 3-D printing technology

2.5.1 Fuse Filament Fabrication

The fuse filament fabrication(FFF), a method for manufacturing the thermoplastic sample, which melt and extrude the thermoplastic polymers by nozzles layer by layer to obtain the designed parts. In Mark Two 3-D printers, there are two heads used to extrude the fused materials, which can allow the fabrication of composite. To improve the mechanical properties of composites, the CF is added in the thermoplastic material-Onyx. Due to the low cost, high efficiency and easy use of FFF, currently it is regarded as the favorable technique to create the polymer matrix composites. It is unavoidable for FFF to have some limitations, such as the second extruder in Mark Two 3-D printer can cause the decrease of available printing area than those with only one extruder, and the possible presence of layer shifting caused by the mutual influence of two extruders, and higher probability of stringing and oozing.

2.5.2 The Deficiency of 3-D Printing

The limitation of 3-D printers may involve the size, for example, the specimen can not be printed very exactly if its size is too small. Another thing is that trying the best to avoid printing posts with diameter five times less than the height. Because the high post is more likely to be affected by shear on layer lines(Markforged, 2019). Normally, the 3-D printer is suitable for mid- and low-volume samples. Determining whether to choose the 3-D printer we should consider some aspects: the requirement of material (stiffness and strength), the use, the cost and the weight of part and so on.

2.5.3 Ways of Filling

There are two kinds of filling ways. The first one is concentric fill, it places the fibre around the wall, which can facilitate the bending resistance about the Z-axis and reinforce the walls to reduce deformation. The user can set the value of "CONCENTRIC FIBER RINGS" to change the amount of fibre layers, and the "START ROTATION PERCENT" is used to specify the initial point of the fibre.

The second way is isotropic fill, the route of material is jagged like the Zigzag. Normally, the default value of "FIBER ANGLE" is 45°, we can also change it according to the demand of users. The advantage of isotropic fill is that it is able to resist bending in the X-Y axis plane. Isotropic materials possess the same material properties in different directions, and the concentric one can show different properties in different directions. In this case, the printing orientation is very vital.

2.5.4 The Advantage of Carbon Fibre in Composite

In another work, it focuses on whether the stiffness and strength increase of a thermoplastic matrix with embedded CF. Its conclusion was that there was a great improvement of thermoplastic performance when adding the continuous CF. In the same way, the filaments added with short CF also present better performance but the improvement of mechanical characteristics is relatively slight(Blok, Longana, Yu, & Woods, 2018).

2.5.5 The Improvement of Mark Two

The difference between Mark One and Mark Two 3-D printers is mainly the different number of nozzles. There is only one nozzle applied for Onyx in Mark One, the improvement of Mark TWO is there are two nozzles used for two materials which can achieve the generation of composite including CF.

There are typical methods which can strengthen the parts we need.

a) Know about the practical condition of loading in specific application: Determine which areas undergo which kind of forces.

b) Direction of printing: The determination of print orientation needs to consider which direction may withstand the maximum loads. The users should change the direction of the specimen to make the most forces travel in the plane with the printing bed.

c) Select the strengthened area: According to the loading condition, to choose which area needs to be reinforced and the ways of reinforcement. In this thesis, through changing the type of CF layers distribution to study whether it can change the properties of material. Normally, we can not only strengthen one side, which makes the material uneven in the panel and may easily cause warping.

d) The roof and floor layers: Normally, the reinforcement layers should start after the finish of roof layers and stop before the floor layers. Moreover, the parts generally need at least four plastic roof and floor layers.

2.5.6 The Advantage and Optimization of 3-D Printing

The conventional ways to produce the low limb prosthesis would need much time and human labour, which can cause many inconveniences and low productivity. Therefore, the 3-D printing technique with the application of modelling-design software is able to reduce the manufacturing time for this type of individual products and improve the accuracy, which can greatly cut down the cost on labour. In addition, Alam, Choudhury, Mamat, and Hussain have created a way of digitally scanning the leg and then making the ankle-foot orthosis according to the results(Alam, Choudhury, Mamat, & Hussain, 2015). If there is a great development of digital scanning of body shape, 3-D printing can be used more widely in the field of prosthesis and orthosis. The adjustment of stiffness of composites used in ankle-foot prosthesis can be achieved through changing the component of CF instead of changing each custom part.

Figure 2.3 The Markforged Mark-Two 3-D printer

CHAPTER 3: METHODOLOGY

3.1 Selection of Methods

For a new material, or a familiar material used in a new application, it is essential for developers and researchers to do some experiments and tests, especially mechanical tests. The testing can support the development, use and optimization of various materials through the comparison with the evaluation standard. The aims of mechanical testing can involve(Chaurasia, Sahoo, Wang, He, & Mogal, 2013):

a) determination of direction of theories formulation at the initial stage;
b) calculation of design process;
c) selection of materials;
d) prediction of material use;
e) control of quality and assurance.

Tensile testing is the most common in mechanical tests, especially for plastic materials. From tests, we can obtain the maximum strength, modulus, toughness and deformation. The bending tests of rigid and semi-rigid plastics are also common in which the standard methods can be divided into three-point and four-point tests. The compression test is often conducted to test the properties of foams and packaging materials.

As Fig 3.1 shown below, part 1 and part 2 of foot prosthesis are mainly subjected to repeated tensile and compression forces when the user is equipped with this prosthesis moves. Part 3 of the device mostly undergoes the bending load. In this case, choosing these three types of tests to measure the strength and modulus of materials which are applied in BioApps RoMicP® foot prosthesis. The main processes and contents of the methodology part are shown in Fig 3.2.

Figure 3.1 BioApps RoMicP® Foot Prosthesis

The key to select the methods of testing is mainly determined by the application of products, and the demands of clients and markets. On the other side, we ought to consider whether the required instrument and equipment are available. For example, the achievement of quality control just needs the implementation of a simple test which can present the related mechanical properties of samples. Therefore, it is prioritized to select the simpler operation methods in the test and the common machines which can provide high accuracy results and be easy to run.

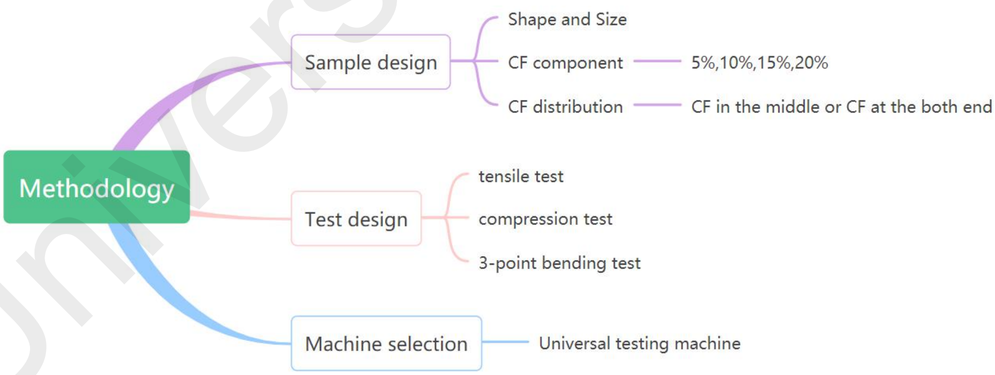


Figure 3.2 The content of methodology part

Furthermore, the internal structure of samples can determine the results in the mechanical tests, which is a complicated issue. So the procedure and type of sample manufacturing can directly influence the performance of it in the tests. Every specimen is special and unique, the testing results are mainly relevant to the whole specimen instead of only the raw material. Therefore, the researchers do not only need to consider the characteristic of one specific material from the specimen used in testing in which the sample size and shape, testing strategy, evaluation process and so on are also extremely vital. So it is necessary to study the structure and component of the specimens.

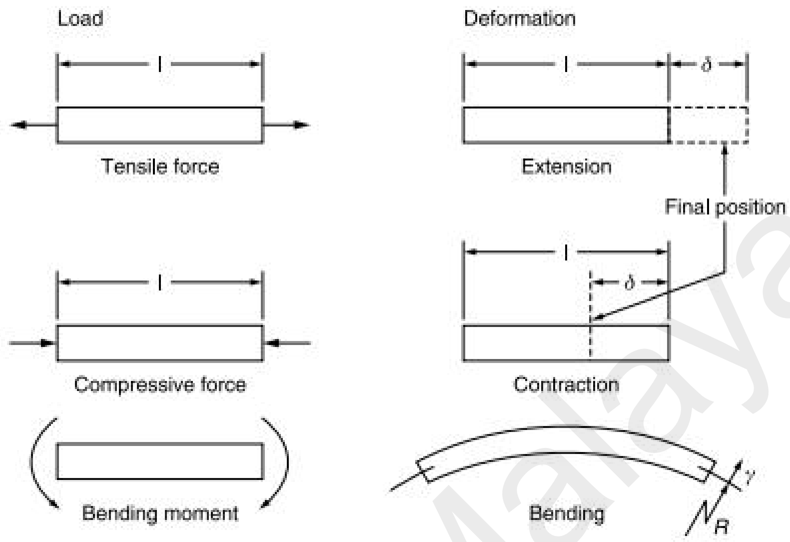


Figure 3.3 The loads with associated deformations of composite materials

In mechanical testing, the formation of samples can be divided into three types, flat sheet, filament wound tube and pultrusion. Relatively, the later two can be relatively easily made. Additionally, these two can be corresponding to many common production processes in industry. The fibre can be arranged along a spiral or circle when producing samples in filament wound tube way. Moreover, it is beneficial for structure consolidation and can reduce the void rate of products and most of the fibre is arranged along the pultrusion axis in the production process.

3.2 Sample preparation with 3-D printer

The additive manufacturing (AM) technique has been widely used in many fields, which allows the production of materials with complex geometries. According to the research aim and the features of AM, we primarily investigate how the component of CF in the composite and the distribution of CF layers affect the mechanical properties of specimens. In this case, to study the influence of components of CF, the samples can be mainly classified into two groups in each type of mechanical testing, one is pure Onyx and another one is carbon fibre-reinforced Onyx. In the group of CF-composites, there are four different components of CF, 5%, 10%, 15%, 20% respectively.

In order to investigate how the distribution of carbon fibre layers affect the mechanical characteristic, two different printing ways are designed in the group of CF-composites. One is to print all the CF layers in the middle part of specimen(Fig 3.4), another one is evenly dividing them into two parts at the both ends of the whole structure(Fig 3.5).

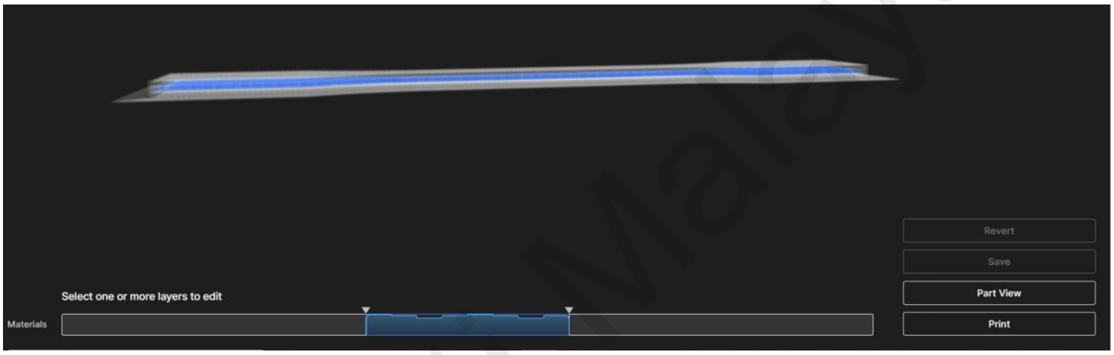


Figure 3.4 Carbon fibre printed in the middle of specimen

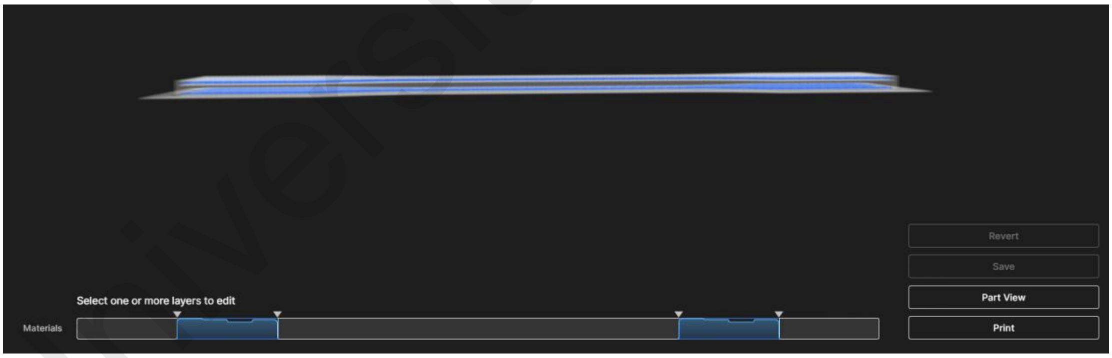


Figure 3.5 Carbon fibre printed at the both ends of specimen

For the selection of samples size, the kind of specimens selected for tensile test is the dog bone-shaped (ISO 527-4:1997, 55mm×10mm×4mm)(Fig 3.6), for compression test is rectangular (ISO 604:2002, 50mm×10mm×4mm)(Fig 3.7), and for 3-point bending test is rectangular (ISO 14125: 1998, fiber-reinforced plastic composites, determination of flexural properties, 100mm×10mm×4mm)(Fig 3.8). The machine used for tensile tests and compression tests is a universal test machine.

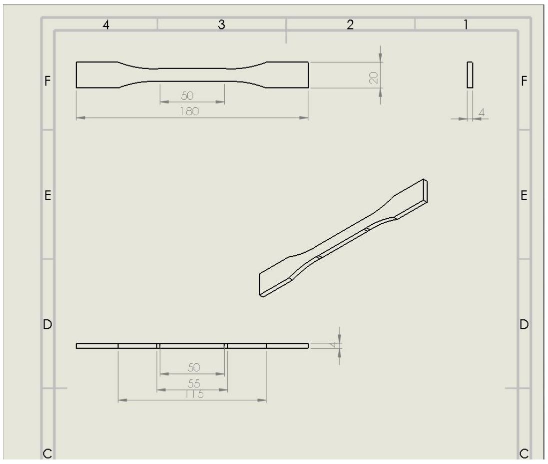


Figure 3.6 Dog bone-shape without carbon fiber used for tensile test

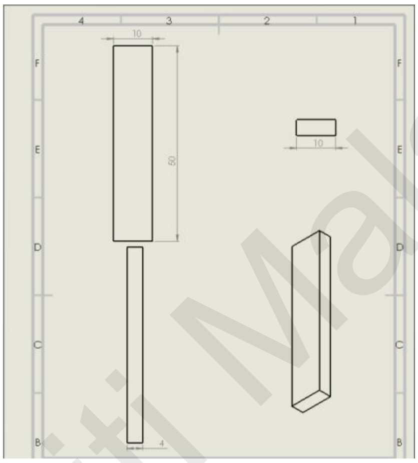


Figure 3.7 Rectangular sample used for compression test

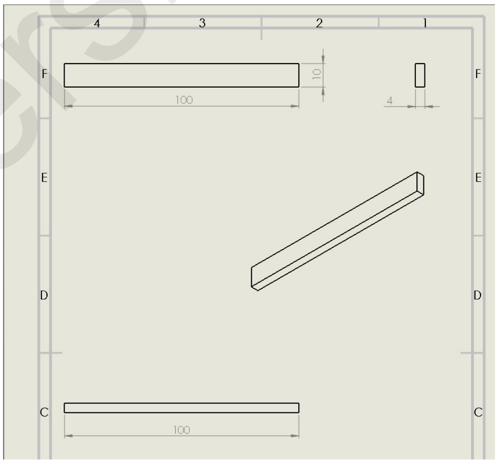


Figure 3.8 Rectangular sample used for 3-point bending test

3.3 Tensile Test

3.3.1 The Function of Tensile Test

In the tensile tests, the main aim is to measure the ultimate tensile stress(UTS) and modulus of a specific material. There is a large amount of information which is about the mechanical behavior under the load. For example, the composite samples can be delaminated or even split, and the initial damage and its later process can be recorded and studied with the increasing load. Then we can observe the process of failure of materials and analyze the reason. It is vital for careful use of materials to determine the UTS and the reason for material failure. In the second half of the 1800s, the metal was the most common engineering material. Therefore, the initial testing methods for composites are closely related to the techniques of metal material testing. The techniques of metal testing are relatively easy because of the isotropic homogeneous property. For instance, a sample withstands loads in the testing machine until it fails in the middle position, and the reduction of the cross-section ("waist") can make the failure far away from the grips. The difference between metal and composites is mainly that the composites are not homogeneous.

3.3.2 The Factors in Testing

In the first conference of testing and design of composite materials in which the funds were provided by American Society for Testing and Materials, there were various samples in various shapes, like bow tie, dog bone and shouldered. Currently, the parallel-sided end-tabbed kind is still used, while the last two have rarely been used in the metal tests. The properties of the tab materials can be completely different from the testing samples, and the reason why selecting the tab materials is that it can provide enough gripping and protection for materials. The aims to test the composite materials are regarded as two different parts. The first one is to create the material with fundamental properties used in follow-up analysis of structure and techniques of design. The final test results can be obtained when the fibre is aligned in the direction of loading. Another aim is to study the properties and the mechanical behavior of the targeted materials(Christel, 1985). There are two basic problems that need to be dealt with in the testing. The first one is to minimize the negative influence, for example, the interaction between the loading ways and the test samples. Because of the structure of the fibre-composite materials, the outermost fibre can occupy most of its strength, and due to the position of them the outermost layer is more likely to damage firstly. Another issue we need to overcome is the tensile stress state should be as pure as possible. However, it is nearly impossible, the most ideal condition is that the test sample is filament which is extremely thin and long. Tensile strength, the maximum stress which the materials can stand with the implementation of external stretching, is opposite to the compression, but the values of them these are different. The measurement of tensile strengths are important for the brittle materials, while is not essential for ductile.

3.3.3 Steps of Testing

The extension of the specimen was measured by an extensometer at gauge length of 100 mm(Ghebretinsae, Mikkelsen, & Akessa, 2019). The samples were tested at room temperature and normal humidity. If there is no undue deformation or failure occurring in a material sample under a load, then defining this kind of capability as the strength of a material which is intrinsic for a material and needs to be tested through experiment. The widespread methods in this aspect used can be tension and compression testing on different engineering materials like metals, polymers and composites, from which we can make the link between the normal stress and the normal strain clearly.

The strain in the mechanical testing should be measured with the suitable standard. When using the strain gauge, the measurement procedures need to be followed carefully. The gauge length has been specified with standards, and it must be greatly shorter than the sample's gauge length. What we need notice is that load was applied parallel to the unidirectional carbon fiber and the samples were loaded until failure(Ghebretinsae et al., 2019). We should avoid that the sample surface which was in direct contact to the support infill has a poor surface finish.

3.3.4 Precautions

Furthermore, there are several problems in composites compared to the metal materials, and they must be solved:

a). The hysteresis influence and zero load stability can be improved through using the high gauge resistances, because it allows high voltages with low current.

b). Try the best to use a gauge with attached lead wires or install the solder wires to the gauge in advance, which can reduce the damage to composite samples by soldering.

c). If possible, the cloth pattern of the autoclave scrim needs to be clean before installing the gauge, which is important especially for the use of contact adhesives.

d). The influence of transverse sensitivity should be gauged through correction.

e). Must place the gauge precisely

3.3.5 Machine selection

The testing machine used can be divided into two types: one is through hydraulic ways to apply a deadweight load into the samples. Another one is through a jack to apply a controlled deflection into the samples. Once the sample is weakened, the load will be lower with the control of displacement. In addition, the uncontrolled failure may happen with the controlled load because the machine keeps applying load to the samples, which is very dangerous and can hinder research about the mechanics of failure. Through Servo Hydraulic one, the machine can provide these two ways of loading and obtain the fatigue. Otherwise, it has the advantages like the loading can be programmed, strain-controlled and high rate. Nevertheless, it requires a higher cost and restricted work distance, which limits the wide use of this kind of machine. Finally, the universal testing machine from MS INSTRUMENTS (SEA) SDN.BHD was selected in tensile tests.(Fig 3.9)

.

Figure 3.9 The Universal Testing Machine used for tensile test from MS INSTRUMENTS (SEA) SDN.BHD

3.3.6 Data collection

The present instrument with a computer-based system used for data collection will not be affected by inertia. Additionally, the rate of data collection is greatly vital, otherwise the important data between two spots can be ignored or lost. Normally, the requirement of accuracy of load indicating system should be 1% or better and try the best to eliminate the effect of inertia, which is the reference of mechanical graph recorders. However, the difference between the maximum load displayed instantly and recorded for a whole testing can be often greater than 1%. In this case, the algorithm used for data collection with greater accuracy is expected to improve the rate of data gathering.

Generally, the samples are clamped by the grip, in which the load in the gripping surface will be transferred to the specimens. Therefore, to transfer the load maximally to the specimen and reduce the harm to it, the process of roughening can be applied in composites. Another way is to place the rough cloth which can be covered with abrasive between the testing samples and grip. If the force applied by grip is not sufficient, the samples will slip, which can normally cause the surface contacting with the grip being torn off. Too much force can also cause negative effects not only in compression tests but also in tensile tests. It can distort the outside fibre at the both ends of samples, which can decrease the failure load.

3.3.7 Strain Measurement

The selection of strain measurement can include the strain gauge and extensometer. To reduce the errors in the use of a contacting extensometer, it normally requires point contact. It can be implemented on the flat samples with the help of curved knife edge, but the great stress on the contact surface can lead to damage to the out layer of composite samples and can even cause premature failure. So the contact stress should be as small as possible on the basis of providing enough force to avoid slipping. Before the failure of samples the extensometer ought to be removed, which can prevent the damage to it. On the other hand, the non-contacting extensometer is also commonly used, which is far away from the samples and then refrains from any damage. However, there is no ideal solution of a non-contacting extensometer when it is applied in the use of stiff test samples. But now the updated generation of it which is equipped with the digital signal processing and video technology is capable of solving many previous issues. Temperature and humidity can also cause the strain difference between the samples itself and the gauge. At last, the testers should consider and notice several factors during the evaluation of data results: the accuracy and precision.

3.4 Compression Test

3.4.1 Selection of Method

The compression test can present how the specimens react and what the behavior it shows under compression, and determine the ductile fracture limitation. It is important to test the compressive fracture and elastic properties of low-ductility and brittle materials. The compression yield point, the modulus of elasticity can be measured in the tests. These characteristics can help the researchers to determine when the materials will fail under compression and whether the materials tested are suitable for a specific application.

Most thermoplastic composites fatigue is related to tensile loading. In fact, the failure of this kind of material often occurs in the position which is loaded with compression. The kind of samples and its fiber alignment can influence the compression strength in static loading and fatigue. The overall buckling and the failure near to the grip regions often happen before the failure of materials, which can easily cause imprecise results. The fiber alignment in composites can greatly affect the compression strength. Normally, the matrix of thermoplastic composites can not be treated as the liquid with low viscous property and be transferred to the fiber arrangement. Therefore, there are more undulating fibers in composites particularly for the mixture of thermoplastic and fiber. It is simpler for the fibers which are relatively not straight in thermoplastic to happen fiber buckling under stress. According to the previous research about the reason for composites' failure under compression, the neighboring one will successively buckle and form kink bands when the fiber starts to buckle. The buckled fibers can be a start for next fatigue damage, and kink bands can also expand with cyclic loading. The compression strength of thermosetting composites is usually higher than thermoplastics, which is due to the higher stiffness and yield stress of many thermosetting composites. Moreover, it is more harmful to thermoplastics with compressive fatigue.

3.4.2 Factors in Testing

The compression of CF and organic fibre which have high modulus and great anisotropic property is relatively lower than glass fibre. Normally, for the fibre with greatly anisotropic characteristic, they have a low ratio of compressive to tensile strength, while the glass fibre is counter.

Generally, compression loading can be applied in three ways: direct loading at the one end of samples, loading the samples through shear force, and combining the direct and shear loading. The widest use of the method is loading the samples end with shear force, which is the same as the steps in the tension test. Furthermore, the shape, precision and material type of the end tabs can all affect the mode of failure and results of strength. The Celanese fixture(Tan, 1992) is one of the earliest fixtures, in which the sample is fixed with the conical wedge grip.

3.4.3 Steps, Machine and Data Collection

Figure 3.10 Universal testing machine used for compression test from MS INSTRUMENTS (SEA) SDN.BHD

As for the testing steps, the selection of machine and collection of data in compression test are as same as tensile test. And we just need to change the upper cross head and lower cross head in force part, while the control part is same.(Fig 3.10)

3.4.4 Precautions

The stress-strain graph of compression is different from in tensile tests. Ductile materials such as aluminum and steel have very similar proportional limitations of deformation in compression and tension. Nevertheless, their mechanical behaviors are completely different in yield point. In the tensile tests, the samples are stretched, necking will take place, finally fracture occurs. However, if the samples are pressed, they will bulge outward on the sides and turn to barrel shape. With the increase of load, some samples may be flattened out, and then they will give greater resistance to the sensor of the testing machine. In this case, the slope of the stress-strain graph is very large. As for brittle samples in compression tests normally shows a linear region at the beginning, but its ultimate stress in compression test is much greater than that in tensile test. Furthermore, the brittle material will break at the biggest load while the ductile one is flattened out.

3.5 3-Point Bending Test

3.5.1 Selection of Method

For the mechanical tests used for the laminated fibre and resins, the testers tend to choose the widely used bending tests which require relatively easy methods and experiment instruments. Moreover, the bending testing can also be utilized for the evaluation of inter-laminar fracture toughness in laminates. For some samples with complicated structure, their strength, stiffness and fatigue behavior in the bending tests can be investigated.

Even though the conclusions from the bending testing are generally as similar as tensile and compression tests, the bending test can not obtain the results about quality of design data. In addition, through the comparison instead of absolute values, the bending tests are beneficial for choosing the suitable type of material and controlling quality. As a result, due to its feasible operation and effective assessment, the bending test is still popular in the whole industry. The bending testing is conducted on the supported beam of unchanging area of cross-section, and it does not involve the end-tabs, or shape change of the samples. The most common ways used in analysis of flexural characteristic of laminates are four-point and three-point tests.

The three-point bending test aims at the measurement of flexural strength and modulus of the material. The flexural strength, the maximum stress which the materials can withstand on the outside of the materials, is calculated based on the surface of the sample on the convex or tension side.

3.5.2 Machine Selection and Data Collection

The machine used in 3-point bending tests is the Universal Testing Machine (S-42-4830, SHIMADZU KUA 0400 MED 00693).

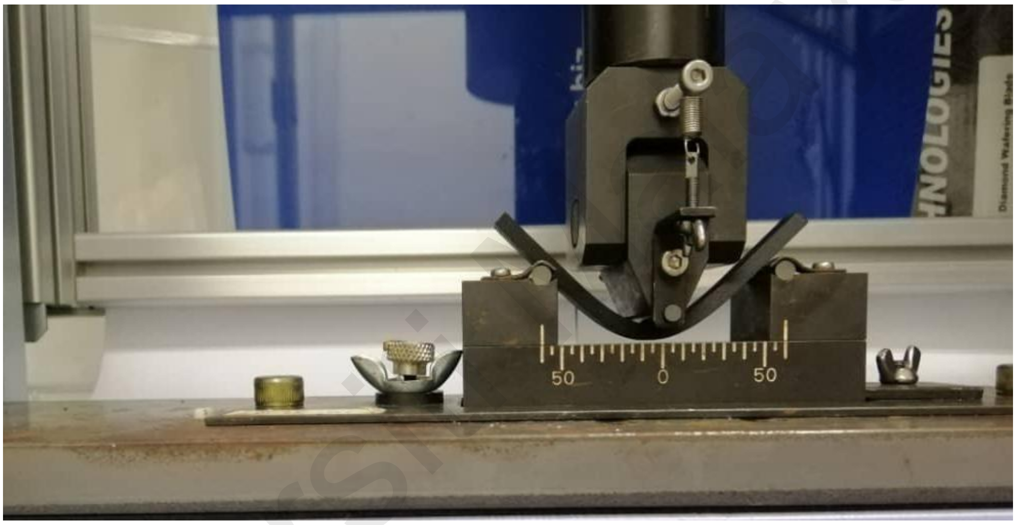


Figure 3.11 Universal testing machine used for bending test from SHIMADZU

The operation steps are: testing sample was simply supported at two end roller support, 60 mm apart. Then we set the speed of the machine as 1 mm/min and force as 5 kN. Once we click the “START” on the computer screen and a concentrated load is uniformly distributed along the width of the beam applied at the mid-span(Ghebretinsae et al., 2019). The output machine is also a computer which can show and save the raw data and graph, which is convenient for us to download and process the experiment data.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Tensile test

4.1.1 Data processing

The results from experiments can be directly obtained from sensors and be saved and exported from computers. However, the massive raw data obtained are Force(N) and Elongation(mm). Then we need to calculate the Strain(mm/mm) and Stress(MPa) on the basis of raw data with the functions which can convert the force values into stress and convert the deflection values into strain values:

$$Stress: \sigma = P/A_0 \qquad (1)$$
$$Strain: \varepsilon = (L - L_0)/L_0 = \delta/L_0 \qquad (2)$$

In the equation for stress, $\boldsymbol{P}$ is the load and $\boldsymbol{A_0}$ is the original cross-sectional area of the test specimen. Because the change of cross sectional area is so small that we can regard it as constant in the whole process. In the equation for strain, $\boldsymbol{L}$ is the current length of the specimen and $\boldsymbol{L_0}$ is the original length. And the final results of pure Onyx specimens are shown in Figure 4.1, and the others containing carbon fibers in the middle are presented in Figure 4.3, at the both ends are shown in Figure 4.5.

4.1.2 Data analysis

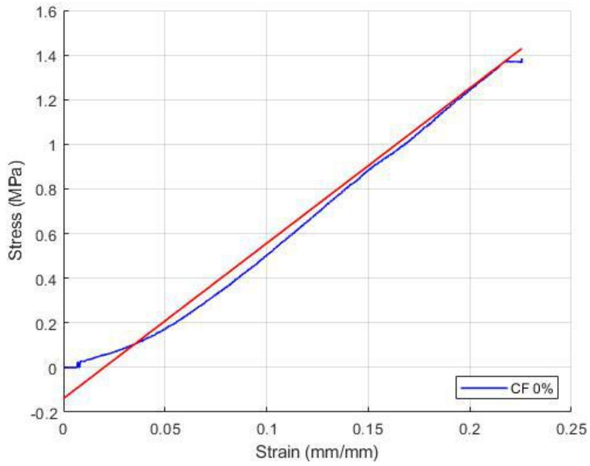


Figure 4.1 The strain-stress graph of the sample with pure Onyx

As shown in Figure 4.2, it is the classical stress-strain curve, and there are several important points which can present the vital properties of a material.

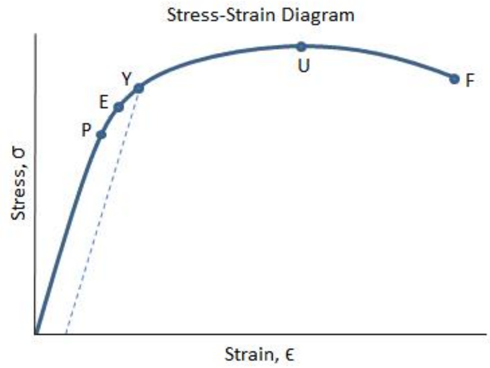


Figure 4.2 The typical strain-stress curve of ductile materials

P: This is the limit in linear area. It indicates the maximum stress when the curve is linear.

E: This point shows the elastic limit. It indicates the maximum stress where there is no permanent set. The curve is not linear from the proportionality limit(point P) to the elastic limit(point E), but the material is still elastic in this area. What's more, once the load is decreased or removed, the material is able to come back to its initial length.

Y: This is called yield point and the stress at this point is named as yield strength. If the stress over this point, the strain will start to grow quickly. As Fig 4.2 shown above, a precise yield point of this ductile material cannot be found, normally, the 0.2% offset method can be used, in which a straight line parallel to the linear region is drawn. This line intersects the x-axis at 0.2% of strain value. The point at which the line intersects the stress-strain curve is regarded as the yield point. Just like as shown in Fig 4.1 and 4.3, there is a red straight line which is parallel to the linear region, and it intersects the x-axis at 0.2% of strain value.

U: This point is the ultimate strength, which represents maximum stress on the stress-strain graph. The ultimate strength is also referred to as the tensile strength. After reaching the tensile strength, ductile materials will display necking. At this point, the cross-sectional area in a specific region begins to reduce greatly.

F: This is the break point or called fracture point. At this point, the material fails.

Therefore, to find the **Y** point (yield point), we can directly use the rules referred above and software MATLAB to draw a straight line(the red one in fig 4.1, 4.3) which has the same slope as the curve in linear region, and it should intersect the x-axis at 0.2% of strain value. Then the intersection point between straight line and strain-stress curve is the yield point. The slope of that straight line is the yield modulus.

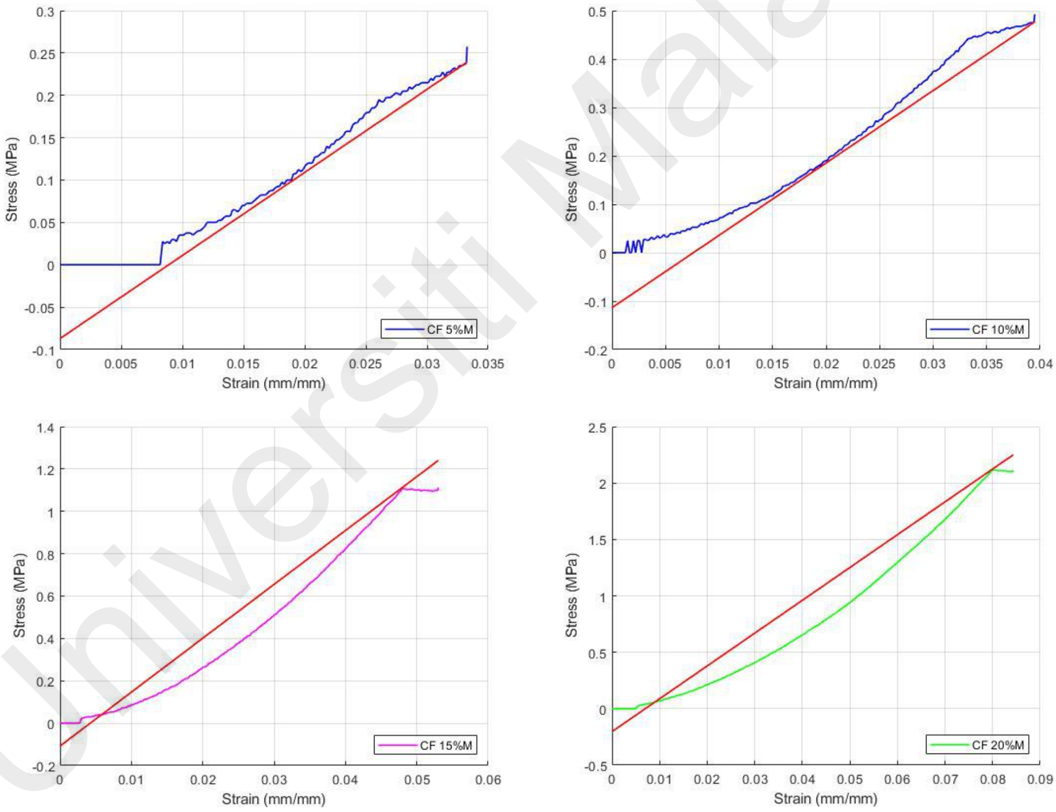


Figure 4.3 The strain-stress graphs of samples with 5%, 10%, 15% and 20% carbon fibre in the middle

Table 4.1 Yield properties of Onyx-Carbon fiber composites when CF in the middle

Samples	Yield Strength (MPa)	Yield Modulus (MPa)	Strain (mm/mm)
CF 0%	1.375	6.951	0.2172
CF 5% M	0.2375	9.807	0.03204
CF 10% M	0.4425	14.95	0.03942
CF 15% M	1.107	25.44	0.04789
CF 20% M	2.118	29.09	0.07996

At last, the comparison among the specimens containing 0%, 5%, 10%, 15% and 20% carbon fibre in the middle are done. From the graph, we can see that the yield strength of the sample containing 20% carbon fiber in the middle (CF 20% M) is biggest, and sort them from the largest one to the smallest one are 0% (CF 0%), 15% (CF 15%M), 10% (CF 10% M), 5% (CF 5% M). It shows that only CF 20% M is effective in improving the yield strength compared to pure Onyx. Other carbon fiber-embedded composites do not show better performance. As for the yield modulus of testing samples, it rises with the increase of composition of carbon fibre.

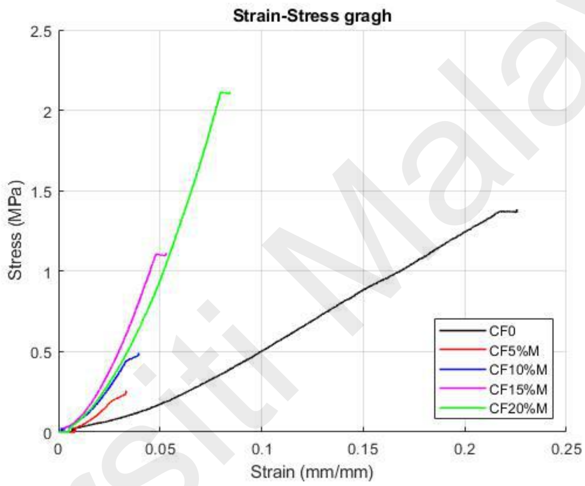
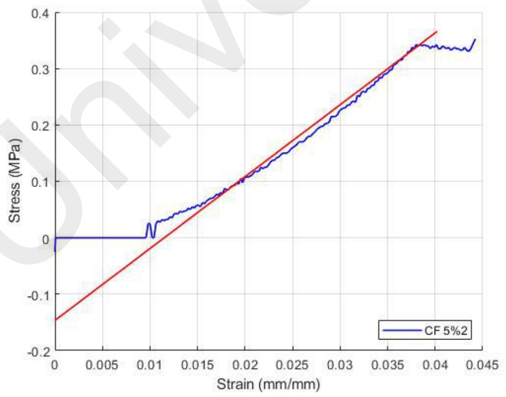
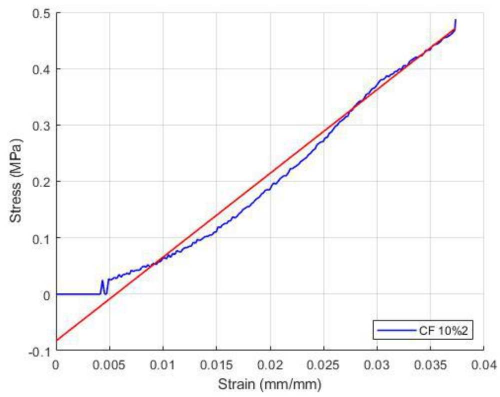


Figure 4.4 The comparison among specimens in which the carbon fiber layers in the middle





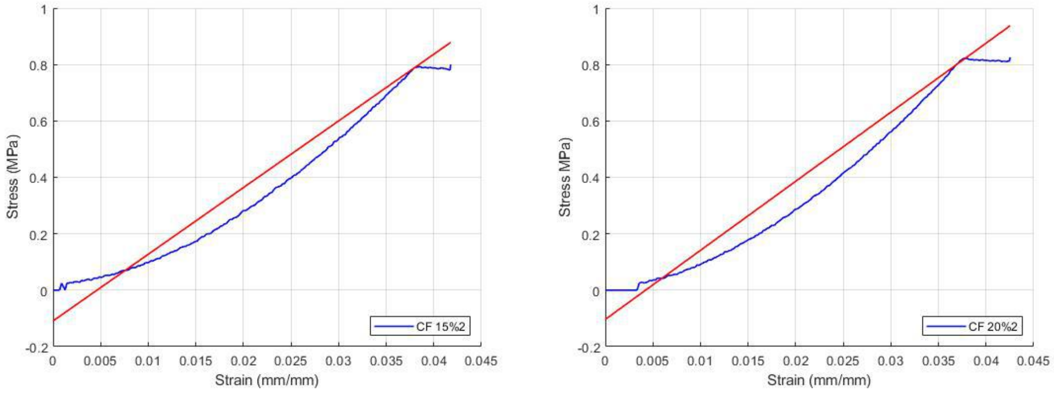


Figure 4.5 The strain-stress graphs of samples with 5%, 10%, 15% and 20% carbon fibre at the both ends

Table 4.2 Yield properties of Onyx-Carbon fiber composites when CF at the both ends

Samples	Yield Strength (MPa)	Yield Modulus (MPa)	Strain (mm/mm)
CF 0%	1.375	6.951	0.2172
CF 5% 2	0.3425	12.74	0.0384
CF 10% 2	0.4675	14.85	0.03733
CF 15% 2	0.79	23.64	0.03784
CF 20% 2	0.8225	24.48	0.03764

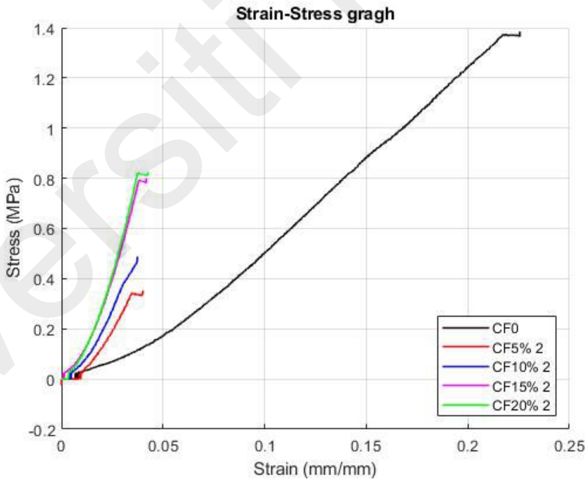


Figure 4.6 The comparison among specimens where the carbon fiber layers at the both ends

In the same way, the comparison among the specimens containing 0%, 5%, 10%, 15% and 20% carbon fibre at the both ends are shown in Figure 4.6. From the graph, we can see that the yield point of the pure Onyx (CF 0%) is the greatest, and sort them from the largest one to the smallest one are 20% (CF 20% 2), 15% (CF 15% 2), 10% (CF 10% 2), 5% (CF 5% 2). It shows that all the CF-reinforced composites in which the carbon fibers laid at the both ends of structure can not optimize the yield strength actually.

However, the value of yield modulus increases with the increase of carbon fibre.

From Fig 4.7, it shows the difference between two different distributions of carbon fiber layers in composites. The composites in which the CF layers were printed in the middle present better performance in yield strength than those at both ends when the components of carbon fiber are 15% and 20%. Otherwise, another two (5% and 10%) compositions show more advantages when the CF layers were set at both ends of specimens. Therefore, when considering Young's modulus and yield strength, the optimum selection is composite with 20% carbon fibre which is distributed in the middle.

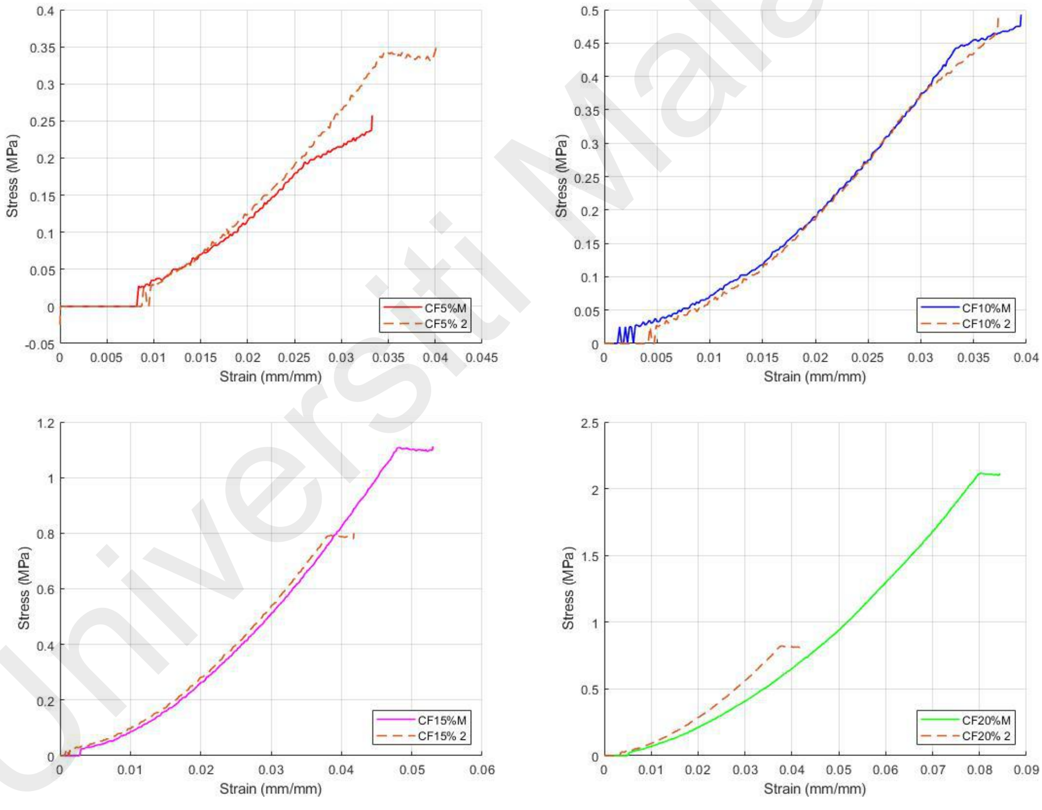


Figure 4.7 Comparison between two different distribution of CF layers

After the analysis of the initial experiment results, the next step is to prepare some new samples and redo the tensile testing to verify that the 20% CF distributed in the middle of the samples can truly improve the yield point and yield modulus effectively. Therefore, we print five 20% CF M (20% CF distributed in the middle) samples and five 0% CF (only pure Onyx) samples. However, we changed the speed of the machine to 5 mm/min this time, because the speed last time was a little high. The results from the second test are shown below.

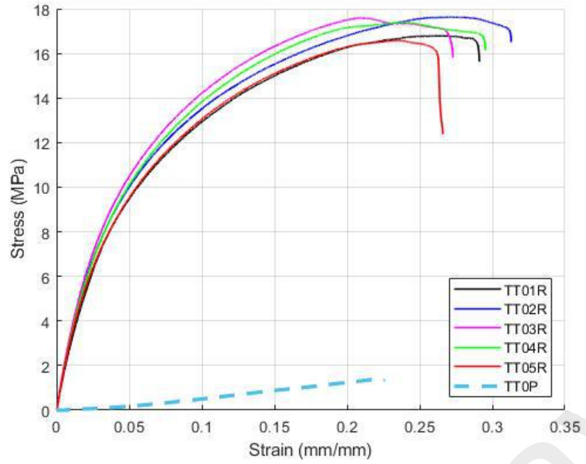


Figure 4.8 The strain-stress graph of pure Onyx

Table 4.3 The 2nd yield property results of Pure Onyx

Samples	Yield Strength (MPa)	Yield Modulus (MPa)	Strain (mm/mm)	Mean Value of strength/modulus/strain
Onyx 1	8.073	303.3	0.03675	
Onyx 2	8.392	285.3	0.0345	8.069MPa/
Onyx 3	8.430	302.8	0.033	287.04MPa/
Onyx 4	8.544	282.6	0.037	0.03425
Onyx 5	6.909	261.2	0.03	

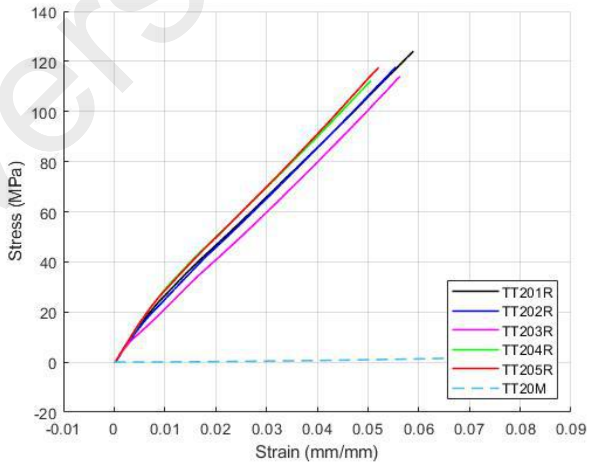


Figure 4.9 The strain-stress curve of 20% carbon fiber which in the middle

Table 4.4 The 2nd yield property results of 20% carbon fiber which in the middle

Samples	Yield Strength (MPa)	Yield Modulus (GPa)	Strain (mm/mm)	Mean Value of strength/modulus/strain
CF 20% 1	124.1	2.023	0.05897	
CF 20% 2	117.8	2.052	0.05544	117.1MPa/
CF 20% 3	114.0	1.978	0.05632	2.065GPa/
CF 20% 4	112.0	2.117	0.05059	0.05468 mm/mm
CF 20% 5	117.6	2.156	0.05206	

From them, we can see that the composite with 20% CF printed in the middle (yield strength is 117.1MPa and Young's modulus is 2.065GPa) shows significant advantages in yield strength and Young's modulus than pure Onyx (yield strength is 8.069MPa and Young's modulus is 287.04MPa). In this case, we can produce some parts in foot prosthesis which will be mainly subjected to tension force by using the materials with 80% Onyx and 20% carbon fibre, and the carbon fibre should be printed in the middle.

4.1.3 Discussion

From the tensile tests, we can get the conclusion about whether the carbon fibre in the composition can be beneficial and useful, and if it is useful, how much carbon fibre can be effective compared to pure Onyx. In addition, it is more convenient for us to design the next step to further the research.

Through discussion, the structure of samples in *Part 2* (when the carbon fiber layers are at both ends) is considered as the most vital factor which can affect the testing results. Its outermost part is 4-layer plastic, then the carbon fibre printed inside, in the middle one is pure Onyx. In this case, even though CF are embedded into the composite, the outermost section can be firstly broken which can not be conducive to the overall structure. By contrast, the *Middle* distribution is that the thick plastic is printed in the outermost and the middle one is completely carbon fibre, so these two parts can both be strong enough to resist tensile force.

4.2 Compression test

4.2.1 Data processing

The way of processing the results from compression testing is the same as tensile tests. We process numerous data from compression tests and draw the diagrams assisted with MATLAB. The results are presented below.

4.2.2 Data analysis

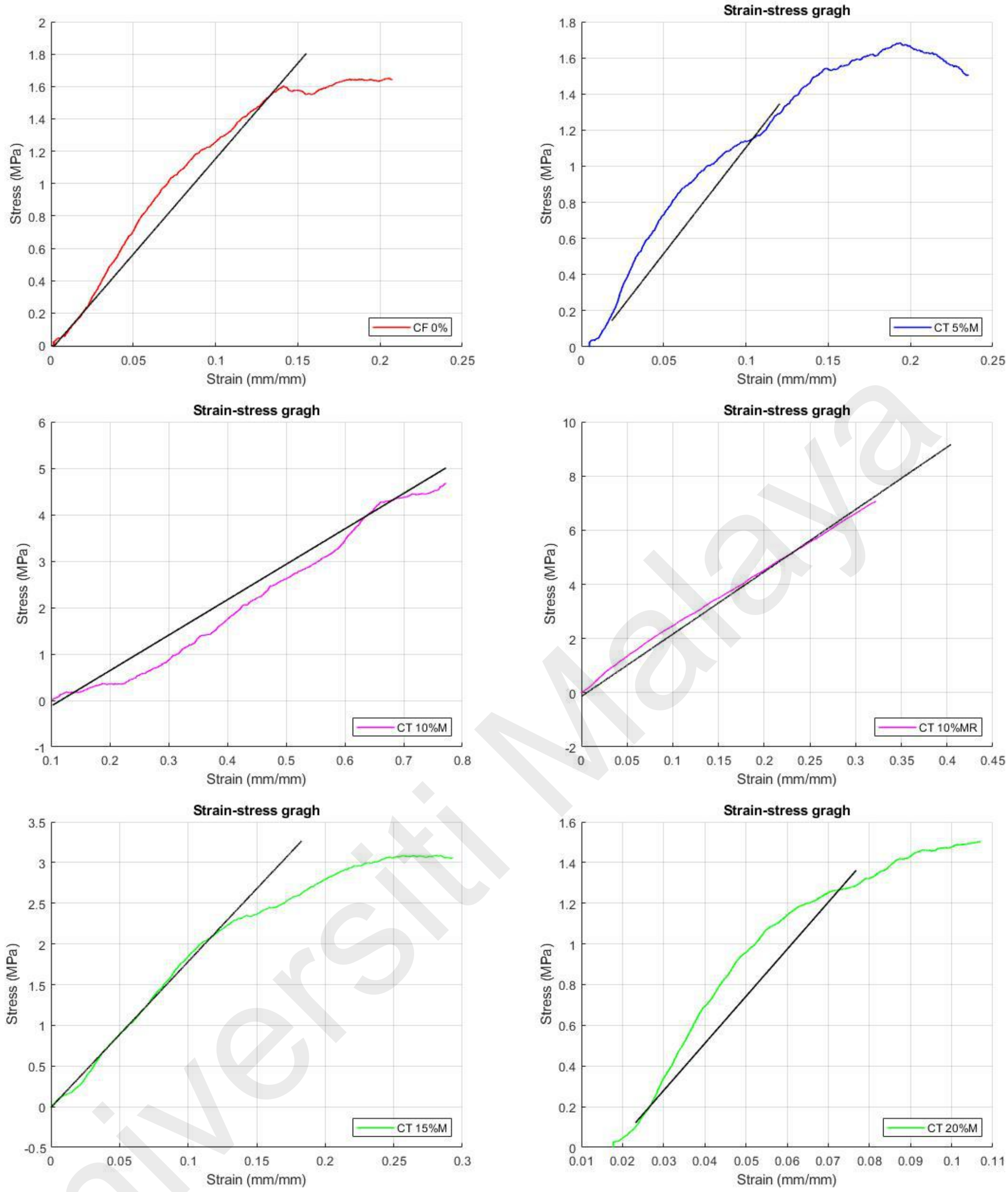


Figure 4.10 The strain-stress graphs of samples with 0%, 5%, 10%, 10%R, 15% and 20% carbon fibre in the middle

Table 4.5 Compression property result of Onyx-CF composites when CF in the middle

Samples	Yield Strength (MPa)	Yield Modulus (MPa)	Strain (mm/mm)
CF 0%	1.534	11.8	01323
CF 5% M	1.157	11.76	0.1045
CF 10% M	4.017	7.633	0.6424
CF 10% MR	5.030	23.00	0.2247
CF 15% M	2.093	17.92	0.1174
CF 20% M	1.269	23.13	0.0724

At last, the comparison among the specimens containing 0%, 5%, 10%, 15% and 20% carbon fibre in the middle are done. From the Figure 4.10 and Table 4.5, the strength of the sample containing 10% carbon fiber in the middle (CF 10% M) shows the best result, and sort them from the largest one to the smallest one are 15% (CF 15% M), 0% (CF 0%), 20% (CF 20% M), 5% (CF 5% M). It shows that only CF 10% M and CF 15% M are effective on improving the strength compared to pure Onyx. Other carbon fiber-embedded composites are not helpful in performance improvement.

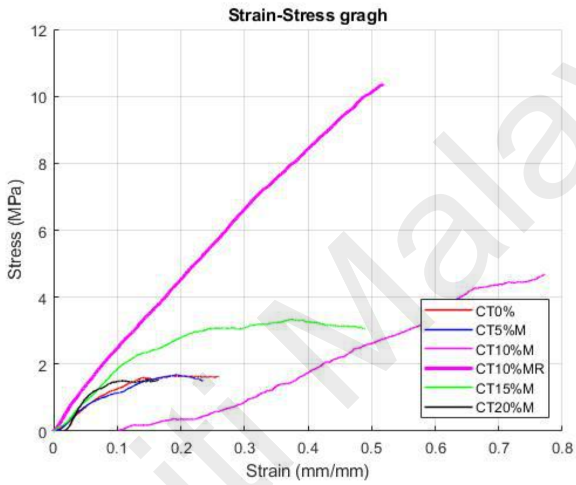
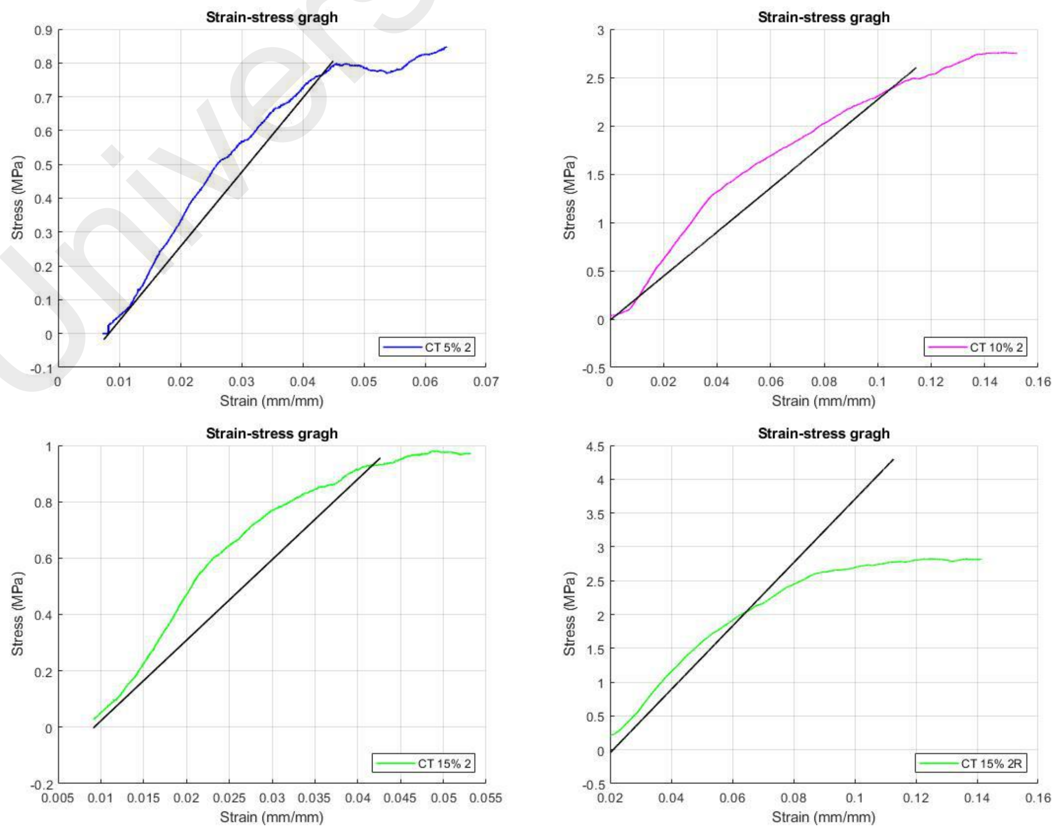


Figure 4.11 The comparison among specimens in which the CF layers in the middle



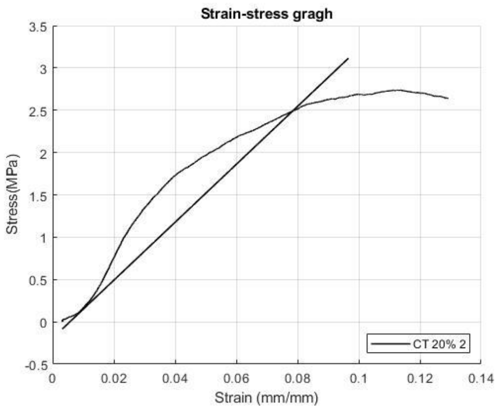


Figure 4.12 The strain-stress graphs of samples with 5%, 10%, 15%, 15%R and 20% CF at the both ends

In the same way, the comparison among the specimens containing 0%, 5%, 10%, 15% and 20% carbon fibre at the both ends are shown in Figure 4.12. From the graph, the strength of the samples containing 20% carbon fibre at the both ends (CF 20% 2) shows the greatest value, and sort them from the largest one to the smallest one are 10% (CF 10% 2), 0% (CF 0%), 15% (CF 15% 2), 5% (CF 5% 2). It shows that only CF 20% 2 and CF 10% 2 are effective in improving the strength compared to pure Onyx. Other carbon fiber-embedded composites do not show any benefits in performance of specimens.

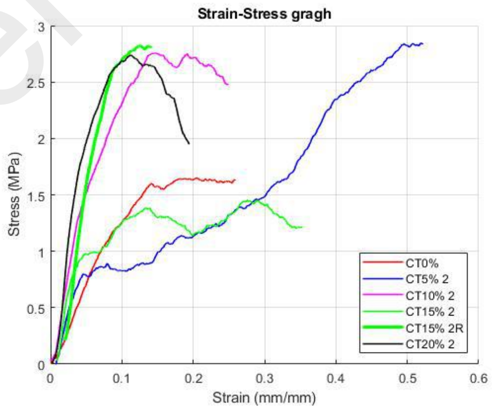


Figure 4.13 The comparison among specimens where the CF layers at the both ends

Table 4.6 Yield property result of Onyx-CF composites when CF at the both ends

Samples	Yield Strength (MPa)	Yield Modulus (MPa)	Strain (mm/mm)
CF 0%	1.534	11.8	0.1323
CF 5% 2	0.7664	21.967	0.0432
CF 10%2	2.384	22.83	0.105
CF 15% 2	0.9309	28.58	0.04178
CF 15% 2R	2.039	46.83	0.06454

CF 20% 2	2.498	34.23	0.07864

From Fig 4.14, it shows that the difference between two distribution ways of carbon fiber layers in composites. Apart from CF 20% 2, other composites present better performance in strength than those at both ends. In conclusion, the specimen with 10% carbon fibre in the middle performs best in yield strength and Young’s modulus. We redo two tests with two samples to verify this result, one is 10% CF M (composite with 10% CF in the middle) and another one is 15% CF 2 (composite with 15% CF at the both ends). Finally, we found that 10% CF M truly performs the best characteristic in the compression test.

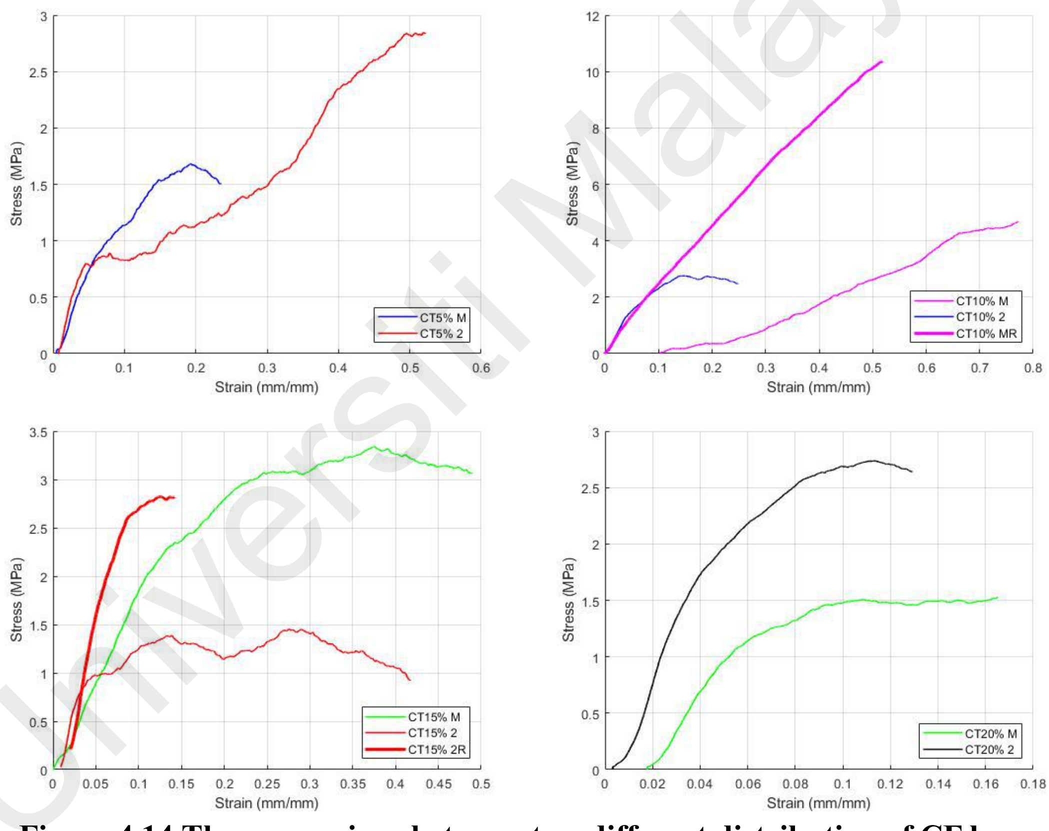


Figure 4.14 The comparison between two different distribution of CF layers

4.2.3 Discussion

Compression force is the most common one in the application of foot prosthesis, nearly each part in the foot prosthetic device can be subjected to compression load. However, in daily life we normally see the compression load in multi-direction instead of only one direction. So there are still some limitations in our tests. After the whole prosthesis is produced, the researchers will do other kinds of experiments to test it or use simulation software to obtain some more accurate and comprehensive information.

4.3 3-point bending test

4.3.1 Data processing

In the 3-point bending test, the stress of rectangular samples can be calculated by the equation below:

$$\delta = \frac{3FL}{2wh^2}$$

F: the force at the fracture point, unit: N

L: the length of the support span, unit: m

w: the width of the rectangular samples, unit: m

h: the height (thickness) of the rectangular samples, unit: m

The flexural strain :

$$\varepsilon_{bend} = \frac{6dh}{L^2}$$

$\boldsymbol{\varepsilon_{bend}}$: the flexural strain of the samples, mm/mm

L: the length of the support span, unit: mm

h: the height (thickness) of the rectangular samples, unit: mm

d: the deflection, unit:mm

Furthermore, the $\boldsymbol{E_{bend}}$ can be estimated from the force-displacement curve using the equation above. The same way as above can also be used, obtaining the yield point from the Strain-Stress graph through drawing a straight line with the same slope as the linear area.

$$E_{bend} = \frac{L^3 F}{4wh^3 d}$$

$\mathbf{E_{bend}}$: the flexural modulus or bending modulus, unit: GPa

F: the force at the fracture point, unit: N

L: the length of the support span, unit: m

w: the width of the rectangular samples, unit:m

h: the height (thickness) of the rectangular samples, unit:m

d: the deflection, unit:m

4.3.2 Data analysis

The huge number of data are gotten from the sensor and computer, we still utilize the MATLAB to process raw data. The results are presented below:

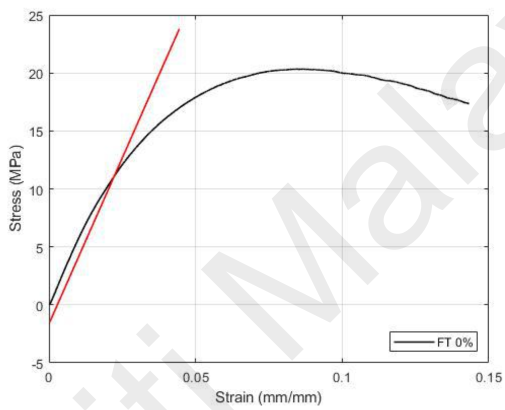


Figure 4.15 The strain-stress graph of pure Onyx in 3-point bending test

Fig 4.15 shows the results of a pure Onyx sample in 3-point bending test. From the graph, we can know that the Onyx is a kind of ductile material. Through the "basic fitting" of this function in MATLAB, the slope of the straight line in the linear region can be drawn(red line). Then move the straight line to the right (distance is 0.2% of the strain-axis range), the intersection point of the curve and the straight line can be obtained. This intersection point is the Yield Point. Using the same way to calculate other results. (Fig 4.16 and Table 4.7).

As Fig 4.16, 4.17 and Table 4.7 shown, the flexural strength and modulus of samples whose CF is printed in the middle increase gradually as the component of carbon fiber increases. It indicates that the CF in specimens can improve the mechanical performance in 3-point bending tests. The best design is that composite with 20% CF when carbon fibre is printed in the middle. For other testing samples whose CF is printed at the both ends of the whole structure, they show the same mechanical behaviors in the bending test (Fig 4.18, Fig 4.19 and Table 4.8). We conclude that composite with 20% CF printed at both ends shows the best performance in the bending test.

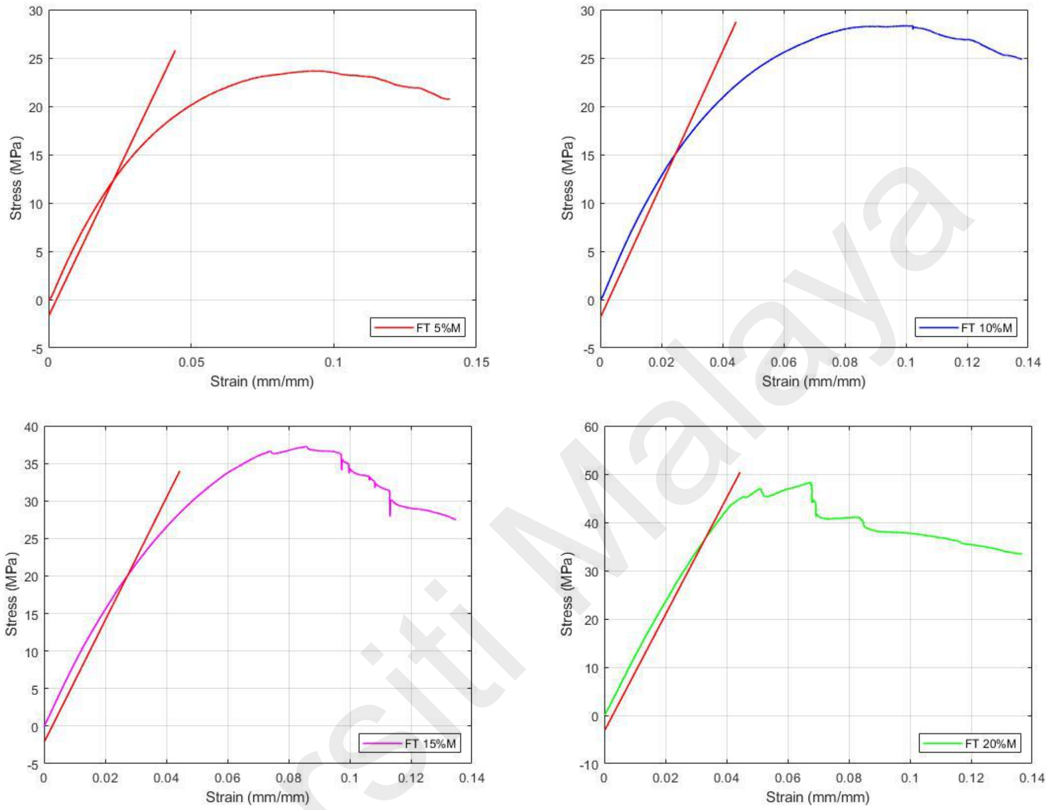


Figure 4.16 The strain-stress graphs of samples with 5%, 10%, 15% and 20% CF in the middle

Table 4.7 Flexural property result of Onyx-CF composites when CF in the middle

Samples	Flexural Strength (MPa)	Flexural Modulus (MPa)	Strain (mm/mm)
CF 0%	11.13	572.2	0.02231
CF 5%M	12.40	619.4	0.02284
CF 10%M	15.28	689.3	0.02433
CF 15%M	20.16	814.3	0.02746
CF 20%M	36.75	1208.0	0.03315

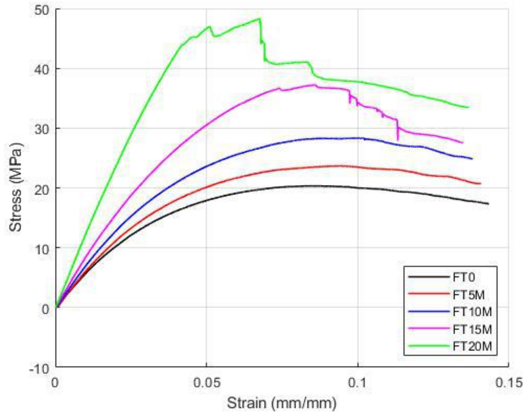


Figure 4.17 The comparison among samples with 0%, 5%, 10%, 15% and 20% CF in the middle

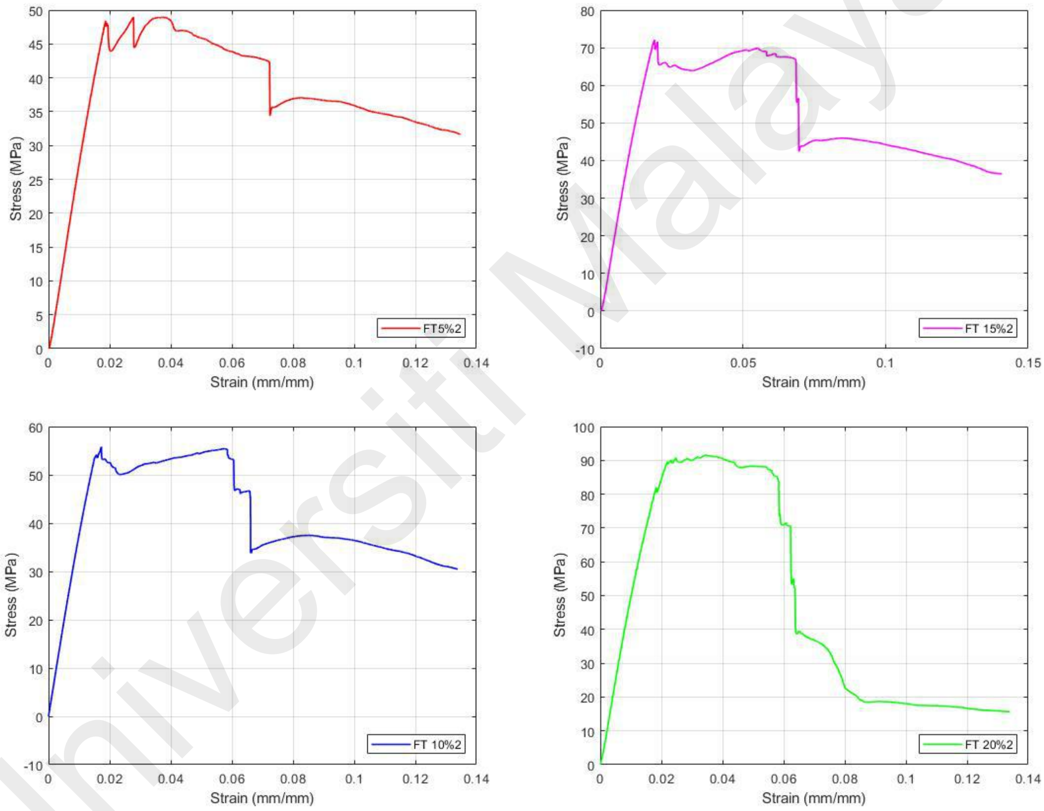


Figure 4.18 The stain-stress graphs of samples with 5%, 10%, 15% and 20% carbon fibre at the both ends

Table 4.8 Flexural property result of Onyx-CF composites when CF at the both ends

Samples	Flexural Strength (MPa)	Flexural Modulus (MPa)	Strain (mm/mm)
CF 0%	11.13	572.2	0.02231
CF 5% 2	48.42	2591.52	0.01869
CF 10%2	53.67	3514.677	0.01521
CF 15% 2	71.92	3796.628	0.01692
CF 20% 2	81.68	4463.547	0.01818

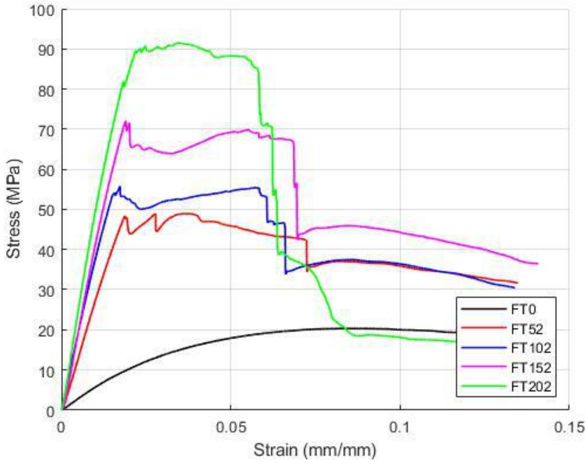


Figure 4.19 The comparison among samples with 0%, 5%, 10%, 15% and 20% CF at the both ends

The results above (green curve is CF 20% 2, purple is CF 15% 2, blue is CF 10% 2, red is CF 5% 2, black is CF 0%) indicate that CF can be beneficial for the mechanical characteristics in bending tests. The next step is continuing to analyze how the two different ways of CF distribution influence the behavior of testing samples. Therefore, inputting the experimental data of two samples with the same content of CF (for example 5% M and 5% 2) into the MATLAB and drawing the curve lines. The comparison results from four groups are displayed below (Fig 4.20).

In Fig 4.20, the blue line presents the characteristics of samples whose CF distributed at the both ends, and the red one means CF in the middle. From the comparison results of four groups (5% CF, 10% CF, 15% CF, 20% CF), the specimens whose CF added at the both ends show a more excellent performance, both in flexural strength and modulus. The blue curve, the region from start point to the yield point can be completely regarded as a straight line, which means that in this period the samples show the property of brittle materials. By contrast, the red line displays the characteristics of ductile materials. In conclusion, the specimen with 20% CF embedded at the both ends performs best in 3-point bending test. We discussed that when carbon fibre is distributed at the both ends of the whole structure, the carbon fibre will break firstly, followed by the Onyx which is in the middle. On the contrary, when carbon fibre is printed in the middle, Onyx at the both ends will break at first. The strength and modulus of carbon fibre is greatly better than pure Onyx, so as presented in Fig 4.20 the blue line(CF at the both ends) is superior to the red line(CF in the middle).

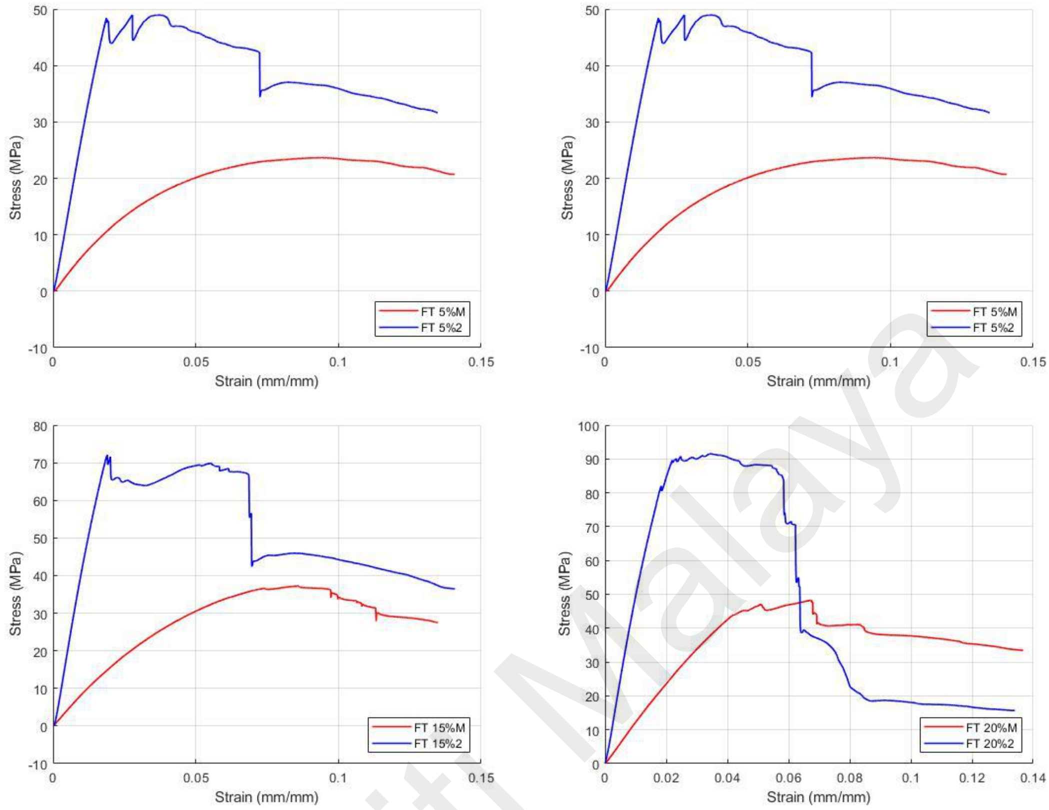


Figure 4.20 The comparison between two samples with different CF distribution

4.3.3 Discussion

In this project, we mainly study how the component and distribution of carbon fiber affect the characteristics of Onyx-CF composite. In fact, there are many other factors which can influence its performance as well. Even though 3-D printing technology is low-cost, and highly efficient and it can also meet customer-specific requirements, there are some unknown effects caused by 3-D printers which need to be studied in the future. For example, whether and how the printer can affect the micro-structure of carbon fibre and Onyx? Whether the material produced by the 3-D printer company can be modified to suit a particular individual or task? The material we used is directly from the printer company, so we can hardly change its micro-structure. But we can compare the performance of testing samples with the same design but different manufacturing methods to study whether 3-D printers are harmful to samples in the future.

CHAPTER 5: CONCLUSION

In this project, the main aim is to study how the CF affects the mechanical characteristics of different parts in BioApps RoMicP® foot prosthesis. Then according to the kinds of forces each part withstands, to optimize their performance. The materials we used involved Onyx and CF, we studied how the component and distribution way of carbon fiber affect the performance of specimens in three different tests, tensile test, compression test and 3-point bending test.

As a result, in the tensile test, the testing sample with 80% Onyx and 20% carbon fiber embedded in the middle showed the most excellent performance, its yield strength is 117.1 MPa and yield modulus is 2.065 GPa. In compression test, the specimen with 90% Onyx and 10% carbon fiber printed in the middle performed best, its yield strength is 5.03 MPa and yield modulus is 23.0 MPa. In 3-point bending test, the results of specimen with 80% Onyx and 20% carbon fiber distributed at the both ends was best, its flexural strength is 81.68 MPa and flexural modulus is 4.464 GPa. This conclusion can be beneficial to produce better foot prosthesis. Like the part 3 in the Fig 3.1, they are mainly subjected to bending force when the user is equipped with this device. So when we print these two parts we'd better select 80% Onyx and 20% carbon fiber as the raw material and the carbon fiber should be printed at the both ends of part.

There are some limitations in this project. Firstly, we only study the macro-structure of composite material, and we did not consider the influence of 3-D printing technique when we aim to optimize the performance of material. Therefore, in future research we should combine micro- and macro-structure to improve the material. Secondly, we only use the 3-D printing technique and believe it will not damage the material. We need to study whether the 3-D printing method has a negative effect on the structure and characteristics of carbon fiber later. Finally, we only test each part in foot prosthesis instead of the complete one. So we need to do the next mechanical experiment using whole foot prosthesis to test whether the performance is improved and how much it improves.

REFERENCES

Akpan, E. I. (2019a). Carbonization, Activation and Graphitization of Lignin-Based Materials. In E. I. Akpan & S. O. Adeosun (Eds.), *Sustainable Lignin for Carbon Fibers: Principles, Techniques, and Applications* (pp. 353-394). Cham: Springer International Publishing.

Akpan, E. I. (2019b). Melt-Processing of Lignin. In E. I. Akpan & S. O. Adeosun (Eds.), *Sustainable Lignin for Carbon Fibers: Principles, Techniques, and Applications* (pp. 281-324). Cham: Springer International Publishing.

Alam, M., Choudhury, I. A., Mamat, A. B., & Hussain, S. (2015). COMPUTER AIDED DESIGN AND FABRICATION OF A CUSTOM ARTICULATED ANKLE FOOT ORTHOSIS. *Journal of Mechanics in Medicine and Biology, 15*(04), 1550058. doi:10.1142/S021951941550058X

Bacon, R. (1960). Growth, Structure, and Properties of Graphite Whiskers. *Journal of Applied Physics, 31*(2), 283-290. doi:10.1063/1.1735559

Bárnik, F., Vaško, M., Handrik, M., Dorčiak, F., & Majko, J. (2019). Comparing mechanical properties of composites structures on Onyx base with different density and shape of fill. *Transportation Research Procedia, 40*, 616-622. doi:https://doi.org/10.1016/j.trpro.2019.07.088

Blok, L. G., Longana, M. L., Yu, H., & Woods, B. K. S. (2018). An investigation into 3D printing of fibre reinforced thermoplastic composites. *Additive Manufacturing, 22*, 176-186. doi:https://doi.org/10.1016/j.addma.2018.04.039

Castle, J. E. (1984). Practical surface analysis by Auger and X-ray photoelectron spectroscopy. D. Briggs and M. P. Seah (Editors). John Wiley and Sons Ltd, Chichester, 1983, 533 pp., £44.50. *Surface and Interface Analysis, 6*(6), 302-302. doi:10.1002/sia.740060611

Chaurasia, A., Sahoo, N. G., Wang, M., He, C., & Mogal, V. T. (2013). Fundamentals of Polymers and Polymer Composite. In A. Nee (Ed.), *Handbook of Manufacturing Engineering and Technology* (pp. 1-33). London: Springer London.

Christel, P. (1985). Potential Applications of Carbon-Carbon Composite Materials for Total Joint Replacement. In S. M. Perren & E. Schneider (Eds.), *Biomechanics: Current Interdisciplinary Research: Selected proceedings of the Fourth Meeting of the European Society of Biomechanics in collaboration with the European Society of Biomaterials, September 24–26, 1984, Davos, Switzerland* (pp. 61-72). Dordrecht: Springer Netherlands.

Christel, P., Meunier, A., Leclercq, S., Bouquet, P., & Buttazzoni, B. (1987). Development of a carbon-carbon hip prosthesis. *Journal of biomedical materials research, 21*(A2 Suppl), 191-218.

Chung, D. D. L. (2017). Processing-structure-property relationships of continuous carbon fiber polymer-matrix composites. *Materials Science and Engineering: R: Reports, 113*, 1-29. doi:https://doi.org/10.1016/j.mser.2017.01.002

Cococcetta, N. M., Pearl, D., Jahan, M. P., & Ma, J. (2020). Investigating surface finish, burr formation, and tool wear during machining of 3D printed carbon fiber reinforced polymer composite. *Journal of Manufacturing Processes*. doi:https://doi.org/10.1016/j.jmapro.2020.04.025

Cummings, D. (1996). Prosthetics in the developing world: A review of the literature. *Prosthetics and Orthotics International, 20*(1), 51-60. doi:10.3109/03093649609164416

Dantas, F., & Gibbons, G. (2020). *Mechanical Performance of Long-fibre Reinforced Polymer Composites by 3D Printing*.

Diaz, A., Guizar-Sicairos, M., Poeppel, A., Menzel, A., & Bunk, O. (2014). Characterization of carbon fibers using X-ray phase nanotomography. *Carbon, 67*, 98-103. doi:https://doi.org/10.1016/j.carbon.2013.09.066

Dorčiak, F., Vaško, M., Handrik, M., Bárnik, F., & Majko, J. (2019). Tensile test for specimen with different size and shape of inner structures created by 3D printing. *Transportation Research Procedia, 40*, 671-677. doi:https://doi.org/10.1016/j.trpro.2019.07.095

Eberhart, J. P. (1991). *Structural and chemical analysis of materials : X-ray, electron and neutron diffraction ; X-ray, electron and ion spectrometry ; electron microscopy*. Chichester, West Sussex, England; New York: Wiley.

Fitzer, E. (1990). Carbon Fibres — Present State and Future Expectations. In J. L. Figueiredo, C. A. Bernardo, R. T. K. Baker, & K. J. Hüttinger (Eds.), *Carbon Fibers Filaments and Composites* (pp. 3-41). Dordrecht: Springer Netherlands.

Foster, A. L., Moriarty, T. F., Zalavras, C., Morgenstern, M., Jaiprakash, A., Crawford, R., . . . Metsemakers, W.-J. (2020). The influence of biomechanical stability on bone healing and fracture-related infection: the legacy of Stephan Perren. *Injury*. doi:https://doi.org/10.1016/j.injury.2020.06.044

Frank, E., Hermanutz, F., & Buchmeiser, M. R. (2012). Carbon Fibers: Precursors, Manufacturing, and Properties. *Macromolecular Materials and Engineering, 297*(6), 493-501. doi:10.1002/mame.201100406

Garcia-Gonzalez, D., Rodriguez-Millan, M., Rusinek, A., & Arias, A. (2015). Investigation of mechanical impact behavior of short carbon-fiber-reinforced PEEK composites. *Composite Structures, 133*, 1116-1126. doi:https://doi.org/10.1016/j.compstruct.2015.08.028

Ghebretinsae, F., Mikkelsen, O., & Akessa, A. D. (2019). Strength analysis of 3D printed carbon fibre reinforced thermoplastic using experimental and numerical methods. *IOP Conference Series: Materials Science and Engineering, 700*, 012024. doi:10.1088/1757-899x/700/1/012024

Jensen, J. S., & Raab, W. (2007). Clinical Field Testing of Vulcanized Jaipur Rubber Feet for Trans-Tibial Amputees in Low-Income Countries. *Prosthetics and Orthotics International, 31*(1), 105-115. doi:10.1080/03093640701321411

Jensen, J. S., & Treichl, H. B. (2007). Mechanical testing of prosthetic feet utilized in low-income countries according to ISO-10328 standard. *Prosthetics and Orthotics International, 31*(2), 177-206. doi:10.1080/03093640701210986

Kang, K.-T., Koh, Y.-G., Son, J., Yeom, J. S., Park, J.-H., & Kim, H.-J. (2017). Biomechanical evaluation of pedicle screw fixation system in spinal adjacent levels using polyetheretherketone, carbon-fiber-reinforced polyetheretherketone, and traditional titanium as rod materials. *Composites Part B: Engineering, 130*, 248-256. doi:https://doi.org/10.1016/j.compositesb.2017.07.052

Koh, Y.-G., Park, K.-M., Lee, J.-A., Nam, J.-H., Lee, H.-Y., & Kang, K.-T. (2019). Total knee arthroplasty application of polyetheretherketone and carbon-fiber-reinforced polyetheretherketone: A review. *Materials Science and Engineering: C, 100*, 70-81. doi:https://doi.org/10.1016/j.msec.2019.02.082

Malquarti, G., Berruet, R. G., & Bois, D. (1990). Prosthetic use of carbon fiber-reinforced epoxy resin for esthetic crowns and fixed partial dentures. *The Journal of Prosthetic Dentistry, 63*(3), 251-257. doi:https://doi.org/10.1016/0022-3913(90)90190-N

Markforged. (2019). *Composites Design Guide_V1*. Retrieved from

. Mechanical Work, Energy, and Power. (2009). In *Biomechanics and Motor Control of Human Movement* (pp. 139-175).

Morales, M. S., & Ogale, A. A. (2013). UV-induced crosslinking and cyclization of solution-cast polyacrylonitrile copolymer. *Journal of Applied Polymer Science, 128*(3), 2081-2088. doi:10.1002/app.38398

Noroozi, S., Sewell, P., Rahman, A., Vinney, J., Chao, O., & Dyer, B. (2013). Modal analysis of composite prosthetic energy-storing-and-returning feet: An initial investigation. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 227*, 39-48. doi:10.1177/1754337112439274

Oleiwi, H. A. N. a. J. K. (2015). Improving Tensile Strength of Polymer Blends as Prosthetic Foot Material Reinforcement by Carbon Fiber. *Journal of Material Science & Engineering, 04*(02). doi:10.4172/2169-0022.1000158

Park, S.-J., & Heo, G.-Y. (2015). Precursors and Manufacturing of Carbon Fibers. In S.-J. Park (Ed.), *Carbon Fibers* (pp. 31-66). Dordrecht: Springer Netherlands.

Park, S.-J., & Lee, S.-Y. (2015). History and Structure of Carbon Fibers. In S.-J. Park (Ed.), *Carbon Fibers* (pp. 1-30). Dordrecht: Springer Netherlands.

Purushothaman, G. (2016). Myoelectric control of prosthetic hands: State-of-the-art review. *Medical Devices: Evidence and Research, Volume 9*, 247-255. doi:10.2147/MDER.S91102

Qiao, W. M., Song, Y., Yoon, S. H., Korai, Y., Mochida, I., Yoshiga, S., . . . Yamazaki, A. (2006). Carbonization of waste PVC to develop porous carbon material without further activation. *Waste Management, 26*(6), 592-598. doi:https://doi.org/10.1016/j.wasman.2005.06.010

Salernitano, E., & Migliaresi, C. (2003). Composite Materials for Biomedical Applications: A Review. *Journal of Applied Biomaterials and Biomechanics, 1*(1), 3-18. doi:10.1177/228080000300100102

Stamopoulos, A., Tserpes, K. I., Prucha, P., & Vavrik, D. (2015). Evaluation of porosity effects on the mechanical properties of carbon fiber-reinforced plastic unidirectional laminates by X-ray computed tomography and mechanical testing. *Journal of Composite Materials, 50*. doi:10.1177/0021998315602049

Stark, G. (2005). Perspectives on How and Why Feet are Prescribed. *JPO: Journal of Prosthetics and Orthotics, 17*(4).

Steen Jensen, J., Nilsen, R., Zeffer, J., Fisk, J., & Hartz, C. (2006). Clinical field testing of vulcanized rubber feet for trans-tibial amputees in tropical low-income countries. *Prosthetics and Orthotics International, 30*(2), 195-212. doi:10.1080/03093640600794692

Tan, S. C. (1992). Stress analysis and the testing of Celanese and IITRI compression specimens. *Composites Science and Technology, 44*(1), 57-70. doi:https://doi.org/10.1016/0266-3538(92)90025-X

Winter, D. A., & Sienko, S. E. (1988). Biomechanics of below-knee amputee gait. *Journal of Biomechanics, 21*(5), 361-367. doi:https://doi.org/10.1016/0021-9290(88)90142-X