

Strength modelling of composite filament fabricated materials using classical laminate theory

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The fear of the Lord is the beginning of wisdom, and the knowledge of the Holy One is understanding.

Proverbs 9:10

ABSTRACT

Additive manufacturing (AM) describes a manufacturing technique that builds 3-dimensional objects by adding layer-upon-layer of material in order to create a product. One subset of AM is 3D printing or rapid prototyping (RP), which has seen extraordinary popularity among engineers, designers and hobbyists. The most significant benefit additive manufacturing offers is the elimination of waste material. This aspect will have significant value for poorer countries as it reduces the cost. While designers have used 3D printing for some time now, it is not clear exactly how strong the printed materials are.

The manufacture of composites using 3D printing is progressing and, therefore, a strength prediction model for the composite filament fabricated materials is needed to understand how the material reacts under loads. With this knowledge, designers can analyse a component to ensure that it will withstand the specified load parameters before going into production. It will also give engineers geometrical freedom when designing. By gaining a better understanding of the fabrication of composites and by which laminate failure theory the composite will abide, the strength of the components can be predicted. Some of the advantages of using composites are that they are lightweight and extremely high strength when fibres are oriented correctly due to the anisotropic nature of fibre reinforced composites. They also do not require subtractive manufacturing processes to produce.

This dissertation focuses on predicting the strength behaviour of 3D printed composites. The material properties used in the composite are determined by a series of testing and used to develop a model to predict the individual mechanical properties of the materials in the composite and how they will react when subjected to a load.

An investigation into laminate- and ply failure theories has been conducted. Research into laminate theories is relevant since, until recently, composites have been constructed by laying fibre on top of each other or weaving them into one another and using a resin as the matrix that holds them together. With the 3D printed process, the type of composite must first be determined before the laminate theory for the composite can be identified.

Experimental testing of the composite by ASTM standards has been done and the results processed with a method called micromechanics. This analyses the materials that contribute to the composite on the level of the individual elements that constitute them. The elastic modulus of the fibre used was determined to be 20.153 GPa, which is 4.20 per cent in range with the 21.00 GPa that Markforged® claimed.

The data has then been used with the developed strength prediction model, based on the classical laminate theory to accurately predict the strength of the composite, given the fibre orientations. The software LAP[®] was then used to verify the results from the prediction model and compare them to the experimental values. With a 0° fibre orientation, composite with ten fibre layers and two nylon layers over 12.7 mm width, LAP[®] predicted a 16.477 GPa modulus of elasticity compared to the 16.870 GPa with experimental testing.

Further investigation into the micromechanics input parameters is required, including the influence of gaps between the fibres and/or the fibre and nylon. This will alter the volume fraction of the materials in the composite and ultimately lead to a more accurate prediction model. Further research is needed in the flexural behaviour of the composite and the influence of temperature on the testing and printing of the composite. Measured against the outcomes, the project has been successful.

Keywords: Additive Manufacturing, composite, prediction model, classical laminate theory

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ABREVIATIONS

AM	Additive Manufacturing
RP	Rapid Prototyping
3D	Three-Dimensional
CAD	Computer-Aided Design
CFF	Composite Filament Fabrication
CTL	Classical Laminate Theory
STL	Stereolithography
GF	Glass Fibre
UTS	Ultimate Tensile Strength
LAP	Laminate Analysis Program

NOMECLATURE

V	Volume	mm^3
H	Height	mm
W	Width	mm
T	Thickness	mm
N	Number of layers	[-]
σ	Stress	Pa
ϵ	Strain	mm/mm
E	Young's modulus	Pa
P	Phase	[-]
ν	Poisson ratio	[-]
G	Shear	Pa
kN	Kilo-Newton	[-]
°	Degree	[-]

CHAPTER 1

INTRODUCTION

This chapter provides introductory information on the strength modelling of composite filament fabricated materials. The problem statement is supplied and followed by the objectives of the study and the methodology. A concise overview of the document is also presented.

1.1 Background and motivation

The term “manufacturing” is used to describe the production of merchandise for use or sale using labour, machines, tools, chemical and biological processing or formulation. During the development stage of a new prototype, the designers or engineers consider the various tools and processes available for producing different parts. Subtractive manufacturing (SM) is the most common form of manufacturing and refers to the process by which 3-dimensional objects are constructed by successively cutting material away from a solid block of material.

Additive manufacturing (AM) describes another manufacturing technique that builds 3-dimensional objects by adding layer-upon-layer of material in order to create a product. One subset of AM is 3-dimensional printing, which has seen extraordinary popularity among engineers. 3D printing or rapid prototyping (RP) is the terms used for a manufacturing process using a computer-aided design (CAD) software to produce a component. The most significant benefit additive manufacturing offers is the elimination of waste material, which poorer countries appreciate significantly for the reduction of cost. While engineers have been using 3D printing for some time now, the strength of the printed materials is not clear. There is, therefore, a need to predict the behaviour of 3D printed materials in terms of strength.

With an increase in the use of composites, there is a demand for accurate and feasible analysis methods. There are a fair amount of laminate failure theories to predict the initiation of global failure. The appropriate theory for this dissertation must be established because of the composites used in 3D printing and differs from traditional composite methods. The use of this technology has surged in the engineering world but, unlike existing technology like SM, the material properties are unclear and the behaviour cannot be predicted. Fibre reinforced composite materials typically exhibit anisotropy, which means some properties vary depending upon which geometric axis or plane they are measured along.

The advantages of composite materials are they are light-weight, low density and offer high strength. Combining the advantages of using composites and the benefits of 3D printing can change the possibilities for engineering design and give geometrical freedom.

1.2 Problem statement

Additive manufacturing (AM) describes a manufacturing technique that builds 3-dimensional objects by adding layer-upon-layer of material in order to create a product. One subset of AM is 3D printing, and whilst designers have used 3D printing for some time now, it is not clear exactly how strong the printed materials are. The manufacture of composites using 3D printing is also progressing and, therefore, a strength prediction model for the composite filament fabricated materials is needed to understand how the material reacts under loads.

The material properties of the 3D printed composite materials must be determined before a prediction model for strength analysis of the 3D printed composites can be developed. Once the prediction model and mechanical properties are known, designers can analyse a component to ensure that it will withstand the load parameters specified before going into production. Being able to predict the behaviour of the composite will not only save the designer's time but also cut down on prototyping costs, save on labour costs and reduce electrical consumption and labour training.

1.3 Objectives

- 1) Tensile testing of nylon and fibreglass reinforced specimens to obtain relevant mechanical properties in correspondence with the classical laminate theory
- 2) Use of micromechanics to determine the mechanical properties of 3D printed fibre in a composite and mathematically predict the strength of composites with pre-defined parameters.

1.4 Scope and research methodology

To address the scope listed below, a short description of the methodology for each objective is found in the following sub-sections. Although some of the processes are iterative, only the final iteration is presented in the dissertation.

1.4.1 Literature overview

The literature investigation focuses on modelling composites in terms of the various types of failure theories for composites. The spectrum of literature considered includes additive manufacturing, material properties and strength modelling and testing standards.

After the investigation into the modelling of composites, the possible contributions of this study are identified. The literature also serves as a background to develop a strength prediction model.

1.4.2 Mechanics of fibre-reinforced composites

The printer used for this dissertation, Markforged® Mark II, uses a printing technology called composite filament fabrication (CFF). This process allows composites to be 3D printed with a unidirectional fibre, which can be printed in any orientation needed. The mechanical properties of this composite are tested for various fibre orientations to establish a better understanding of how the load is distributed throughout the composite.

1.4.3 Experimental procedure

To gain a better understanding of how the composite reacts under load, an experimental procedure is needed. The relevant testing standard for the composite is obtained and test specimens printed at predefined fibre orientations. From the experimental data, the mechanical properties are found using composite fundamentals described in the mathematical model section of this report.

1.4.4 Mathematical model

The strength of the composite must be predicted using a mathematical model, given the material's mechanical properties, layer thickness and the angle at which the layers are oriented. The model is developed by firstly examining the type of composite created by the printer to determine the failure theory by which the composite should abide. The types of composite are shown in Figure 1.

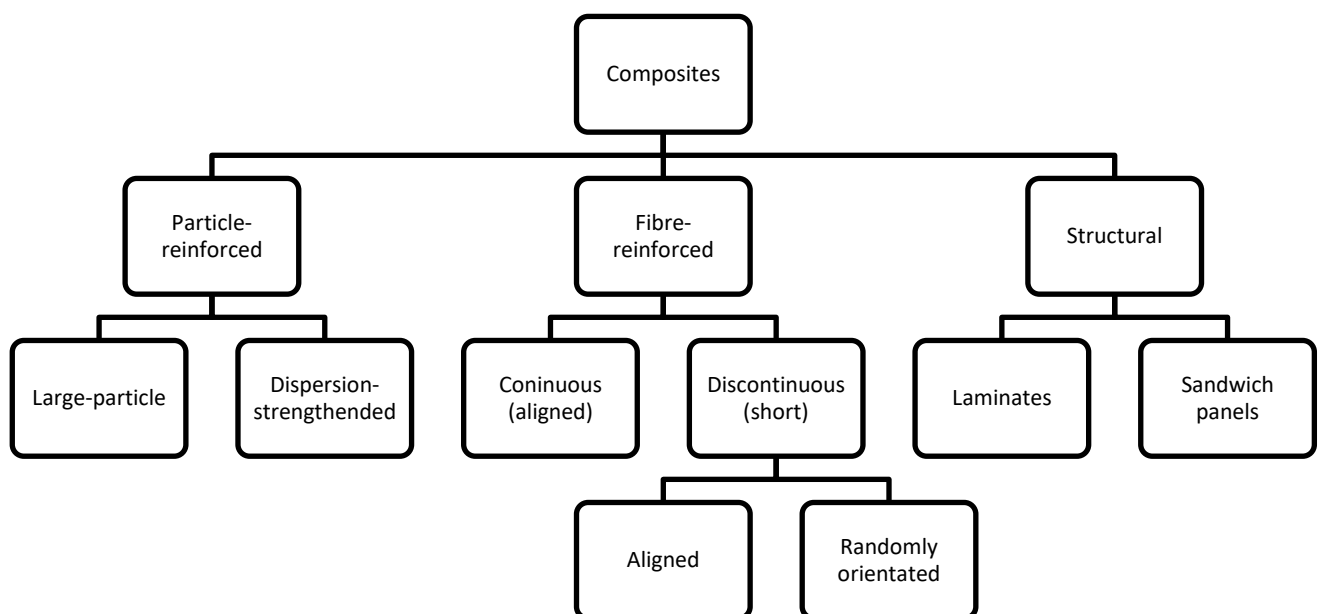


Figure 1: Types of composites

Examining the types of composites and looking at the material data sheet that Markforged® [1] supplied, it is clear that the composite is firstly fibre-reinforced with fibreglass, Kevlar or carbon fibre. Furthermore, the fibre used is continuous in nature according to Markforged® [1]. Taking all of these characteristics into account, the composite should abide by the classical laminate theory (CLT).

The model is initially developed in Matlab® using fundamentals of CLT. Laminate Analysis Program (LAP) uses the same fundamentals and is used to verify the Matlab® model.

1.4.5 Model verification

The mathematical model used to determine the strength of the composite must be verified to ensure accuracy. Various fibre orientations that do not contribute to the material's mechanical properties are selected and printed for testing. The new orientations are simulated and compared to the experimental results.

1.5 Chapter breakdown of the dissertation

Chapter 2 gives an overview of the literature applicable to, and discusses the leading technologies of additive manufacturing, material properties, composites and testing. This is done to enlighten the reader on the theory of composites and the associated technologies. The chapter describes the theory behind the mechanics of fibre-reinforced composites and includes a few necessary strength calculations, explanations of some of the composite characterisation and how the different types of fibre configurations influence the mathematical model discussed in Chapter 5.

Chapter 3 discusses the experimental procedure during testing. It focuses on the testing standards and the experimental data gathered from tensile testing. Chapter 4 includes the composite materials, the printer used, the equipment used for testing and how micromechanics is used to determine the material engineering properties of the fibre and matrix respectively.

Chapter 5 discusses the mathematical model used to predict the strength of the 3D printed composite. In this chapter, existing software is shown and used to predict the strength of the composite and the verification of the software used. Finally, chapter 7 discusses the conclusions from the results and practical experience. Appropriate recommendations are made from these conclusions.

CHAPTER 2

LITERATURE REVIEW

This chapter looks into the literature applicable to the leading technologies of additive manufacturing, composite material properties and strength modelling. This is done to understand the theory of composite filament fabrication and its mechanical properties.

2.1 Composite strength modelling design

The design for modelling composite strength must consider the following:

- Composite characteristics
- Fibre orientation constraints
- Material mechanical properties
- Rules of mixture

This literature study is an in-depth look into the four main design requirements for a composite strength model namely, the composite's characteristics, the mechanical properties of the material, the amount of fibre versus matrix and the classical laminate theory.

Fibre-reinforced composites use a polymer matrix supported by woven or aligned high-strength fibres. Manufacturing composites requires stacking multiple layers of fibres and infusing the interstitial spacing with a polymer resin. The fibres are stronger in the axial direction and weaker in the radial direction; the fibres provide anisotropy to the strength of the composite. [2]

A composite is a material system composed of a combination of two or more materials that differ in form and chemical composition and are noticeably insoluble in each other. The majority of composites consists of two phases, one is termed the matrix phase and surrounds the other phase, which is termed the dispersed phase or reinforcement phase. As the composite consists of two different materials, the mechanical property is a function of the two phases. [3] The composite mechanical properties are strongly dependent on each of the parameters mentioned above and each of the individual matrix and fibre properties and their respective volume contents. [4]

Composites are commonly used in mechanical systems where high strength is needed but weight saving is a factor. Material tests of unidirectional laminates are essential to create the necessary material data, under quasi-static and fatigue loads [5]. Till recently, composites were created with plies of woven fibre and fused with a resin.

The Markforged® composite 3D printer can print composite parts using a new technology they call composite filament fabrication (CFF). [6]

2.2 The concept of CFF and volume fractions

CFF uses thermoplastic (polymer that becomes liquid when heat is applied and solidifies when cooled) materials injected through indexing nozzles onto a platform. They are then reinforced with continuous strands of fibre embedded in the thermoplastic matrix [7, 8]. The STL (stereolithography) files generated from a CAD model are sent through a slicer that “slices” the object into layers with the thickness depending on the layer height [9]. Each “slice” then has its geometric properties and it is this geometric pattern that the extruder follows. The nozzle traces the cross-sectional pattern while dispensing the thermoplastic. After the layer has been traced, the thermoplastic has already hardened, ensuring a good building platform for the next layer. Once the layer has been traced, the platform drops down to the thickness of the layer height and the next layer is printed [10]

With CFF, each layer can consist of either fibre or matrix. To determine the individual mechanical properties of the two materials the composite consists of, a better understanding of the specimen’s internal structure is needed. The schematic in Figure 2 will be used to determine the geometry and structure of the test sample.

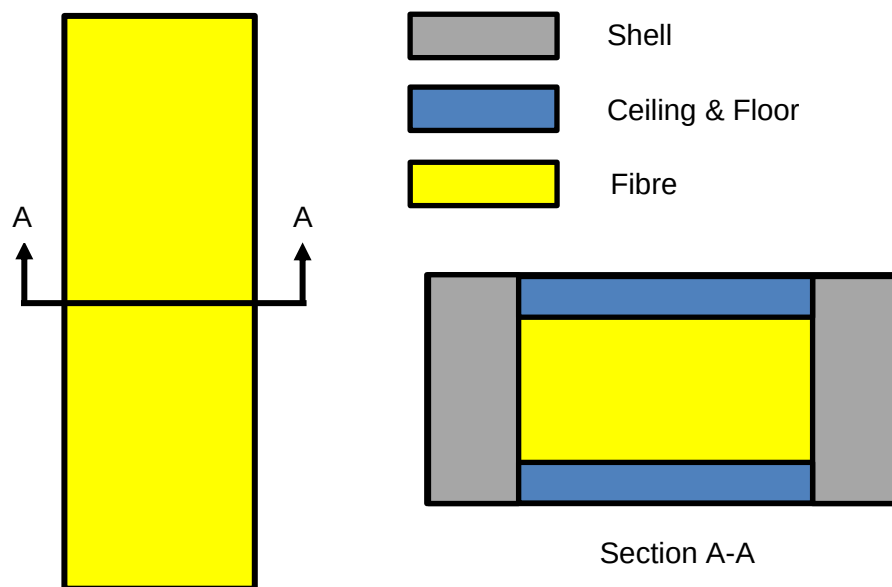


Figure 2: Schematic of the structure of fibre-reinforced 3D printed test specimen

Using volume fractions, the amount of each component of the test specimen is determined from the geometry of the sample. The volume of the sample can be described with (1): [11]

$$V_{tensile} = H \cdot W \cdot T \text{ [mm}^3\text{]} \quad (1)$$

with H being the sample height, W the width of the sample and T the sample thickness. The volumes of the floor and ceiling of the specimen are chosen as the same amount of layers and can be described by (2) and (3). The volume of the wall of the sample is described by (4) and lastly, the volume of the fibre is described by (5) [11]

$$V_{floor} = (W - W_{shell} \cdot 2) \cdot H \cdot T_{layer} \cdot N_{floor} \quad (2)$$

$$V_{ceiling} = (W - W_{shell} \cdot 2) \cdot H \cdot T_{layer} \cdot N_{ceiling} \quad (3)$$

$$V_{wall} = W_{shell} \cdot 2 \cdot H \cdot T_{layer} \cdot N_{wall} \quad (4)$$

$$V_{fibre} = (W - W_{shell} \cdot 2) \cdot H \cdot T_{layer} \cdot N_{fibre} \quad (5)$$

with W_{shell} being the width of the sample's shell and T_{layer} the sample's layer thickness. The number of layers in the wall, fibre, floor and ceiling are represented by N_{wall} , N_{fibre} , N_{floor} and $N_{ceiling}$ respectively. Knowing all the volume amounts of the sample, volume fractions can be determined as described in (6), (7), (8), (9) and (10) [11]

$$V_{f_{floor}} = V_{floor} / V_{tensile} \quad (6)$$

$$V_{f_{ceiling}} = V_{ceiling} / V_{tensile} \quad (7)$$

$$V_{f_{wall}} = V_{wall} / V_{tensile} \quad (8)$$

$$V_{f_{matrix}} = V_{f_{ceiling}} + V_{f_{floor}} + V_{f_{wall}} \quad (9)$$

$$V_{f_{fiber}} = 1 - V_{f_{matrix}} \quad (10)$$

with the volume fractions of the ceiling, floor and wall all contributing to the matrix phase of the composite's volume fraction and the fibre being the volume not occupied by the matrix. The volume fractions described are only for specimens where the fibre infill is at 100 per cent. Alternatively, if the fibre is used for all of the infills, additional volume fractions would have to be determined.

The technique of using volume fractions to determine each component's mechanical properties is a common practice for composite modelling [11–15]. In the study, the mechanical properties of the composite 3D printed specimen are determined using concentric layers of fibre. Furthermore, the study found that the specimens experienced premature failure because the specimen geometry was not from the correct testing standard.

2.3 Markforged Mark II 3D printer

Markforged Inc. was established in Cambridge, United States, in 2013 and was founded to solve problems in traditional manufacturing. The company uses the CFF technology explained in the previous sections. As the name indicates, the fibres are continuous, unlike alternative fibre-reinforced composites. This gives the printed products better performing mechanical properties. With a printing size of 320 x 132 x 160 mm, the printer is more than capable of printing the desired specimen size.

To achieve composite 3D printing, the machine uses a dual extrusion head – one for the core material and the other for the fibre. As the fibre is continuous, an internal cutter trims the fibre strand after the correct length of fibre has been printed in a layer. All the slicing is processed through their cloud-based slicing software, Eiger. This means that samples can be prepared on any computer with an internet connection and sent to the printer, which is also connected to the internet, for better print job management.

2.4 Composite characteristics and orientation constraints

Several factors influence the strength and other properties of fibre-reinforced composites including the orientation of the fibres, the fibre concentration and the distribution of the fibres. Continuous fibres are typically aligned and better over-all properties are realised when the fibre distribution is uniform. The mechanical behaviour of such composites depends on several factors including the stress-strain behaviours of the two phases, the volume fractions and the direction of the applied stress or load. Furthermore, the mechanical properties of composites with aligned fibres are highly anisotropic, that is, they are dependent on the orientation of the fibres. [3]

2.4.1 Tensile stress-strain behaviour – Longitudinal loading

Firstly, the stress-strain behaviour for the situation to which the stress is applied along the direction of alignment, the longitudinal direction, is considered and shown in Figure 3. Also indicated in this figure is the fracture strengths in tension for both the fibre and matrix, σ_f^* and σ_m^* respectively, and their corresponding fracture strains, ϵ_f^* and ϵ_m^* . [3]

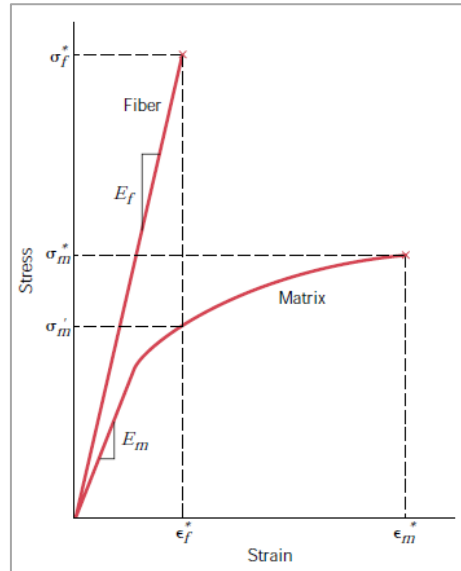


Figure 3: Stress-strain curves for typical fibre matrix materials [3]

A fibre-reinforced composite consisting of fibre and matrix materials will exhibit the uniaxial stress-strain response illustrated in Figure 4. In the initial Stage I region, both fibres and matrix deform elastically and this portion of the curve is usually linear. For a composite of this type, the matrix yields and deforms plastically while the fibres continue to stretch elastically as the tensile strength of the fibres is significantly higher than the yield strength of the matrix termed Stage II. This stage is generally very nearly linear but of diminished slope relative to Stage I. In passing from Stage I to Stage II, the proportion of the applied load that the fibres carry increases and the modulus of a composite can be seen to increase with the fibre content. [4]

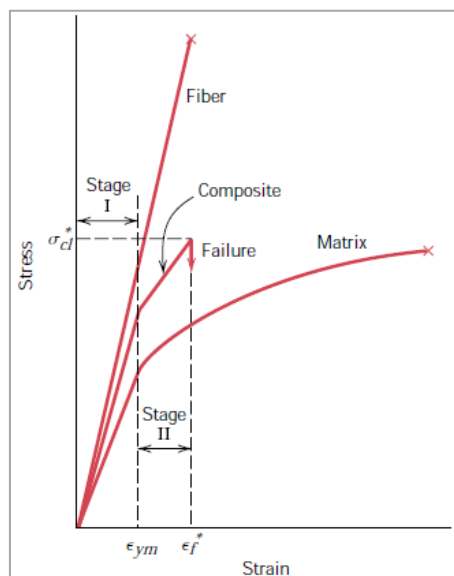


Figure 4: Stress-strain curve for an aligned fibre-reinforced composite [3]

The composite failure begins as the fibres start to fracture, which corresponds to a strain of approximately ϵ_f^* as noted in Figure 4. Composite failure is not catastrophic for a couple of reasons. First of all, not all fibres fracture at the same time since there will always be considerable variations in the fracture strength of brittle materials. Also, even after fibre failure, the matrix is still intact since as $\epsilon_f^* < \epsilon_m^*$ [3].

The matrix surrounding the fibre break is loaded in shear and transfers stress back onto the broken fibre [16–19]. Therefore, the nearby fibres will locally carry stress concentrations but the magnitude decreases with increasing distance from the fibre break. [20–25].

2.5 Mechanical properties and prediction modelling

The mechanical properties of a material are often defined in terms of the behaviour at loads that do not produce failure or failure behaviour itself. For solids, the first case is generally characterised by the modulus that is defined as the stress divided by the strain. Accurate mechanical property measurements are required to select materials and design a structure for its intended application. Engineers use this knowledge to make material decisions in both safety-critical and non-safety critical designs. These properties are determined with accepted measurement standards, certified databases or reference materials. [26]

3D finite element models with varying degrees of refinement have been developed in the past to more accurately capture stress concentrations and non-linear material and geometric behaviour [27, 28]. Initial models of the braided textile architectures produced good correlations and included manufacturing-induced effects like tow consolidations [29]. These methods have produced accurately-predicted strengths for composites but most methods for composite strength prediction are based on woven composites. In order to model a composite that is not woven, as in the case of this study, a new approach is needed. Even in the ideal scenario that the fibre, matrix and interfacial properties are measured accurately, deviations from experimental measurements may still occur [32].

The mechanical properties of the materials used in a composite can be modelled by using various laminate theories. The theory that is most often used in studies is the classic laminate theory (CLT) [33, 34]. This theory is used for a composite of a stack of plies, which in the case of the 3D printed composites, is represented by the layers. G.W. Melenka's study differs slightly from the CLT by focusing on the average stiffness method to predict the strength of the composite [11]. With this method, the density of each material and a Poisson ratio of each component is needed. An accurate Poisson ratio of the fibre cannot be determined as the fibres are enclosed by a ductile matrix.

M. Elasswad conducted another study that focused on determining the amount of fibre to be used within a part by using the least-weight and the optimisation cost function methods. The model uses the ratio of bending rigidity per unit mass and the price is maximised to identify the optimum parameters [35].

F. van der Klift studied carbon fibre-reinforced thermoplastic (CFRTP) test specimens. The specimens were tested in the longitudinal direction to obtain an overview of the mechanical properties of 3D printed CFRTP materials. The properties from the study were then compared with the literature values known for the composite materials [8]. The majority of past work done on this subject is focused on the theoretical portion and only F. van der Klift was able to do practical examples of his work.

2.6 Mechanics of fibre-reinforced composites

Typically, a composite consists of two different materials that exhibit the desired properties of both constituents. The matrix phase gives excellent compressive strength whereas the fibre provides tensile strength. The fibre phase is typically a ceramic or polymer fibre that is embedded into the matrix phase. The matrix phase can be a thermosetting resin like epoxy or polyester or even a thermoplastic or other metals. The most common forms of fibre used are:

- Carbon
- Aramid
- Glass

2.6.1 The stiffness of long fibre composites

Firstly, it should be noted that the most suitable material for a given application may not necessarily be the stiffest material. To obtain the least deflection per unit of mass, the merit index must be maximised E/ρ^2 . A simple slab model, where the fibre and matrix phases are represented by slabs of material, can be used to predict Young's modulus in axial and transverse using the thickness in proportion to their volume fractions E and $(1 - E)$. [3]

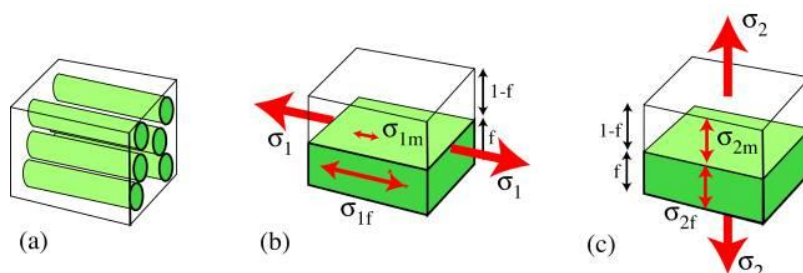


Figure 5: Slab model [3]

2.6.2 Axial loading

For long fibre composites, the strain distribution is essentially homogeneous during axial loading. The same strain assumption is valid and the model works to a high degree of precision.

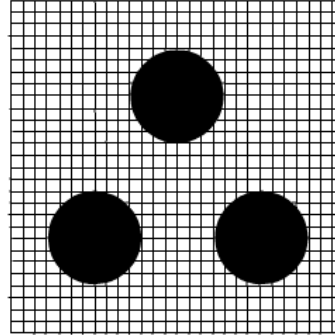


Figure 6 : Axial loading illustration [3]

When we consider when the fibre strain is equal to the matrix strain, then the following applies

$$\varepsilon_1 = \varepsilon_{1f} = \frac{\sigma_{1f}}{E_f} = \varepsilon_{1m} = \frac{\sigma_{1m}}{E_m} = \frac{\sigma_1}{E_1} \quad (11)$$

For composites in which the fibres are much stiffer than the matrix ($E_f \gg E_m$), the reinforcing fibre phase experiences much higher stress ($\sigma_{1f} \gg \sigma_{1m}$) than the matrix phase and the load is redistributed. The overall stress σ_1 can be expressed in terms of the two contributions

$$\sigma_1 = (1 - f)\sigma_{1m} + f\sigma_{1f} \quad (12)$$

where f is the volume fraction of the fibre

$$f = \frac{V_f}{V_f + V_m} \quad (13)$$

Thus, Young's modulus of the composite can be written as

$$E_1 = \frac{\sigma_1}{\varepsilon_1} = \frac{(1 - f)\sigma_{1m} + f\sigma_{1f}}{\left(\frac{\sigma_{1f}}{E_f} \right)} = (1 - f)E_m + fE_f \quad (14)$$

The equation (13) is referred to as the “rule of mixtures” and shows that the axial stiffness is expressed by a weighted mean of the stiffness of the two components, depending only on the volume fraction of fibres. [11–14]

2.6.3 Transverse loading

When transverse loading is considered, the axial loading stress assumption will not work. In the centre, the region of the matrix is in “series” with the fibres with high stress and strain while the matrix is in contact with the fibres. The matrix region is in “parallel” with the fibres with low stress and strain. Because of this phenomenon, the Halpin-Tsai expression is used.

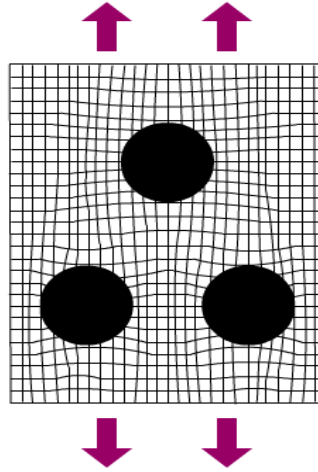


Figure 7: Transverse loading illustration [3]

The Halpin-Tsai equations are used to empirically express the relationship of the composite's material in terms of the mechanical properties of the two phases and their proportions and the geometry of each phase. Halpin and Tsai showed that the composite's property could be expressed in terms of the reinforcing phase P_f and the matrix phase, P_m . This factor changes for different properties in the same composite. The equations (15) and (16) are derived from the Halpin-Tsai expression for transverse loading,

$$E_1 = E_m \left(\frac{1 + \xi \eta f}{1 - \eta f} \right) \quad (15)$$

where

$$\eta = \frac{\left(\frac{E_f}{E_m} \right) - 1}{\left(\frac{E_f}{E_m} \right) + \xi} \quad (16)$$

The factor ξ is used to describe the influence of the geometry of the reinforcing phase on a particular property.

2.7 The strength of long fibre composites

When an arbitrary stress state is applied to a body, the three most important modes of failure are

- Axial tensile failure
- Transverse tensile failure
- Shear failure

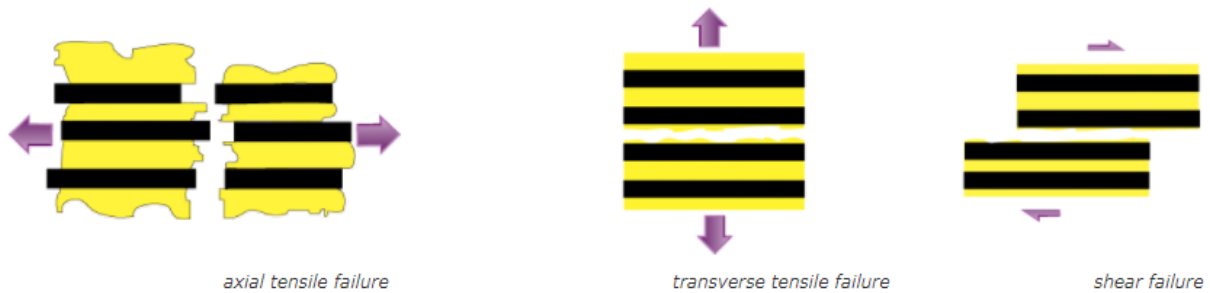


Figure 8: Composite modes of failure [3]

2.7.1 Axial strength

In the most common scenario, it is assumed that the matrix and fibre phase both deform elastically and consequently undergo brittle fracture. As a result, the same strain condition is applied and two possible cases can occur:

- a) Matrix phase has the lower failure strain ($\epsilon_{fu} > \epsilon_{mu}$)
- b) Fibre phase has the lower failure strain ($\epsilon_{fu} < \epsilon_{mu}$)

2.8 Stress-strain relations for an orthotropic lamina

Fibre composites differ from conventional engineering materials in that the properties are highly directional. This directionality affects the way in which the materials are used. The fibres can be arranged in a component with the highest strength and stiffness in the direction of the highest load. This allows components to be manufactured with higher strength and stiffness in comparison to standard materials. In this section, the stress-strain relationship for an individual ply or lamina will be examined. This forms the basic building block for the following sections where the relationship will be applied to layers of the lamina.

2.8.1 Orthotropic properties

Figure 9 shows a unidirectional layer of some orthotropic material when the coordinate systems are used. The x–y coordinate system is referred to as the global system while the 1–2 system is the fibre direction coordinate system.

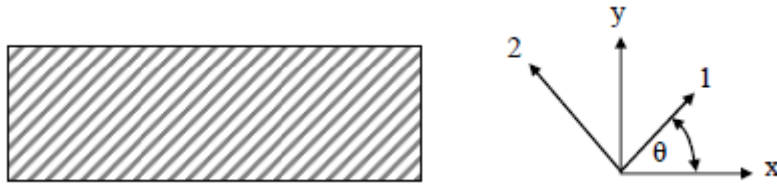


Figure 9: Orthotropic material unidirectional layer

Since the material is orthotropic, the material properties are different in the 1 and 2 directions. The stress-strain and stiffness in the 1 and 2 directions are then given by σ_1 , ϵ_1 , E_{11} and σ_2 , ϵ_2 , E_{22} . It is thus possible to write Hooke's law for each of the two directions and the shear strain:

$$\epsilon_1 = \frac{\sigma_1}{E_{11}}, \epsilon_2 = \frac{\sigma_2}{E_{22}}, \gamma_{12} = \frac{\tau_{12}}{G_{12}} \quad (17)$$

The Poisson ratio for an orthotropic material can be defined as follows: A stress in direction 1 will result in a strain in direction 2 owing to the Poisson ratio. The Poisson ratio for the in-plane 1–2 directions are given by:

$$\epsilon_1 = -\nu_{21}\epsilon_2, \epsilon_2 = -\nu_{12}\epsilon_1 \quad (18)$$

The through-plane strain is given by:

$$\epsilon_3 = \frac{\sigma_3}{E_{33}} \quad (19)$$

If the strain in the 1 direction due to loadings in all three directions is considered, the following equation can be obtained:

$$\epsilon_1 = \frac{\sigma_1}{E_{11}} - \nu_{21} \frac{\sigma_2}{E_{22}} - \nu_{31} \frac{\sigma_3}{E_{33}} \quad (20)$$

Similar results can be obtained in every direction. This can be arranged in matrix notation to give the following:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_{11}} & \frac{-\nu_{21}}{E_{22}} & \frac{-\nu_{31}}{E_{33}} & 0 & 0 & 0 \\ \frac{-\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & \frac{-\nu_{32}}{E_{33}} & 0 & 0 & 0 \\ \frac{-\nu_{13}}{E_{11}} & \frac{-\nu_{23}}{E_{22}} & \frac{1}{E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{Bmatrix} \quad (21)$$

or

$$\{\varepsilon\} = [S]\{\sigma\} \quad (22)$$

The S matrix is symmetrical for elastic materials so that

$$E_{11}\nu_{21} = E_{22}\nu_{12} \quad (23)$$

2.8.2 Orthotropic properties for in-plane stresses

Since many engineering structures from laminates are thin in the through-thickness, only the two-dimensional components of the proceeding equations are used. This can be obtained by setting

$$\sigma_3 = \tau_{13} = \tau_{23} = 0$$

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_{11}} & \frac{-\nu_{21}}{E_{22}} & 0 \\ \frac{-\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} \quad (24)$$

The stresses can be obtained in terms of the strains by the inverse of the matrix as

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} \quad (25)$$

with

$$[Q] = \begin{bmatrix} \frac{E_{11}}{1-\nu_{12}\nu_{21}} & \frac{\nu_{21}E_{11}}{1-\nu_{12}\nu_{21}} & 0 \\ \frac{\nu_{21}E_{11}}{1-\nu_{12}\nu_{21}} & \frac{E_{22}}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \quad (26)$$

2.8.3 Transformation of coordinates

In this section, a transformation will be given with which the local 1–2 stresses can be written in terms of the global x–y stresses. The transformations will be extended to writing the global stresses in terms of the global strains with the material properties known in terms of the local coordinate system.

By using the same method to derive Mohr's circle, it can be shown that

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = [T] \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \quad (27)$$

with

$$[T] = \begin{bmatrix} \cos^2 \theta & \sin^2 \theta & 2 \sin \theta \cos \theta \\ \sin^2 \theta & \cos^2 \theta & -2 \sin \theta \cos \theta \\ -\sin \theta \cos \theta & \sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta \end{bmatrix} \quad (28)$$

The inverse relation is given by

$$\{\sigma\}_{xy} = [T]^{-1} \{\sigma\}_{12} \quad (29)$$

with

$$[T]^{-1} = \begin{bmatrix} \cos^2 \theta & \sin^2 \theta & -2 \sin \theta \cos \theta \\ \sin^2 \theta & \cos^2 \theta & 2 \sin \theta \cos \theta \\ \sin \theta \cos \theta & -\sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta \end{bmatrix} \quad (30)$$

The same transformation can be used with strain components, bearing in mind that the tensor definition of strain is the engineering strain divided by two. It is thus possible to show that

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = [\bar{Q}] \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad (31)$$

2.8.4 Experimental methods for obtaining lamina properties

To analyse the lamina, it is necessary to obtain its stiffness properties. This can be obtained experimentally as discussed in this section.

The stiffness properties required are the following. Young's modulus in the 1 direction, E_{11} , Young's modulus in the 2 direction E_{22} , the in-plane shear modulus G_{12} , and one of the in-plane Poisson ratios ν_{12} or ν_{21} .

2.8.4.1 E_{11} and ν_{12}

In order to obtain Young's modulus in the 1 direction, a standard tension test must be conducted on unidirectional coupons that are equipped with strain gauges to measure the strain in the 1 and 2 direction as shown in Figure 10.

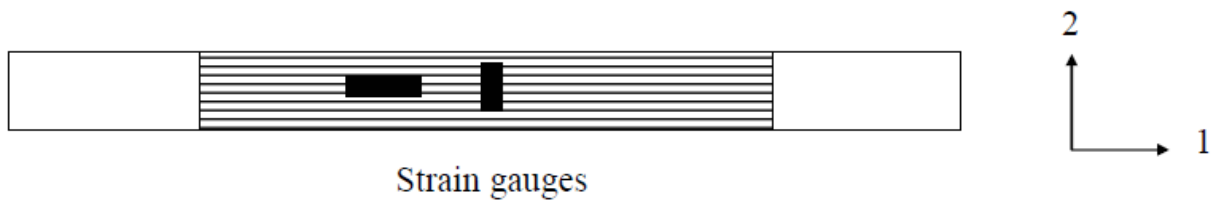


Figure 10: E_{11} and ν_{12} experimental procedure

2.8.4.2 E_{22}

In order to obtain Young's modulus in the 2 direction, a tension test must be done with the fibres orientated perpendicularly to the applied loads as shown in Figure 11.



Figure 11: E_{22} experimental procedure

2.8.4.3 G_{12}

The value for shear can be obtained in a tension test where the test coupons are made up of fibres at an angle to the direction of the applied force. Usually 45° is used for this test. The response to this test can then be used to calculate the value of G_{12} as shown in equation (32).

$$G_{12} = \frac{4}{\frac{4}{E_x} - \frac{1}{E_1} - \frac{1}{E_2} + \frac{2\nu_{12}}{E_1}} \quad (32)$$

where E_x is the strain measured in this test. The other stiffness properties are measured in the previous tests.

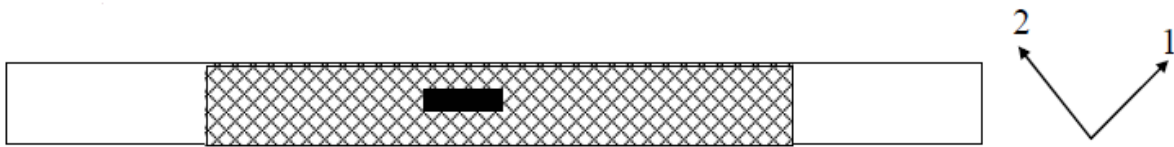


Figure 12: G_{12} experimental procedure

2.8.5 Rule of mixture model

If the fibre and resin volume fractions in a composite are known, the simple rule of mixture models can be used to find the stiffness properties of the composite, with V_f and V_m the volume fractions of the fibre and resin respectively. The stiffness properties of the composite are determine using equations (33), (34), (35) and (36).

$$E_{11} = V_f E_f + V_m E_m \quad (33)$$

$$\nu_{12} = V_f \nu_{12f} + V_m \nu_{12m} \quad (34)$$

$$\frac{1}{E_{22}} = \frac{V_f}{E_{2f}} + \frac{V_m}{E_{2m}} \quad (35)$$

$$\frac{1}{G_{12}} = \frac{V_f}{G_{12f}} + \frac{V_m}{G_{12m}} \quad (36)$$

CHAPTER 3

EXPERIMENTAL PROCEDURE

In this chapter, the experimental procedure used to extract the data of the composite material will be discussed. The test is done according to the ASTM standards, with some modifications done to the geometry of the tensile specimen. The orientation of the reinforced continuous fibre will be altered in each configuration in order to obtain a data basis of the strongest print setting for each practical situation. It should be noted that, according to ASTM standards, at least five specimens of each configuration must be tested.

3.1 Materials

Markforged, Cambridge, MA, USA supplied the filament. It is their propriety blend and has a diameter of 1.75 mm. The filament used is Markforged nylon and, prior to use, this polymer was stored in a moisture-sealed Pelican 1430 modified dry box to prevent deterioration of the filament from moisture absorption during storage [9]. Markforged also supplied the reinforced glass fibre (GF). While GF is referred to as 'fibres', these are composed of fibre bundles infused with a sizing agent.

3.2 Testing standards

A testing standard is a method for a test in science or engineering and it is a definitive procedure that must be followed to get accurate results. Testing standards are used to measure material properties reliably and are standardised and documented and published by their respective user communities. ASTM International is globally recognised for the development and delivery of voluntary consensus standards for a wide range of materials, products, and services [10].

3.2.1 Tensile

The ASTM standard D3039 is used for the tensile testing of the nylon-fibreglass composite, as used by Markforged® themselves in their material properties report [11]. The standard describes all relevant information, including specimen geometry, testing procedures and the calculation of material properties. More information on the standard can be found in Annexure 2.

As the composite is 3D printed, some alternation is made to the geometry of the specimen to, firstly, reduce the production time and reduce cost. The specimen geometry used is described in the next sections.

3.3 Markforged Mark II composite 3D printer

Figure 13 shows a photograph of the Markforged Mark II 3D printing equipment from which test specimens were fabricated. The printing process consists of two stages, each of which is performed by a separate print head. These stages are, firstly, nylon (matrix) printing and, secondly, fibre-reinforcement printing. The nylon and fibre layers are printed with a hot end temperature of 263°C onto a non-heated print bed. The design of the 3D printer allows continuous fibre reinforcement to be positioned as required.

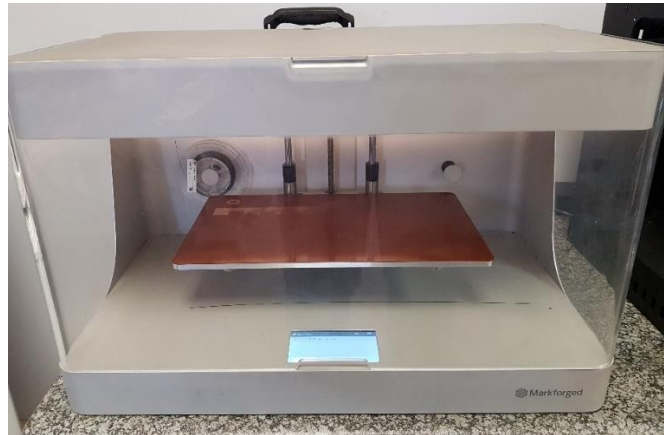


Figure 13: Markforged Mark II Composite 3D printer

3.4 Specimen geometry

A fair amount of geometric changes has been evaluated for this study to optimise for the correct specimen dimension. Customarily, when starting a testing process, the specimen dimensions are collected from the relevant standard. As CFF is not tested frequently, some investigation into specimen dimensions was done.

3.4.1 ASTM D638

The first specimen dimension correlates to ASTM D638, which is used for the tensile testing of plastics. In this standard, the commonly known “dog bone” specimen is used and various sizes explained in Figure 14. The standard explains that each “type” of specimen should be printed and tensile tested. From the results, the specimen type is then used as the correct size where the failure zone is located in the gauge length.

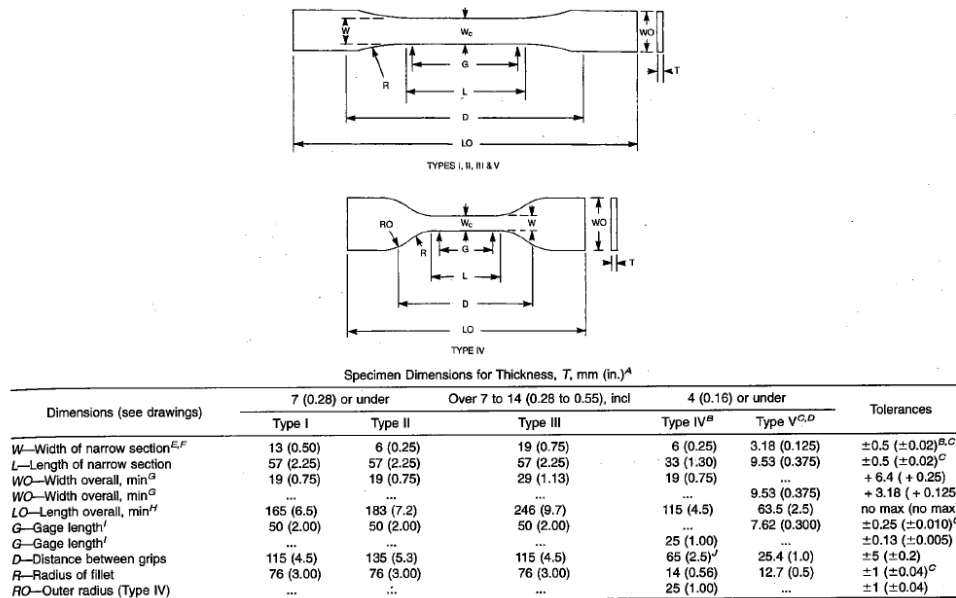


Figure 14: ASTM D638 Specimen dimensions [40]

This standard was investigated as the matrix phase is a thermoplastic, even though the fibre phase is not. Another issue with this geometry is the placing of fibre as seen in Figure 15.

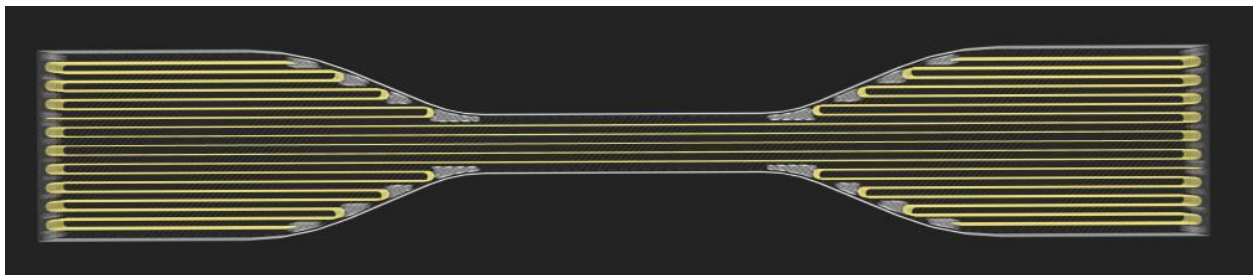


Figure 15: D638 Eiger 0°

With this geometry, only 5 fibre strands per layer can be tested with the rest of the geometry only being used to grip the specimen. This could still be used but only in the 0° fibre orientation. As soon as a different angle is used, for instance 45°, the fibres are placed in such a way that they cannot be tested correctly as seen in Figure 16.



Figure 16: D638 Eiger 45°

The standard is still used for testing of the matrix phase in order to obtain results for the nylon, however. The specimen type chosen is Type IV and part print settings as described in Table 1.

Table 1: D638 Part print settings

Parameter	Value
Material	Nylon
Layer Height	0.1
Roof & Floor Layers	4
Wall Layers	2
Infill	100 %

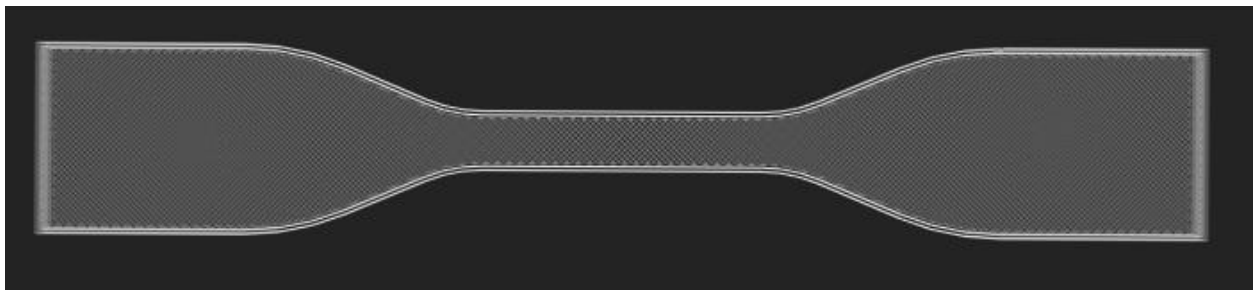


Figure 17: D638 Eiger

3.4.2 ASTM D3039

After looking at the standards used for plastic tensile testing, ASTM D3039 was investigated. This focuses on the tensile properties of polymer matrix composite materials. This standard describes a specimen geometry that is rectangular and doesn't have any geometrical changes. This is useful for getting as much fibre as possible into the specimen at all angles. The geometry that the standard recommends is explained in Table 2.

Table 2: ASTM D3039 Tensile specimen geometry recommendations

Fibre Orientation	Width [mm]	Overall Length [mm]	Thickness [mm]	Tab Length [mm]	Tab Thickness [mm]	Tab Bevel Angle [°]
0° unidirectional	15	250	1.0	56	1.5	7 or 90
90° unidirectional	25	175	2.0	25	1.5	90
Balanced and	25	250	2.5	Emery cloth	-	-
Random-discontinuous	25	250	2.5	Emery cloth	-	-

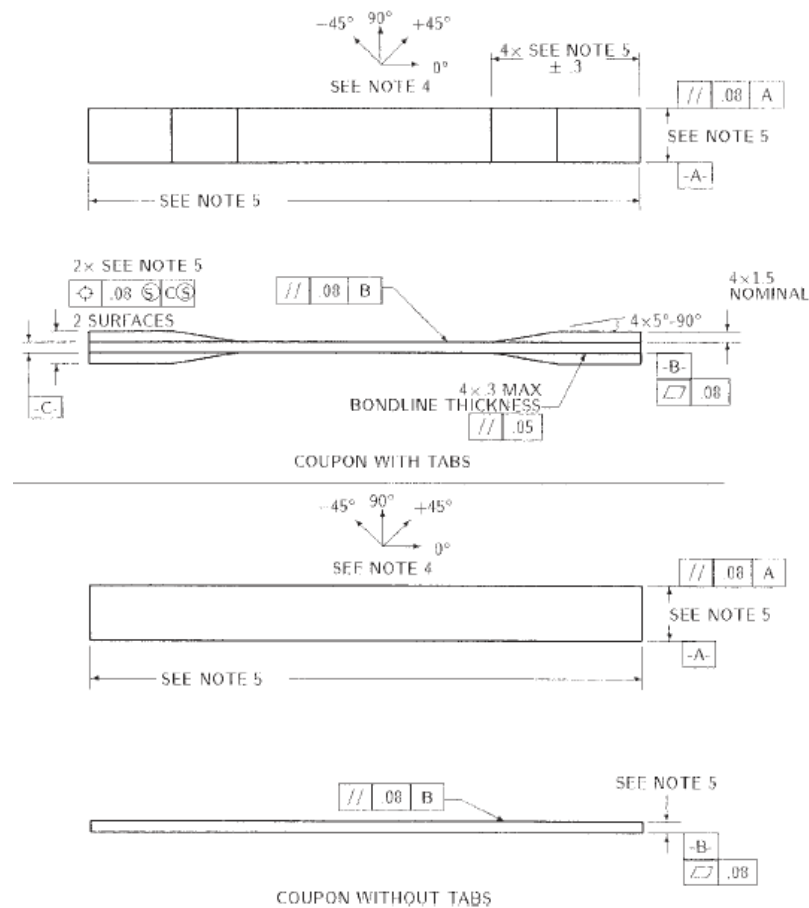


Figure 18: ASTM D3039 Tension test specimen drawing (SI) [26]

This geometry was proven to work very well for positioning the fibres in all the required directions and having the cross-sectional area the same throughout the specimen. Both specimens, with and without tabs, were printed and tested. The use of tabs was found to be very useful in the gripping force used. The specimens without bevels were prone to fail at the grips of the tensile tester. To counter this, the tabs were printed with only nylon, as seen in Figure 19.

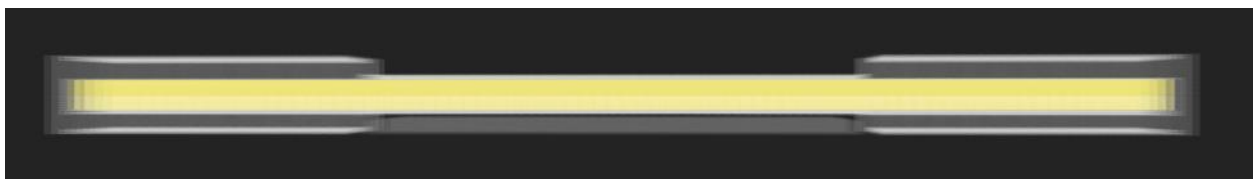


Figure 19: ASTM D3039 Eiger tabbed specimen

The added tabs printed with nylon started yielding to premature failure in certain fibre orientations, however. This was because the gripping force had to be much higher than the fibre and not allow it to just “slip” out of the tabs, as seen in Figure 20.



Figure 20: ASTM D3039 Tested specimen with tabs

After evaluating the results of the tabbed specimen, un-tabbed specimens were used and the gripping force on the tensile testing machine was reduced. Adequate force was, therefore, applied without damaging the fibres and causing premature failure. After investigating this design, the last constraint that had to be investigated was the length chosen so that, in the worst case 45° fibre orientation, the top and bottom grips grip at least one fibre, as explained in Figure 21.

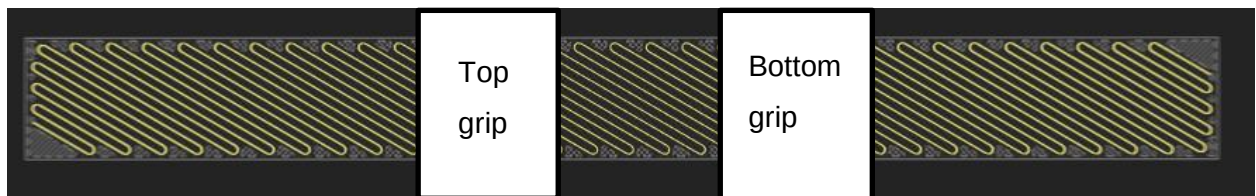


Figure 21: ASTM D3039 specimen gripping

After evaluating all the criteria for successful testing and still correlating to standard ASTM D3039, the following specimen dimensions were chosen:

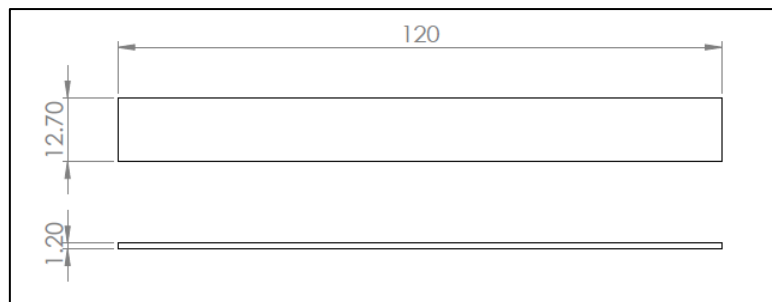


Figure 22: Specimen dimensions

Fibreglass printed test pieces comprised 12 layers (1.2 mm thickness). To produce 3D printed samples comparable to moulded composites, these fibre layers were distributed evenly throughout the sample thickness.

Control test pieces consisted of a solid nylon print (40 layers), which contained no fibre and, according to standard ASTM D638, typical fabrication times of between 90 and 120 min

(depending on fibre used) were required for a single test specimen. The resulting composite dimensions were examined using a Vernier calliper.

The tensile specimen was 120 x 12.7 x 1.2 mm in size, in accordance with standard ASTM D3039 and nylon tensile specimens 114 x 19 x 4 mm in accordance with ASTM D638. [36–40]

3.5 Fibre orientation

To calculate the mechanical properties of the fibreglass in the specimen, the amount of nylon is reduced to the minimum. This is meant to have 10 layers were fibreglass with a top and bottom nylon layer thickness of 1 layer and wall layer thickness of 1 layer. The nylon holds the fibre in place. For the mechanical properties of nylon, the specimen was printed at 100 per cent infill. All the angles are in respect of the length of the sample.

3.5.1 0° Fibre orientation

In this case, the fibre is orientated at 0° in respect of the length of the sample and thus also the direction of loading. Theoretically, this is the most robust orientation and, owing to the constraints of the nylon on the top and bottom layer, also the best way to test the fibre as a single component. Figure 23 shows how the composite is formed with the yellow portion as the fibre and the translucent portion being the nylon.

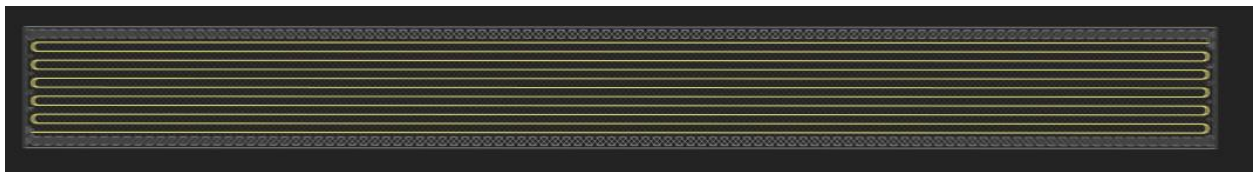


Figure 23: 0° Fibre orientation – Eiger representation

3.5.2 90° Fibre orientation

In this scenario, the fibre is oriented at 90° in respect of the length of the sample. This orientation is theoretically the weakest. This is an excellent configuration to test the de-bonding strength of the resin between the fibre strands.

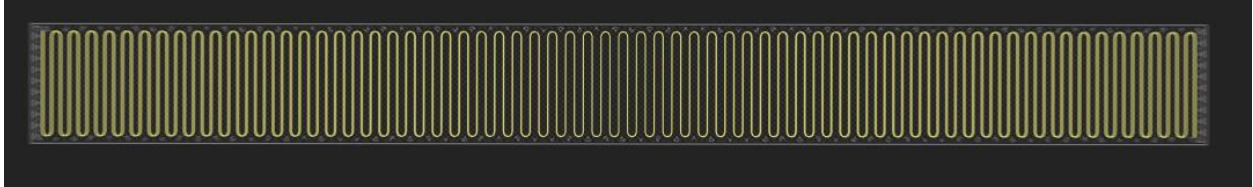


Figure 24: 90° fibre orientation – Eiger representation

3.5.3 45°/135° fibre orientation

The final fibre-related orientation is where the fibre is oriented at 45° on the one layer and then 135° for the next layer. This is to establish the in-plane shear modulus of the composite. This orientation, when clamped over the same fibre strand, is used to determine how the two layers shear from one another between layers.



Figure 25: 45°/135° fibre orientation – Eiger representation

3.5.4 Pure nylon

In this case, there is no reinforcement in the specimen. The specimen's geometry is changed as the sample is no longer a composite. This geometry is that of the standard ASTM D638, which is used for the tensile properties of plastics.

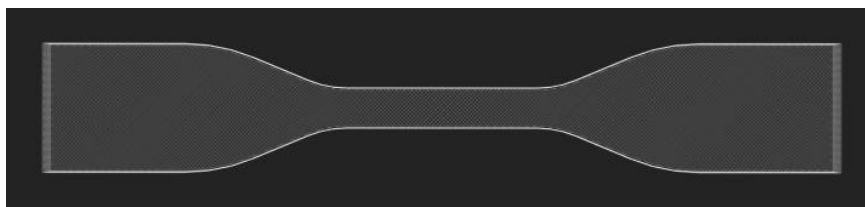


Figure 26: Pure nylon – Eiger representation

3.6 Characterisation equipment

The tensile tests were done with an MTS Landmark® 318.10 hydraulic tester (Figure 27). The testing machine can exert a maximum tensile force of 100 kN and is used for all the testing. In accordance with the standard used, the cross-head was set at a rate of 2 mm/min. The machine uses hydraulic ribbed grips to clamp the specimen and is set to 5 MPa as per the standard. The machine logs the force and the displacement is measured with the cross-head. To ensure more accurate results, however, an MTS 634 extensometer was used.



Figure 27: MTS Landmark

The tensile testing machine is equipped with software designed to produce the results in the form of a report and export them to an Excel file. To use the full potential of the testing machine, both the report and the raw data were used. The report consists of various data from the test, including the calculated modulus of elasticity, load at yield, stress at yield, peak load, break load and calculated elongation. All these calculations are done through pre-defined parameters set at the beginning of the test.

The raw data, exported in Excel form, is used for Matlab® calculations to verify the results from the machine and for the prediction model. The values exported include the actuator displacement (mm), load (kN), time (s) and extensometer reading (mm/mm).

CHAPTER 4

RESULTS

In this chapter, all the knowledge in the preceding chapters is used to examine and discuss the results from the experimental procedure. It should be noted that an iterative approach was used for the experimental process and only the final iteration of results is discussed. All calculations were done using MATLAB® and Microsoft Excel. The results discussed in this chapter will be used for the mathematical model in the following chapter.

4.1 Tensile testing

As detailed in the introduction, Van der Klift et al. reported problems with ‘discontinuities’ (the start and end points of the fibre reinforcement). The discontinuity caused premature failure and Van der Klift resorted to cutting the specimens preferentially around these anomalies to avoid this effect [7]. To overcome this ‘discontinuity’ issue in this study, the fibre end was laid beyond the gripping points (for tensile specimens). This approach avoided the need for cutting and, as specimens were not modified between printing and testing, it provided a more accurate representation of the mechanical performance of the FDM process.

In order to obtain statistically significant data, five specimens of each test condition were tested as stipulated in ASTM D3039. After each test, the raw data was exported through the tensile testing machine to an Excel file to be used for calculations.

4.2 MATLAB®

A Matlab® model was developed to calculate the various mechanical properties from the Excel data exported from the machine. This model was purely to verify the machine’s software and simplify changing parameters after testing with regards to percentage offset for yield etc. The full code can be found in Annexure 1.

4.2.1 0° fibre orientation tensile testing results

A batch of 5 specimens per orientation was tested and the results were tabulated in Table 3.

Table 3: 0° fibre orientation tensile testing results

Test Specimen	Max Load	% deviation	UTS	% deviation	Young's Modulus	% deviation
1	4.72	4.50%	309.53	4.50%	16.96	0.63%
2	5.16	4.54%	338.82	4.54%	16.79	0.39%
3	4.99	0.98%	327.28	0.98%	16.97	0.67%
4	4.83	2.19%	317.01	2.19%	16.79	0.40%
5	5.00	1.17%	327.88	1.17%	16.77	0.51%
Average	4.94	2.67%	324.10	2.67%	16.85	0.52%

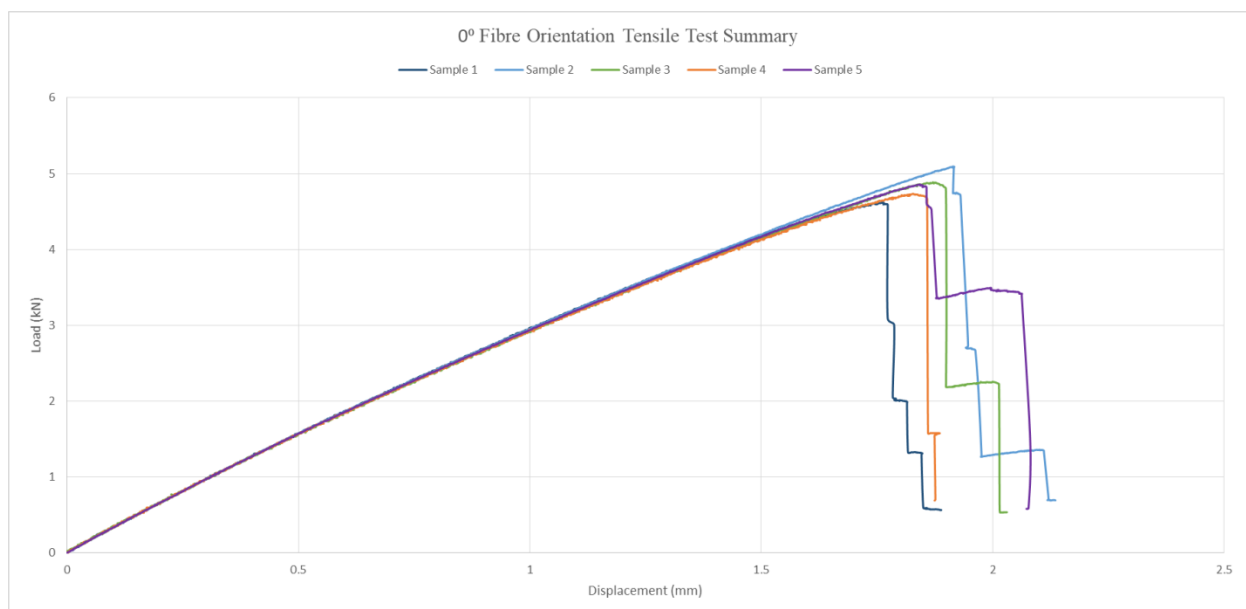


Figure 28: 0° fibre orientation tensile testing results graph

Figure 28 shows that there is a slight non-linear curve for the material and no yielding portion. This is a common phenomenon when composites are tested in tensile. The displacement at the breaking load is within a five per cent region of each other and is mostly spread out as some fibres are still able to hold load after the first layer breaks. For all the fibres to break simultaneously, the specimen must be placed exactly perpendicular to the grips.



Figure 29: 0° fibre orientation specimen post testing

As seen in Figure 29, the specimen failed in the centre of the length, showing that the geometry used is adequate for the input parameters. As the fibres started failing, they formed a small bulge in the geometry and the individual fibres breaking could be heard while testing.

4.2.2 90° fibre orientation tensile testing results

As with the first fibre orientation, a batch of 5 specimens per orientation was tested and the results were tabulated in Table 4.

Table 4: 90° fibre orientation tensile testing results

Test Specimen	Max Load	% deviation	UTS	% deviation	Young's Modulus	% deviation
1	0.336	2.442%	22.039	2.442%	1.298	4.128%
2	0.343	4.632%	22.511	4.632%	1.430	14.686%
3	0.336	2.545%	22.062	2.546%	1.380	10.656%
4	0.318	2.880%	20.894	2.880%	1.062	14.826%
5	0.306	6.739%	20.064	6.740%	1.064	14.644%
Average	0.328	3.848%	21.514	3.848%	1.247	11.788%

The results for the 90° fibre orientation proved to be more difficult to determine as can be seen from the percentage deviation of the results. This is mainly because this is the weakest orientation of the fibre. However, the nylon is consistent in each direction and the only strength the fibres contributed was the delamination of the fibres from each other bonded by the resin. The graph in Figure 30 is constructed from the results used to determine the material properties in the 90° fibre orientation.

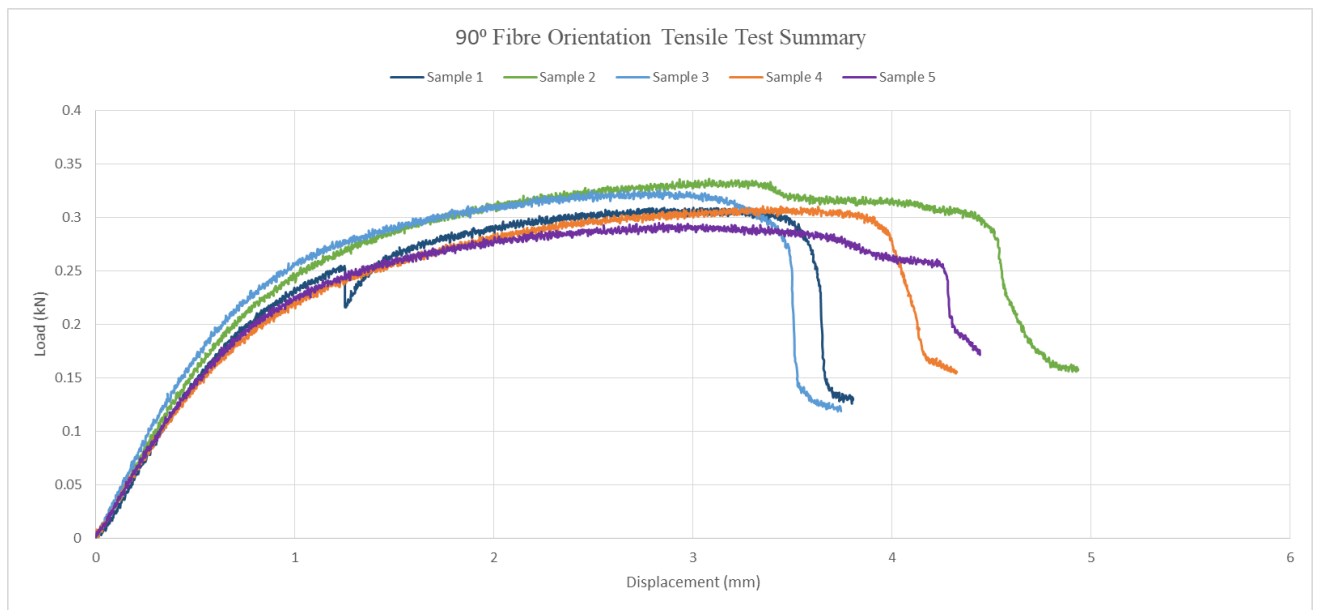


Figure 30: 90° fibre orientation tensile testing results graph

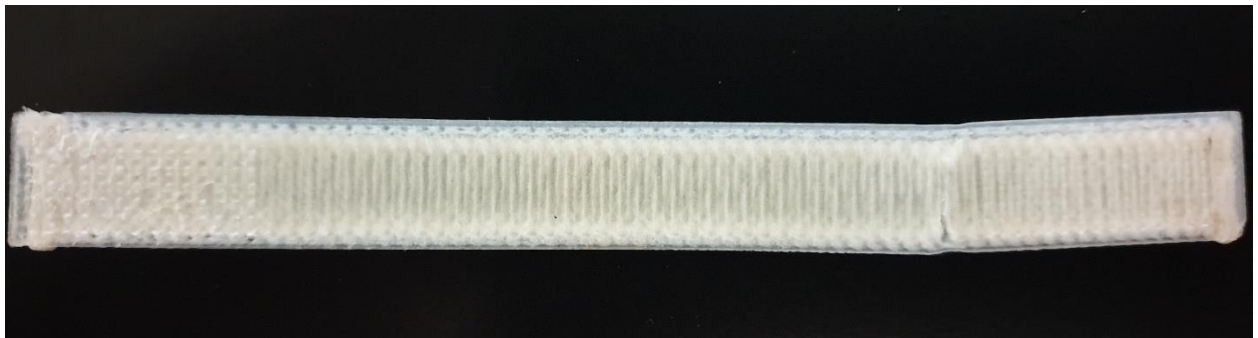


Figure 31: 90° fibre orientation specimen post-testing

As seen from Figure 31, the 90° fibre orientation is the weakest of the orientations and the fibres are only held together with the resin.

4.2.3 45°/135° fibre orientation tensile testing results

As with the previous fibre orientation, a batch of 5 specimens per orientation was tested and the results were tabulated in Table 5.

Table 5: 45°/135° fibre orientation tensile testing results

Test Specimen	Max load	% deviation	UTS	% deviation	Young's Modulus	% deviation
1	1.386	5.072%	90.928	5.072%	0.979	10.196%
2	1.235	6.356%	81.039	6.356%	1.299	19.242%
3	1.392	5.556%	91.348	5.557%	0.990	9.155%
4	1.302	1.249%	85.458	1.249%	1.043	4.255%
5	1.346	2.049%	88.312	2.048%	1.026	5.833%
Average	1.319	3.803%	86.539	3.803%	1.090	9.621%

With the testing of the 45°/135° fibre orientation, the motivation behind the geometrical change is found. With the fibres orientated at an 45°/135° angle, the upper and lower ends of the fibre are gripped in the jaws of the tensile tester to get more accurate results. The graph in Figure 32 is constructed from the results used to determine the material properties in the 45°/135° fibre orientation. The graph also shows a sharp drop off at 7 mm which is due to the maximum extension of the extensometer being reached and had to be removed to continue testing.

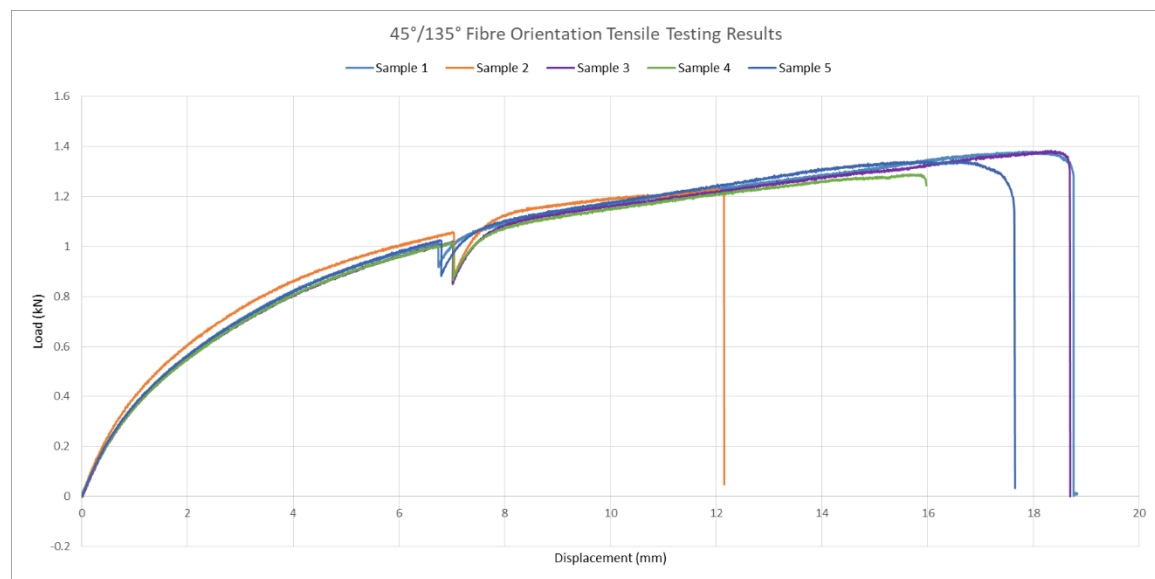


Figure 32: 45°/135° fibre orientation tensile testing results graph



Figure 33: 45°/135° fibre orientation specimen post-testing

Figure 33 shows how the layers of fibre are separated from one another as expected when testing in the orientation. The purpose, as explained, is to determine the shear strength of the layers.

4.2.4 Results summary

From all the results for the different orientations, a final material properties table can be populated as in Table 6.

Table 6: Material engineering properties tensile

Fibre orientation	Tensile strength (MPa)	Deviation (%)	Elastic modulus (Gpa)	Deviation (%)
0°	324.10	2.67	16.85	0.52
90°	21.514	3.848	1.247	11.788
45°/135°	86.539	3.803	1.090	9.621

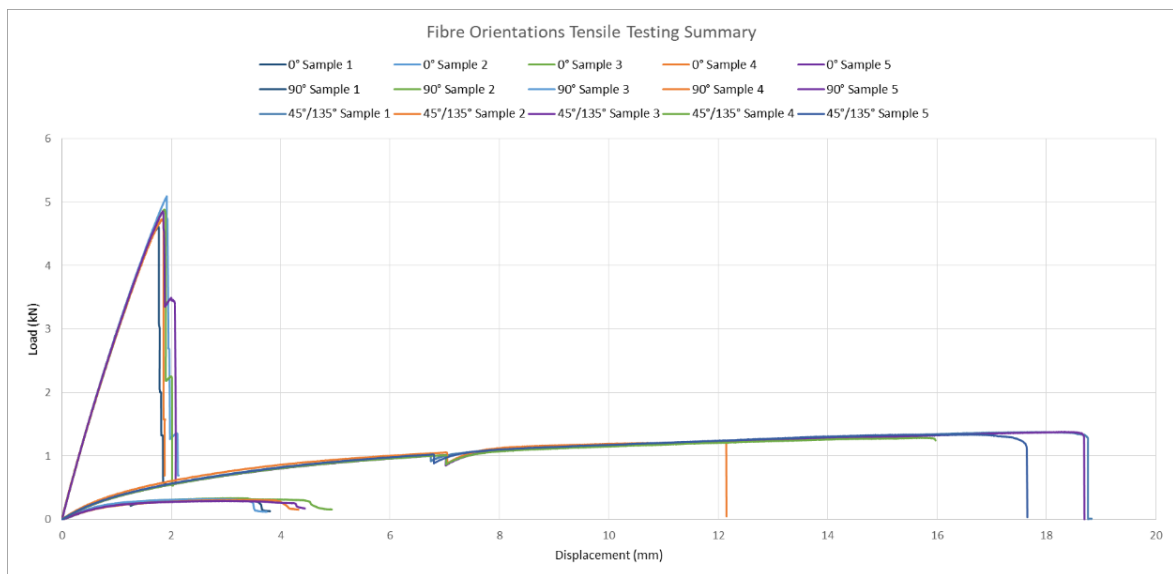


Figure 34: All fibre orientation tensile testing summary

CHAPTER 5

MATHEMATICAL MODEL

In this chapter, the mathematical model to predict the material properties of the nylon and fibreglass composite is discussed. The software used for this is MATLAB® and LAP®.

5.1 Matlab® model

The mechanic properties obtained through the experimental process followed in Chapter 3 is now used in a developed Matlab® model to predict the first ply failure experienced in the composite. In the process of calculating the final product, a series of calculations is done including all the equations explained in Chapter 2.

The mathematical model consists of two separate sections. The first section determines the mechanical properties of each material by using micromechanics. This step is the core of the prediction model as the individual mechanical properties are unknown and cannot be tested. It was noted that the fibre element of the composite had been tested by Markforged® and values obtained but, because the test consisted of a single strand of unprinted fibre, a more realistic value was needed.

In the process of using the micromechanics, one of the materials used in the composite must be known. In this case, the matrix series, which consisted of pure nylon, could be tested separately and the mechanical properties determined. This was done by using the raw data from the MTS machine and processing it through a separate Matlab® model for verification. It was also used in Chapter 4.

5.2 Micromechanics

In order to obtain the material engineering properties of the specimen, the values in Table 6 must be processed further using micromechanics to obtain the mechanical properties of the fibre phase. Matlab® is used to calculate this, based on the rule of the mixture model described in Chapter 2. This code can be found in Annexure 1. The development of this code is described step by step in this section.

Figure 35 shows a cross-sectional image of a test specimen that has been used to determine the dimensions of the different portions of the specimen.

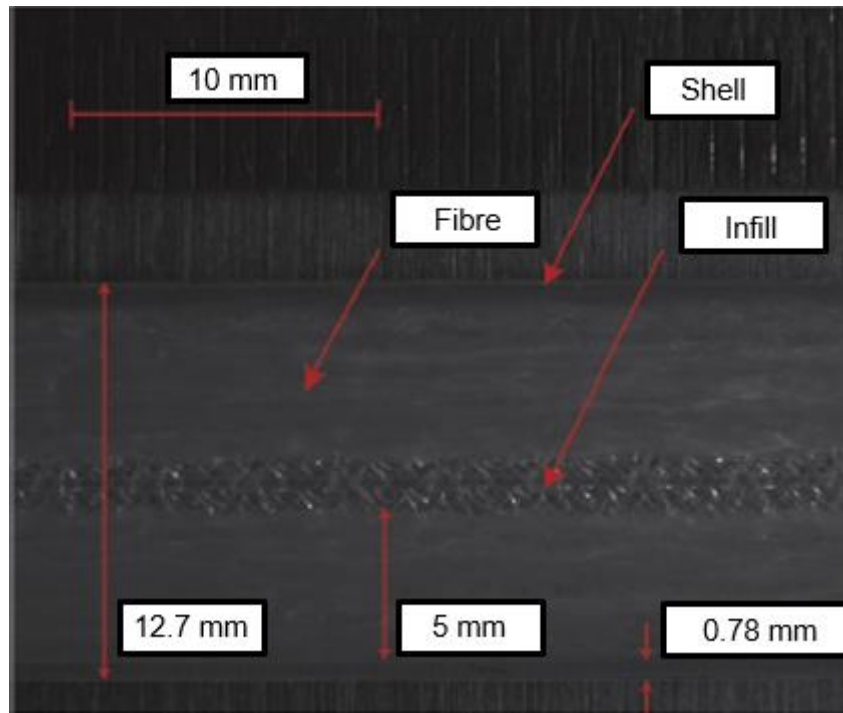


Figure 35: Cross-sectional image of a test specimen

5.2.1 Step 1: Declare initial conditions

The first step in determining the material engineering properties of the individual materials used in the composite is to declare the initial conditions of the composite as can be seen in Table 7.

Table 7: Micromechanics inputs and nomenclature

Parameter	Description	Value	Unit
h	Height of specimen	120	[mm]
w	Width of specimen	12.7	[mm]
t	Thickness of the specimen	1.2	[mm]
w_{shell}	Width of shell	0.78	[mm]
t_{layer}	Layer thickness	0.1	[mm]
n_{floor}	Number of floor layers	1	[-]
$n_{ceiling}$	Number of ceiling layers	1	[-]
n_{solid}	Number of solid layers	1	[-]
n_{infill}	Number of infill layers	1	[-]
w_{fiber}	Width of fiber	0.7	[mm]
n_{fiber}	Number of fibre layers	-	[-]
n_{wall}	Number of wall layers	-	[-]

$$n_{fiber} = t / t_{layer} - n_{floor} - n_{ceiling} \quad (37)$$

$$n_{wall} = t / t_{layer} \quad (38)$$

Equations (37) and (38) are used to determine the number of fibre layers and wall layers respectively. After the inputs have described the composite, the material properties of the known material, in this case, the nylon, must be declared. The values, shown in Table 8, are obtained from the experimental procedure in Chapter 4.

Table 8: Nylon inputs and nomenclature

Parameter	Description	Value	Unit
E_11_m	Nylon modulus of elasticity at 0°	456.641×10^6	[Pa]
E_22_m	Nylon modulus of elasticity at 90°	456.641×10^6	[Pa]
G_12_m	Nylon modulus of elasticity at 45°/135°	456.641×10^6	[Pa]
v_12_m	Nylon Poisson ratio	0.4	[-]
UTS_11_T_matrix	Nylon ultimate tensile strength at 0°	54×10^6	[Pa]
UTS_22_T_matrix	Nylon ultimate tensile strength at 90°	10.8×10^6	[Pa]
UTS_11_C_matrix	Nylon ultimate compressive strength at 0°	44.073×10^6	[Pa]
UTS_22_C_matrix	Nylon ultimate compressive strength at 90°	44.073×10^6	[Pa]
UTS_S12_matrix	Nylon ultimate tensile strength at 45°/135°	48×10^6	[Pa]

With the matrix's material properties known, the next set of information required is the material properties of the composite as tested. The values, shown in Table 9, are obtained as described in section 5.6.1.

Table 9: Specimen inputs and nomenclature

Parameter	Description	Value	Unit
E_11	Specimen modulus of elasticity at 0°	16.85×10^9	[Pa]
E_22	Specimen modulus of elasticity at 90°	1.247×10^9	[Pa]
G_12	Specimen modulus of elasticity at 45°/135°	1.090×10^9	[Pa]
v_12	Specimen Poisson ratio	0.45	[-]
UTS_11_T	Specimen ultimate tensile strength at 0°	324.10×10^9	[Pa]
UTS_22_T	Specimen ultimate tensile strength at 90°	21.514×10^9	[Pa]
UTS_11_C	Specimen ultimate compressive strength at 0°	186.479×10^9	[Pa]
UTS_22_C	Specimen ultimate compressive strength at 90°	70.10×10^9	[Pa]
UTS_S12	Specimen ultimate tensile strength at 45°/135°	86.539×10^9	[Pa]

To determine the amount of fibre vs nylon, the rule of mixture is used based on the volume of each section of the composite. The volume of each part of the composite is determined as shown in equations (39), (40), (41), (42) and (43).

- Total sample volume

$$V_{tensile} = h \times w \times t \quad (39)$$

- Floor volume

$$V_{floor} = (w - (w_{shell} \times 2)) \times h \times t_{layers} \times n_{floor} \quad (40)$$

- Ceiling volume

$$V_{ceiling} = (w - (w_{shell} \times 2)) \times h \times t_{layers} \times n_{ceiling} \quad (41)$$

- Wall volume

$$V_{wall} = w_{shell} \times 2 \times h \times t_{layers} \times n_{wall} \quad (42)$$

- Fibre volume

$$V_{fiber} = (w - (w_{shell} \times 2)) \times h \times t_{layers} \times n_{fiber} \quad (43)$$

After the volume of the different sections of the composite is determined, volume fractions are calculated as illustrated in equations (44), (45), (46), (47) and (48).

- Volume fraction of floor

$$V_{floor} = \frac{V_{floor}}{V_{tensile}} \quad (44)$$

- Volume fraction of ceiling

$$V_{ceiling} = \frac{V_{ceiling}}{V_{tensile}} \quad (45)$$

- Volume fraction of walls

$$V_{wall} = \frac{V_{wall}}{V_{tensile}} \quad (46)$$

- Volume fraction of specimen matrix

$$V_{matrix} = V_{ceiling} + V_{floor} \quad (47)$$

- Volume fraction of fibre

$$V_{fiber} = 1 - V_{matrix} \quad (48)$$

Equation (48) assumes that there are no air gaps in the sample and the sample only consists of fibre and matrix phases. With the volume fractions calculated, the amount of fibre versus nylon is known and the rule of mixtures can be applied to determine the material properties of the fibre as seen in equations (49), (50), (51), (52), (53), (54), (55) and (56).

$$E_{11_{fiber}} = \frac{(E_{11} - E_{11_{matrix}} \times V_{matrix})}{V_{fiber}} \quad (49)$$

$$E_{22_{fiber}} = \frac{(E_{22} - E_{22_{matrix}} \times V_{matrix})}{V_{fiber}} \quad (50)$$

$$G_{12_{fiber}} = \frac{(G_{12} - G_{12_{matrix}} \times V_{matrix})}{V_{fiber}} \quad (51)$$

$$\nu_{12_{fiber}} = \frac{(\nu_{12} - \nu_{12_{matrix}} \times V_{matrix})}{V_{fiber}} \quad (52)$$

$$UTS_{11_{Compression-Fiber}} = \frac{(UTS_{11_{Compression}} - UTS_{11_{Compression-Matrix}} \times V_{matrix})}{V_{fiber}} \quad (53)$$

$$UTS_{22_{Compression-Fiber}} = \frac{(UTS_{22_{Compression}} - UTS_{22_{Compression-Matrix}} \times V_{matrix})}{V_{fiber}} \quad (54)$$

$$UTS_{11_{Tensile-Fiber}} = \frac{(UTS_{11_{Tensile}} - UTS_{11_{Tensile-Matrix}} \times V_{matrix})}{V_{fiber}} \quad (55)$$

$$UTS_{22_{Tensile-Fiber}} = \frac{(UTS_{22_{Tensile}} - UTS_{22_{Tensile-Matrix}} \times V_{matrix})}{V_{fiber}} \quad (56)$$

$$UTS_{S12_{Fiber}} = \frac{(UTS_{S12} - UTS_{S12_{Matrix}} \times V_{matrix})}{V_{fiber}} \quad (57)$$

Table 10: Fibre nomenclature

Parameter	Description	Unit
E_11_f	Fibre modulus of elasticity at 0°	[Pa]
E_22_f	Fibre modulus of elasticity at 90°	[Pa]
G_12_f	Fibre modulus of elasticity at 45°/135°	[Pa]
v_12_f	Fibre Poisson ratio	[-]
UTS_11_T_fiber	Fibre ultimate tensile strength at 0°	[Pa]
UTS_22_T_fiber	Fibre ultimate tensile strength at 90°	[Pa]
UTS_11_C_fiber	Fibre ultimate compressive strength at 0°	[Pa]
UTS_22_C_fiber	Fibre ultimate compressive strength in 90°	[Pa]
UTS_S12_fiber	Fibre ultimate tensile strength in 45°/135°	[Pa]

After applying the rule of mixture model, the following material engineering properties for fibreglass are obtained and tabulated in Table 11.

Table 11: Fibreglass material engineering properties

Material property	Value
E_{11}	19.657 [Gpa]
E_{22}	1.382 [Gpa]
G_{12}	1.559 [Gpa]
v_{12}	0.46
UTS_{11}	319.78 [Mpa]
UTS_{22}	20.65 [Mpa]
UTS_{12}	82.70 [Mpa]

The values in Table 11 are for the composite of fibre and resin within the nylon and are the reason why the fibre values are lower than pure fibre as obtained and tested by Markforged [1]. A comparison of the values is tabulated in Table 12. The resin properties cannot be calculated because the resin is a Markforged trade secret.

Table 12: Micromechanics vs Markforged fibreglass comparison

Property	Micromechanics	Markforged	% difference
E_{11}	19.657 [Gpa]	21.00 [Gpa]	6.40

5.3 Classical laminate theory

In this section, a Matlab® version of the classical laminate theory is used to determine the strength of a composite with pre-defined parameters. The parameters determined from the micromechanics mathematical model are also used as input parameters as various other properties must be defined. The parameters needed are explained in Chapter 2.

Various software packages have been developed to calculate the in-plane stresses of composites using the classical laminate theory. The one that stands out is known as Laminate Analysis Program (LAP). LAP is a software tool for the design and analysis of composite material laminates [21]. The solution algorithms employed are based on the CLT as discussed in Chapter 2.

The program requires the definition of primary material engineering properties at the layer level and the definitions of stacking sequences and loadings or constraints respectively. Material stiffness properties can be constant or piecewise functions of stress or strain. The properties entered into the program are from Chapter 4 and the micromechanics.

5.3.1 Step 1: Create new materials

The first step is to create a new material for both the fibreglass and the nylon. In this step, the program requires some basic mechanical properties. The values needed for calculations and the description of each parameter are found in Table 13.

Table 13: LAP input parameters

Parameter	Description	Unit
E11	Modulus of elasticity at 0°	[Pa]
E22	Modulus of elasticity at 90°	[Pa]
G12	Modulus of elasticity at 45°/135°	[Pa]
v12	Poisson ratio	[-]
S11 T	Ultimate tensile strength at 0°	[Pa]
S22 T	Ultimate tensile strength at 90°	[Pa]
S11 C	Ultimate compressive strength at 0°	[Pa]
S22 C	Ultimate compressive strength at 90°	[Pa]
S12	Ultimate tensile strength at 45°/135°	[Pa]

Populating the material properties as described for the fibre and the nylon can be seen in Figure 36 and Figure 37.

The screenshot shows the 'Materials' tab in a software interface. The 'Name' list on the left contains 'FIBERGLASS' and 'NYLON'. The 'FIBERGLASS' material is selected, and its properties are displayed on the right. The properties are organized into sections: Elastic properties (E11, E22, G12, v12), Resin properties (resin E, resin v, nominal VF, actual VF), and Ultimate Strength properties (S11 T, S11 C, S12, S22 T, S22 C, F12). The values for FIBERGLASS are: E11 = 19657, E22 = 1382, G12 = 1559, v12 = 0.46, S11 T = 319.78, S11 C = 210.9, S12 = 82.7, S22 T = 20.65, S22 C = 74.4, and F12 = auto. The 'Logd' dropdown is set to 'T'. The 'Units' are set to mm, kN, deg, and °C. The 'Auto-Solve' checkbox is checked. The 'BFS data...' and 'Design data...' buttons are at the bottom.

Property	Value
E11	19657
E22	1382
G12	1559
v12	0.46
resin E	
resin v	
nominal VF	
actual VF	
Ultimate Strength properties:	
S11 T	319.78
S11 C	210.9
S12	82.7
S22 T	20.65
S22 C	74.4
F12	auto

Figure 36: LAP fibreglass material engineering properties

The screenshot shows the 'Materials' tab in a software interface. The 'Name' list on the left contains 'FIBERGLASS' and 'NYLON'. The 'NYLON' material is selected, and its properties are displayed on the right. The properties are organized into sections: Elastic properties (E11, E22, G12, v12), Resin properties (resin E, resin v, nominal VF, actual VF), and Ultimate Strength properties (S11 T, S11 C, S12, S22 T, S22 C, F12). The values for NYLON are: E11 = 456.641, E22 = 456.641, G12 = 456.641, v12 = 0.4, S11 T = 54, S11 C = 30, S12 = 48, S22 T = 10.8, S22 C = 30, and F12 = auto. The 'Logd' dropdown is set to 'T'. The 'Units' are set to mm, kN, deg, and °C. The 'Auto-Solve' checkbox is checked. The 'BFS data...' and 'Design data...' buttons are at the bottom.

Property	Value
E11	456.641
E22	456.641
G12	456.641
v12	0.4
resin E	
resin v	
nominal VF	
actual VF	
Ultimate Strength properties:	
S11 T	54
S11 C	30
S12	48
S22 T	10.8
S22 C	30
F12	auto

Figure 37: LAP nylon material engineering properties

The parameters left blank include the thermal expansion coefficients, the moisture expansion coefficients and the nominal and actual fibre volume fractions. These factors were assumed to have had a small enough effect on the results for them not to be calculated.

5.3.2 Step 2: Create a composite lay-up

The following information to be declared is the composite lay-up. In this section, the composition of the composite must be created. The parameters required for this are the number of layers, the material used in the layers, the thickness of the layer and the angle of the matrix or fibre. It is useful to be able to create multiple lay-up configurations. Figure 38 shows the populated table.

Stacking Sequence	Material	Thickness	Angle
1	NYLON	0.1	0
2	FIBERGLASS	0.1	0
3	FIBERGLASS	0.1	0
4	FIBERGLASS	0.1	0
5	FIBERGLASS	0.1	0
6	FIBERGLASS	0.1	0
7	FIBERGLASS	0.1	0
8	FIBERGLASS	0.1	0
9	FIBERGLASS	0.1	0
10	FIBERGLASS	0.1	0
11	FIBERGLASS	0.1	0
12	NYLON	0.1	0

Figure 38: LAP composite lay-up configuration

5.3.3 Loading

The next tab is the loading tab where all possible loading combinations can be edited. The loading types include strain, moment and force in x, y and xy directions. Various other parameters like the operating temperature and moisture content can be included. For this study, a load has been applied in the x-direction as seen in Figure 39. This load represents the load exerted onto the specimen when testing in tensile. It should be noted that the direction is in respect of the length of the specimen.

Lay-up: 0 Load: T

Units: mm kN deg °C -

Materials | Lay-ups | Loadings | Print Reports | Preferences

Name	Type	Magnitude	Order	Steps
T	ex	1000	1	1
	Ny	0	1	1
	Nxy	0	1	1
	Mx	0	1	1
	My	0	1	1
	Mxy	0	1	1

Top Operating Temperature: 0

Bottom Operating Temperature: 0

Moisture Content (%): 0

Tools... Design data...

Figure 39: LAP loading configuration

5.3.4 Preferences

The preferences tab is the last to be used. In this portion of the program, the strength calculations, volume fraction correction method and non-linear solutions can be edited. This option was chosen as the rule of mixtures is used to calculate the mechanical properties of the specimen. Regarding the failure theory of composites, the Tsai-Hill criteria were chosen as seen in Figure 40.

Lay-up: 0 Load: T

Units: mm kN deg °C -

Materials | Lay-ups | Loadings | Print Reports | Preferences

For This Datafile

Strength Calculations

Failure criteria used to track local failure:

- ☐ Tsai-Wu
- ☒ Tsai-Hill
- ☐ Hoffman
- ☐ Max. Stress
- ☐ Max. Strain
- ☐ Custom

Thickness + Stiffness corrections

Volume fraction correction method:

- ☐ None
- ☒ Rule of Mixtures
- ☐ Halpin-Tsai

Non-Linear Solutions

☒ Monitor Results step by step

For the last % of the steps...

...delay each step by msec.

Alert Zero Stiffness:

- ☒ with Sound
- ☐ with Message

Design data...

Figure 40: LAP preferences tab

5.3.5 Results

The final step is to solve the composite configuration and LAP displays the results in a separate window according to the parameters selected for display. The results include the effective stiffness, effective coefficients, expected strength, load vector, strain vector, BFS strength criterion results, ABD matrix and the inverse ABD matrix. The most important portion for this study is the expected strength portion which, using the Tsai-Hill criteria, showcases the load at which the first ply failure will occur.

Effective Stiffness :				Effective Coefficients :			
	Membrane	Flexural		Membrane	Flexural		
E _{xx} =	16457.2	11568.6	kN/mm ²	α _{xx} =	(undefined)	(undefined)	
E _{yy} =	1239.95	1022.51	kN/mm ²	α _{yy} =	(undefined)	(undefined)	
G _{xy} =	1375.27	1094.58	kN/mm ²	α _{xy} =	(undefined)	(undefined)	
ν _{xy} =	0.45568	0.4468		β _{xx} =	(undefined)	(undefined)	
ν _{yx} =	0.034333	0.039491		β _{yy} =	(undefined)	(undefined)	
E _{bxx} =		1665.88	kN mm	β _{xy} =	(undefined)	(undefined)	
E _{lyy} =		147.241	kN mm				
G _J =		630.478	kN mm				
Expected Strength :							
+N _x :	load at first ply failure	= 321.272 kN/mm	(layers 1-12)				
	ultimate load	= 321.272 kN/mm					
+N _y :	load at first ply failure	= 22.2506 kN/mm	(layers 1-12)				
	ultimate load	= 22.2506 kN/mm					
-N _x :	load at first ply failure	= 211.886 kN/mm	(layers 1-12)				
	ultimate load	= 211.886 kN/mm					
-N _y :	load at first ply failure	= 80.1139 kN/mm	(layers 1-12)				
	ultimate load	= 80.1139 kN/mm					
N _{xy} :	load at first ply failure	= 87.5447 kN/mm	(layers 1-12)				
	ultimate load	= 87.5447 kN/mm					
Load Vector :				Strain Vector : (HTM)			
			(effective stress)				
N _{xx} =	1.9749e+007	kN/mm	1.6457e+007	ε _{xx} =	1000	-	
N _{yy} =	0	kN/mm	0	ε _{yy} =	-455.68	-	
N _{xy} =	0	kN/mm	0	ε _{xy} =	0	-	
M _{xx} =	0	kN	0	κ _{xx} =	0	1/mm	
M _{yy} =	0	kN	0	κ _{yy} =	0	1/mm	
M _{xy} =	0	kN	0	κ _{xy} =	0	1/mm	
BFS strength criterion results :							
E'	= 7685.47	kN/mm ²					
K _{IC}	= (undefined)						
G _{IC}	= (undefined)						
Unnotched Longitudinal Compressive Strength	= (undefined)						
Failing layers :	-						
Problems encountered :							
	The lay-up is not symmetric.						
	The lay-up is not in longitudinal compression.						
ABD Matrix :							
			$\begin{bmatrix} \text{kN/mm} & \text{kN} \\ \text{kN} & \text{kN mm} \end{bmatrix}$				
20062.6	688.81	0	0	0	0		
688.81	1511.59	0	0	0	0		
0	0	1650.33	0	0	0		
0	0	0	1695.8	66.9685	0		
0	0	0	66.9685	149.885	0		
0	0	0	0	0	157.62		
Inverse ABD Matrix :							
			$\begin{bmatrix} \text{mm/kN} & 1/\text{kN} \\ 1/\text{kN} & 1/(\text{kN mm}) \end{bmatrix}$				
5.06363e-05	-2.30742e-05	0	0	0	0		
-2.30742e-05	0.000672068	0	0	0	0		
0	0	0.00060594	0	0	0		
0	0	0	0.000600284	-0.000268206	0		
0	0	0	-0.000268206	0.00679159	0		
0	0	0	0	0	0.00634439		

Figure 41 – LAP results window 0° fibre orientation

The process is repeated for all three fibre configurations and only the relevant data is compared with the experimental data. Table 14 shows the data from LAP compared with the experimental data for the expected strength. This value is the maximum load the tensile testing machine can apply to the specimen before the fibre starts breaking.

Table 14: Expected strength LAP vs experimental

Fibre orientation	Fibre/nylon layers	Width/thickness	LAP	Experimental (Gpa)	% fault
0°	10/2	12.7/1.2	321.272	324.10	0.87
90°	10/2	12.7/1.2	22.251	21.514	3.43
45°/135°	10/2	12.7/1.2	126.6	86.539	46.29

It is clear from the values in Table 14 that LAP can be used as a software package to predict the strength of the 3D printed composites within a specified accuracy. This also confirms the literature from Chapter 2, that the Markforged printed composite should abide by the classical laminate theory.

The data in Table 14, with specific reference to the 45°/135° fibre orientation, shows a rather large % fault between the LAP and Experimental. This large difference is due to the nature of the fibre layers joining into each other. Traditional composite layers is woven into each other, whereas the printed composites is simply glued together with the resin matrix.

The next information gathered from the experiment is the effective stiffness LAP predicted regarding the specimens only from the 0° fibre-orientation configuration data. The mechanical properties calculated from Figure 41 are compared to the properties from the experimental procedure and are tabulated in Table 15.

Table 15: 0° fibre orientation material engineering properties comparison

Property	Fibre/nylon layers	Width/thickness	LAP	Experimental	% fault
E_{11}	10/2	12.7/1.2	16.457 [Gpa]	16.854 [Gpa]	2.36
E_{22}	10/2	12.7/1.2	1.239 [Gpa]	1.247 [Gpa]	0.64
G_{12}	10/2	12.7/1.2	1.375 [Gpa]	1.090 [Gpa]	26.15
ν_{12}	10/2	12.7/1.2	0.456	0.45	1.32

From Table 15, it is clear that LAP predicted the other fibre orientation properties very accurately.

5.4 Verification of results

In order to verify that CFF abides by the classical laminate theory, the strength can be modelled using LAP with inputs determined by micromechanics; three different orientations are printed and compared. These orientations are chosen so a variety of orientations from 10° to 45° can be tested to establish if the specimens will follow a typical composite trend line for unidirectional composites. The verification also focused on whether the micromechanics mathematical model calculated sufficiently accurate material properties.

5.4.1 10° fibre orientation

The first specimens were printed in 10° and compared to results from LAP. The experimental results from the tensile tests are compared to the results from LAP with the lay-up as defined in Figure 42.

Stacking Sequence	Material	Thickness	Angle
1	NYLON	0.1	0
2	FIBERGLASS	0.1	10
3	FIBERGLASS	0.1	10
4	FIBERGLASS	0.1	10
5	FIBERGLASS	0.1	10
6	FIBERGLASS	0.1	10
7	FIBERGLASS	0.1	10
8	FIBERGLASS	0.1	10
9	FIBERGLASS	0.1	10
10	FIBERGLASS	0.1	10
11	FIBERGLASS	0.1	10
12	NYLON	0.1	0

Figure 42: LAP 10° fibre orientation lay-up

The results from LAP and the experimental data are compared in Table 16. Figure 43 also shows how the failure zone of the 10° fibre orientation is very similar to that of the 0° fibre orientation.



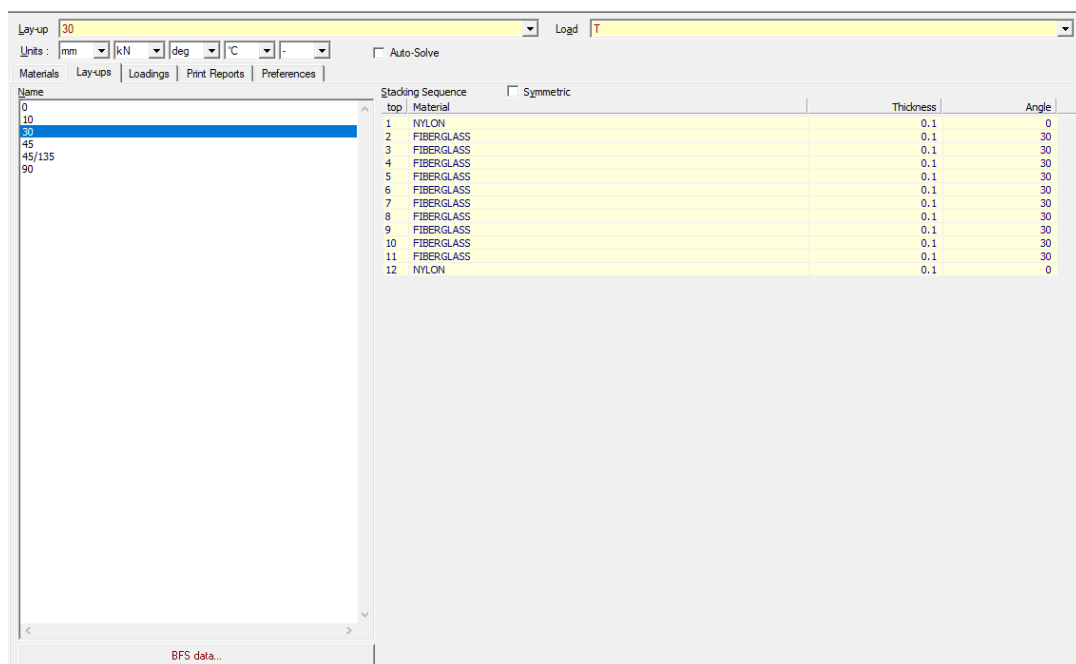
Figure 43: 10° fibre orientation specimen post-testing

Table 16: 10° fibre orientation material engineering properties comparison

Property	Fibre/nylon layers	Width/thickness	LAP	Experimental	% fault
UTS	10/2	12.7/1.2	263.051	212.92	23.54
E_{11}	10/2	12.7/1.2	12.846	13.755	6.61

5.4.2 30° fibre orientation

The second batch of specimens was printed in 30° and compared to results from LAP. The experimental results from the tensile tests are compared to the results from LAP with the lay-up as defined in Figure 44.

**Figure 44: LAP 30° fibre orientation lay-up**

The results from LAP and the experimental data are compared in Table 17.

Table 17: 30° fibre orientation material engineering properties comparison

Property	Fibre/nylon layers	Width/thickness	LAP	Experimental	% fault
UTS	10/2	12.7/1.2	83.227	79.099	5.22
E_{11}	10/2	12.7/1.2	4.723	5.546	14.84

5.4.3 45° fibre orientation

Lastly, specimens were printed in 45° and compared to results from LAP. The experimental results from the tensile tests were compared to the results from LAP with the lay-up as defined in Figure 45.

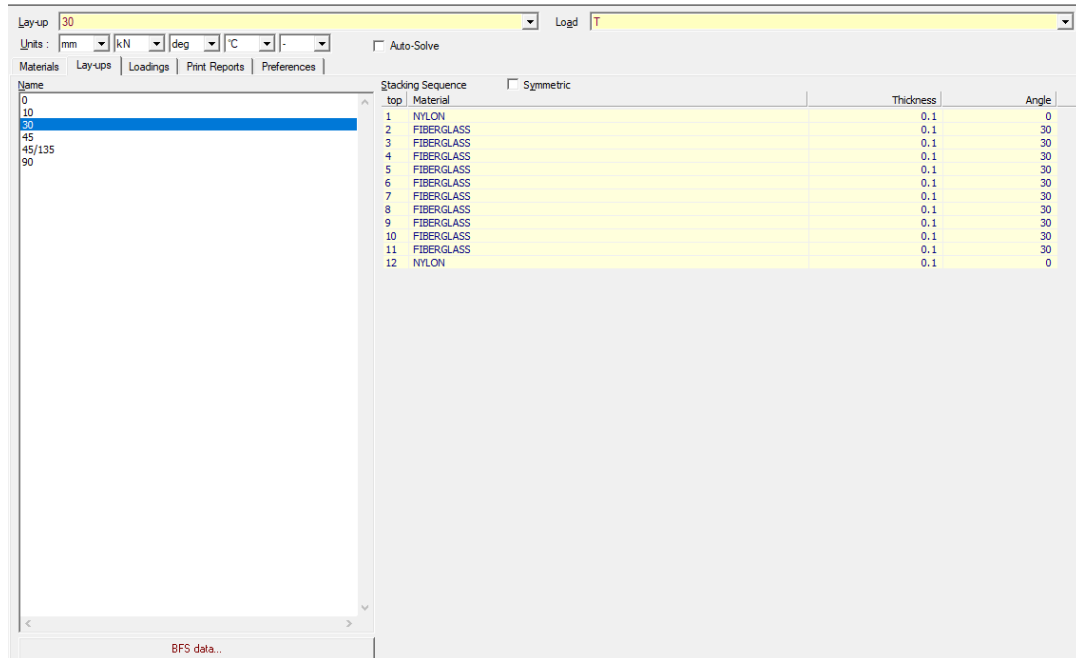


Figure 45: LAP 45° fibre orientation lay-up

The results from LAP and the experimental data are compared in Table 18.

Table 18: 45° fibre orientation material engineering properties comparison

Property	Fibre/nylon layers	Width/thickness	LAP	Experimental	% fault
UTS	10/2	12.7/1.2	44.462	41.874	6.18
E_{11}	10/2	12.7/1.2	2.598	3.379	23.11

5.5 Discussion

The results found in the previous section support the literature that the Markforged composite abides by the classical laminate theory. The values are within an acceptable degree of deviation for LAP to be used as a prediction software package for the expected strength of the 3D printed composite from Markforged.

Figure 46 illustrates the comparison between LAP and the experimental values. This trend line correlates with the typical trend of a unidirectional composite. The larger difference in the region from 10° to 30° is mainly caused by the increase in the air gaps between the fibres. The micromechanics, therefore, has to accommodate such an event. When the orientation increases to 45° and up to 90°, most of these air gaps are filled with either fibre resin or parts of the nylon being forced into the smaller cavities.

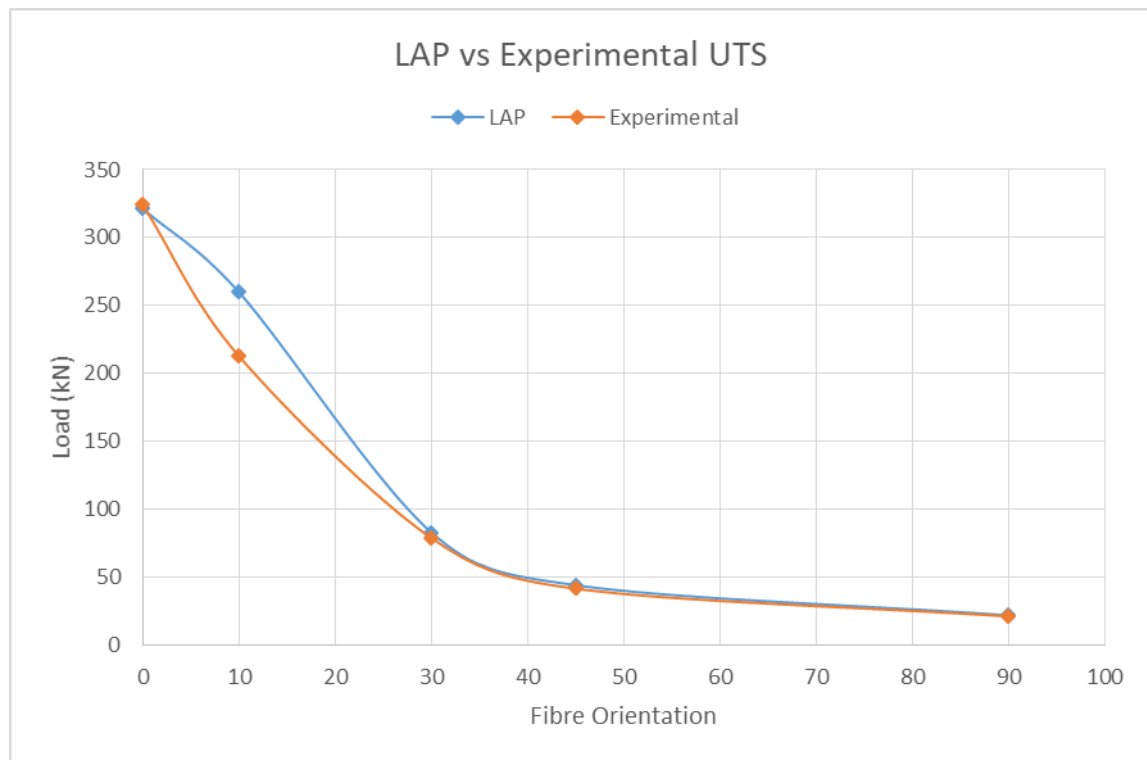


Figure 46: LAP vs experimental UTS

The overall comparison between the values from experimental procedures and those from LAP are quite similar, considering the assumptions used for this model. To improve the difference between these two methods, the mathematical model to determine the individual material properties of the composite can be improved. It should be noted that this model only uses unidirectional fibre orientations and does not account for combinations of fibre orientation lay-ups. The results also proves that the micromechanics mathematical model can calculate the expected results.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

In this chapter, all the work from the preceding chapters is taken into account and the appropriate recommendations for future work are made from the conclusions.

This study shows the lack of mechanical properties known for 3D printed materials, especially CFF materials. After the characterisation process, the mechanical properties' results indicate that 3D printed composites, as with the fibreglass and nylon used in this study, abide by the classical laminate theory. Using micromechanics, the material properties of the fibre section of the composites can be determined accurately. These material properties can then be put into a Matlab® model of the classical laminate theory or software using this theory to predict the strength of a composite, given different fibre orientations.

The theory of micromechanics showed accurate results in determining the material properties of the individual materials in the composite. Using volume fractions, considering the geometry of the printed fibres and assuming there are no gaps between the fibres and/or the fibres and nylon, showed sufficient results. The model can be altered for precision by introducing the gap theory. This theory investigates the gaps between the fibres and the nylon with the fibre by taking measurements and microscopic photos. These gaps will then introduce an additional volume fraction that can be used with the rule of mixtures.

Given the correct material properties and under the Tsai-Hill failure criterion, the LAP predicted the strength of the composites very accurately in comparison with the experimental data obtained. The program is exceptionally powerful with composite predictions and, given the correct parameters in all fields provided, the software would be even more accurate. It should be noted that this is only valid for the tested fibreglass-nylon composite and further testing is required to confirm this for other composite combinations.

Further investigation into regulating the temperature at which the specimens are printed and tested will improve the results. It will also give a better understanding of the thermal impact on the composite. Resin is hugely reliant on temperature and some of the testing was done in the winter, which may have influenced the results.

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APPENDIX 1: MATLAB MODEL FOR MECHANICAL PROPERTIES

```
%% Markforged test
%
% This function is used to determine the material properties of Markforged
% composite materials, with the main focus on nylon and fibreglass.
% Compression tests are done according to ASTM D6641
%
% Inputs: P_f = maximum load to failure [N]
%         w = specimen gauge width [mm]
%         h = specimen gauge thickness [mm]
%
% Outputs: F_cu = laminate compressive strength [MPa]
%          theta_i = tensile strength at i_th data point [MPa]

clc
clear
%% Import all values from excel sheet

Lg_D6641_0 = xlsread('D3039_Mark_0.xlsx','3','A:A');
P_D6641_0 = xlsread('D3039_Mark_0.xlsx','3','B:B');
Extensometer = xlsread('D3039_Mark_0.xlsx','3','D:D');

%% Calculate cross-sectional area of specimen

w = 12.7;
h = 1.2;

A_compression = w*h;

L_0 = 20;
%% Calculate laminate compressive strength

P_f = max(P_D6641_0);
F_cu = P_f/(A_compression);

% Determine best slope for given data

sigma = P_D6641_0./A_compression;
epsilon = Lg_D6641_0./L_0;
epsilon_extenso = Extensometer;

sigma_size = size(sigma,1);
sigma_size_yield = sigma_size*0.5;

n = zeros(sigma_size,1);
E_1 = zeros(sigma_size,1);
E_2 = zeros(sigma_size,1);
value = zeros(sigma_size,1);
r_1 = zeros(sigma_size,1);
turn_loop = zeros(sigma_size,1);

m = zeros(sigma_size,1);
x_location = zeros(sigma_size,1);
y_location = zeros(sigma_size,1);

%%
```

```

for i = 1:100

    n(i) = size(sigma,1)*(0+i/100);

    [curvefit,gof] = fit(epsilon(1:round(n(i))), sigma(1:round(n(i))),
'poly1', 'normalise','on');

    r_1(i) = gof.rsquare;
end

%%
[MaxVal,MaxIndex] = max(E_1);
E = MaxVal;

slope_index = find(r_1(15:100)<0.9996,1) + 14;

p_true =
polyfit(epsilon(1:round(((slope_index/100)*sigma_size))),sigma(1:round(((slope_index/100)*sigma_size))),1);

E_1_true = p_true(1);
E_2_true = p_true(2);

x1 = epsilon;
y1 = polyval(p_true,x1);

x1_offset = x1 + 0.002;

[xi,yi] = polyxpoly(x1_offset,y1,epsilon,sigma);

F_yield = min(yi);

E_location = min(xi);

x = [0.002 E_location];

y = [0 F_yield];

%% Plot graphs

plot(epsilon,sigma)
title('D6641 5^o Specimen 4')
xlabel('Strain [-]')
ylabel('Stress [MPa]')
hold on
plot(epsilon_extenso,sigma)
plot(x1,y1)
hold on
pl = line(x,y);
pl.Colour = 'red';
pl.LineStyle = '--';

fprintf('Cross-sectional area = %0.1f mm^2\n',A_compression)
fprintf('Maximum load before failure = %0.2f N\n',P_f*1000)
fprintf('Ultimate compression strength = %0.2f MPa\n',F_cu*1000)
fprintf('Yield strength = %0.2f MPa\n',F_yield*1000)
fprintf('Young's modulus of elasticity = %0.5f GPa\n',E_1_true)

```

ANNEXURE 2: ASTM STANDARDS

8.1 ASTM D3039: Tensile properties of polymer matrix composite materials

The ASTM standard D3039 is used for the tensile testing of the nylon-fibreglass composite, as used by Markforged themselves in their material properties report [11]. The standard describes all relevant information including specimen geometry, testing procedures and the calculation of material properties.

8.1.1 Specimen geometry

The design of mechanical test coupons, especially those using end tabs remains, to a large extent, an art rather than a science, with no industry consensus on how to approach the engineering of the gripping interface [24]. Each major composite testing laboratory has developed gripping methods for the specific material systems and environments commonly encountered within that laboratory. It is, therefore, difficult to recommend a universally useful approach. The geometry of the test coupon is, therefore, broken down into the following three levels:

<u>Purpose</u>	<u>Degree of geometry definition</u>
5.1.1.1 General requirements	Mandatory shape and tolerances
5.1.1.2 Specific recommendations	Non-mandatory suggested dimensions

8.1.1.1 General requirements

It is not necessary to use tabs. The key factor in the selection of specimen tolerances and gripping methods is the successful introduction of load into the specimen and the prevention of premature failure caused by a significant discontinuity. Therefore, determine the need to use tabs and specification of the major tab design parameters, by the end result: acceptable failure mode and location. A complete list of requirements for specimen shape, dimensions and tolerances is shown in Table 19.

Table 19: Tensile specimen geometry requirements [24]

Parameter	Requirement
Coupon requirements:	
Shape	Constant rectangular cross-section
Minimum length	Gripping + 2 times width + gauge length
Specimen width	As needed
Specimen width tolerance	± 1 % of width
Specimen thickness	As needed
Specimen thickness tolerance	± 4 % of thickness

Specimen flatness	Flat with light finger pressure
Tab requirements (if used):	
Tab material	As needed
Fibre orientation (composite tabs)	As needed
Tab thickness	As needed
Tab thickness variation between	$\pm 1\%$ tab thickness
Tabs:	
Tab bevel angle	5 to 90°, inclusive
Tab step at bevel to specimen	Feathered without damaging specimen

8.1.1.2 Specific recommendations

The specimen width and thickness should be selected to promote failure in the gauge section and should ensure enough fibres are present in the cross-section to be statistically representative of the bulk material. The gauge should be located as far from the grips as reasonably possible and a significant amount of material under stress should be provided to produce a more statically-significant result. Table 20 shows geometry recommendations for typical material configurations. A number of testing laboratories have found the above to produce acceptable failure modes on a wide variety of material systems.

Table 20: Tensile specimen geometry recommendations [24]

Fibre orientation	Width [mm]	Overall length [mm]	Thickness [mm]	Tab length [mm]	Tab thickness [mm]	Tab bevel angle [°]
0° Unidirectional	15	250	1.0	56	1.5	7 or 90
90° Unidirectional	25	175	2.0	25	1.5	90
Balanced and symmetric	25	250	2.5	Emery cloth	---	---
Random-discontinuous	25	250	2.5	Emery cloth	---	---

8.1.2 Procedure

Following final specimen machining and any conditioning but before the tension testing, determine the specimen area as $A = w \times h$, at three places in the gauge section. Report the area as the average of these three determinations to an accuracy within 1% of the sample width and thickness [24].

8.1.2.1 Speed of testing

Set the speed of testing to effect a nearly constant strain rate in the gauge section. The strain rate should be selected so as to produce failure within 1 to 10 min. If the ultimate strain of the material cannot be reasonably estimated, initial trials should be conducted using standard speeds until the ultimate strain of the material and the compliance of the system are known. The suggested standard speeds are:

- **Strain-controlled tests:** A standard strain rate of 0.01 min^{-1} .
- **Constant head-speed tests:** A standard head displacement rate of 2 mm/min .

The MTS Landmark machine that will be used for the testing of the composite is very advanced and thus a speed of 2 mm/min will be used.

8.1.2.2 Extensometers

For most purposes, the extensometer gauge length should be in the range of 10 to 50 mm. Extensometers shall satisfy, at a minimum, Practise E 83 [25], Class B-1 requirements for the strain range of interest and shall be calibrated in accordance with Practise E 83 [25]. The requirements are met by the MTS 634.31F-24 extensometer, shown in Figure 47. The extensometer will be set at a distance of 15 mm to reduce material cost of the ASTM D3039 specimen geometry.



Figure 47 - MTS 634 extensometer [26]

8.1.3 Calculation

After the data has been extracted, various calculations can be done to determine the material properties of the composite material.

8.1.3.1 Tensile stress/tensile strength

The ultimate tensile strength can be determined by using (58). If the tensile modulus is to be calculated, the tensile stress at each required data point can be determined using

$$F^u = P^{\max} / A \quad (58)$$

$$\sigma_i = P_i / A \quad (59)$$

where:

F^{tu} = ultimate tensile strength, [MPa],

P^{max} = maximum load before failure, [N],

σ_i = tensile stress at i th data point, [MPa],

P_i = load at i th data point, [N],

A = average cross-sectional area, [mm²].

8.1.3.2 Tensile strain/ultimate tensile strain

If tensile modulus or ultimate tensile strain is to be calculated and material response is being determined by an extensometer, tensile strain can be determined from the indicated displacement at each required data point using

$$\epsilon_i = \delta_i / L_g \quad (60)$$

where:

ϵ_i = tensile strain at i th data point,

δ_i = extensometer displacement at i th data point, [mm],

L_g = extensometer gage length, [mm].