Analysis and modelling of 3D printed springs for use in spacecraft

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ANALYSIS AND MODELLING OF 3D PRINTED SPRINGS FOR USE IN SPACECRAFT

ENEA SACCO

A thesis submitted to Nanyang Technological University
in partial fulfilment of the requirement for degree of
Doctor of Philosophy
Supervised by Moon, Seung Ki (Assoc. Prof.)

**NANYANG
TECHNOLOGICAL
UNIVERSITY**
SINGAPORE

Mechanical and Aerospace Engineering
Nanyang Technological University
Singapore
June 2, 2020

Statement of Originality

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This thesis contains material from 1 paper(s) published in the following peer-reviewed journal(s) / from papers accepted at conferences in which I am listed as an author.

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The contributions of the co-authors are as follows:

- Prof Moon provided the initial project direction and revised the manuscript drafts.
- I prepared the manuscript drafts.

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Date

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Enea Sacco

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ACRONYMS

- 3DP** 3D Printing 10, 13, 18, 20, 24, 28, 29, 36, 37, 72
- 3DPrint** 3D Printing in Zero-G Experiment 14
- ABS** Acrylonitrile Butadiene Styrene 14–16, 18, 29, 30, 49, 50, 60, 82, 127, 162, 201, 203
- ACES** Automated Additive Construction System 33
- ACME** Additive Construction with Mobile Emplacement 33, 34
- ALD** Atomic Layer Deposition 26
- AM** Additive Manufacturing 1–3, 5, 6, 8–10, 12–14, 16, 18, 20, 22–24, 26–31, 34, 36–41, 45, 50, 53, 58, 60, 65, 67, 94, 95, 111, 132, 137, 160–162, 164, 171, 172, 175, 176, 178
- AMAZE** Additive Manufacturing Aiming Towards Zero Waste and Efficient Production of High-Tech Metal Parts 26, 27
- AMF** Additive Manufacturing Facility 14–16
- AMFS** Additive Manufacturing For Space 2, 5, 6, 10, 14, 20, 22, 24, 26–28, 32, 38, 39, 41, 172
- AMSC** America Makes & ANSI Additive Manufacturing Standardization Collaborative 38
- AMSII** Additive Manufacturing Structural Integrity Initiative 39
- BC** Boundary Condition 140–143, 146–148
- BJP** Binder Jet Printing 36
- BVP** Boundary Value Problem 139
- CAD** Computer Aided Design 97
- CFT** Curve Fitting Toolbox 107, 116, 193, 194, 196, 208
- CGT** Cold Gas Thruster 3, 42, 43, 172
- CIRAS** Commercial Infrastructure for Robotic Assembly and Services 19
- CT** Computer Tomography 14, 23
- DED** Direct Energy Deposition 24, 27
- DFAM** Design for Additive Manufacturing 37, 38, 172
- DIC** Digital Image Correlation 72–74, 83, 173, 182, 183, 186, 203, 205
- DLP** Digital Light Processing 1
- DMLS** Direct Metal Laser Sintering 26, 28, 29

DMP Direct Metal Printing 36
EBF³ Electron-Beam Freeform Fabrication 24
EBM Electron Beam Melting 9, 23, 24
EOS Elctro Optical Systems 48
ESA European Space Agency 10, 35
FDM Fused Deposition Modeling 49, 57
FEA Finite Element Analysis 52, 58, 88–90, 93, 98, 99, 110, 137, 175, 177
FFF Fused Filament Fabrication 3, 14, 16, 18, 19, 29, 30, 34, 36, 49, 51, 58, 82, 88, 108, 111, 136, 154, 173
FH Falcon Heavy 13
GRC Glenn Research Center 22, 23, 26
GSFC Goddard Space Flight Center 26
HCF High-Cycle Fatigue 23
HIP Hot Isostatic Pressing 22, 23
ISAM In-Space Additive Manufacturing 14, 18, 172
ISM In-Space Manufacturing 14, 17–19, 172
ISRU In-Situ Resource Utilization 32–36, 172
ISS International Space Station 14–18, 22, 29, 172
JPL Jet Propulsion Laboratory 32
LBM Laser Beam Melting 23
LCUSP Low Cost Upper Stage-Class Propulsion 24
LENS Laser Engineered Net Shaping 2, 24, 35, 153
LEO Low Earth Orbit 13, 24, 49
LFMT Laser Freeform Manufacturing Technology 24
LOM Laminated Object Manufacturing 36
MIS Made In Space 14, 16, 19
MOV Main Oxidizer Valve 28
MPMT Multipurpose Precision Maintenance Tool 16, 17
MSFC Marshall Space Flight Center 14, 26
MSFC-STD-3716 Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware 39
MSFC-STD-3717 Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes 39
MSG Microgravity Science Glovebox 14
NASA National Aeronautics and Space Administration 10, 13–15, 18, 22, 24, 28, 30, 32, 33, 39, 43
NRC National Research Council 12
NTP Nuclear Thermal Propulsion 26
ODE Ordinary Differential Equation 148
OSIRIS-REx Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer 12, 13
PBF Powder Bed Fusion 22, 27, 36, 39
PC Polycarbonate 14, 15, 30, 49
PDE Partial Differential Equation 139, 140, 147
PE Polyethylene 14, 15
PEEK Polyetheretherketone 32, 50

PEI Polyetherimide 50
PETG Polyethylene Terephthalate Glycol 49
PLA Polylactic Acid 3, 5, 7, 30, 49, 50, 52–54, 58, 74, 76, 78, 81–83, 85, 95, 100, 103, 105–108, 112, 114, 117, 125–130, 154, 157–159, 161, 162, 169, 173–177, 201, 205
PPT Pulsed Plasma Thruster 30
RFP Rapid Freeze Prototyping 1
SEM Scanning Electron Microscope 60
SLA Stereolithography 1, 31
SLM Selective Laser Melting 1, 7, 22, 24, 25, 35, 37, 39, 48
SLS Selective Laser Sintering 1, 32, 34, 167
TAS Thales Alenia Space 10, 29
TPU Thermoplastic Polyurethane 49, 50
TUI Tethers Unlimited, Inc. 18
UTM Universal Testing Machine 71, 72, 76, 81, 90, 97, 101, 102, 107, 112, 187, 188

Summary

The use of additive manufacturing in the space industry is growing and there are many developments being made in a wide variety of fields, from tools for astronauts to rocket combustion chambers to habitats on other worlds. Yet there are still several knowledge gaps that slow the development of standards and therefore the widespread use of 3D printing in the space industry. One of the gaps is the application of 3D printing to springs for use in spacecraft mechanisms. Consequently, the objective of this research is to analyse and model the behaviour of these widespread components. The first step is to characterise the material, which in this case is PLA printed using material extrusion with two different in-fills, using the orthotropic model. Another material, ULTEM 9085, was also used later in the research. The results showed that the two in-fill are mechanically similar but one is slightly better under shear stresses. Based on the understanding of the material characteristics, simulations are conducted using tensile coupons with varying numbers of perimeters and then compared to samples printed with the same characteristics. The simulations and experimental results are in close agreement with some slight differences that are negligible. Following this, 3D printed springs are investigated and design guidelines are developed: square wire cross-section is easier to print and mono directional in-fill produces stronger springs. The springs are tested both in the pre and post-deformation regions of the force-displacement plots. Testing showed that springs still behave semi-elastically while after plastic deformation. Comparison between ULTEM 9085 and PLA springs lead to the observation that smaller layers increase the stiffness of the springs. The next step of the research is the derivation of an equation for the calculation of the stiffness of 3D printed springs. Two methods are attempted and one is successful, leading to an equation that predicted spring constants that agreed very closely with experimental data. Finally a cost analysis of springs printed with ULTEM 9085 is performed, PLA was not considered because it was only used for developing the model. Various methods for reducing the cost are then investigated. The research presented in this thesis increases the knowledge of 3D printed materials in several ways. First a characterization of printed PLA is made which can be used as reference, given the printing settings. The behaviour of 3D printed springs in the plastic region can be used as a safety feature. Finally, the equation that predicts the spring constant can be used to save time in design processes and is the starting point for developing more equations that allow the full use of 3D printing's design freedom for springs.

CHAPTER 1

INTRODUCTION

1.1 Background

Additive Manufacturing (AM), also referred to colloquially as 3D printing, is a novel manufacturing technique that involves depositing layers of material one on top of the other to produce objects [46]. It is called additive manufacturing to distinguish it from machining, joining, and forming which instead typically remove material until the part is formed.

3D printing started as rapid prototyping in the 1980s where an early form of Stereolithography (SLA) [47] for producing plastic prototypes was developed to help visualization of parts during development. Today's 3D printers are able to produce functional parts as well as prototypes and many types of AM have been developed, for example material extrusion [26], Selective Laser Melting (SLM) [48], Selective Laser Sintering (SLS) [49], Digital Light Processing (DLP) [50], and Rapid Freeze Prototyping (RFP) [51]. They all use the same principle of layering material but differ in technique and material used.

AM is especially relevant in the production of complex and customized struc-

tures that used to be hard if not impossible to make [52, 53]. The space industry is a sector where low volume, highly customised parts are the norm so it is perfect for AM. Many space agencies and private companies have begun using AM for two main reasons. Firstly, mass savings from 40% to 90% are possible [54] and mass is directly related to cost since heavier objects cost more to launch. Secondly, AM can manufacture complex parts much faster than traditional manufacturing, reducing fabrication times from one year to only 4 months [55].

Research in Additive Manufacturing For Space (AMFS), AM that is directly applied to space, is varied. From using it to print CubeSat propulsion systems [9], to printing ceramics [56], to using Laser Engineered Net Shaping (LENS) [57] with Lunar and Martian regolith [58], to potentially printing an entire spacecraft in orbit [59]. Regolith is the term used to describe the lunar soil [60] but can be used to also for the Martian soil.

There are several problems with AM, though, since it is a manufacturing process that is difficult to model. Despite this, progress has been made in characterizing AM materials and efforts are being made to model and predict the material properties [46].

Spacecraft, like any machine, require mechanical components to work. One of the simplest and most used components is the mechanical spring, a device that can store and release mechanical energy. They come in many shapes and sizes and are used in many mechanisms, from clocks to vehicle suspension to antennas on spacecraft [61]. One area that is lacking research is 3D printing of springs, with an end goal to use them on spacecraft, and that is what this research attempts to remedy.

1.2 Motivation

There are two main reasons for using 3D printing in the space industry: design freedom and mass savings, which are intertwined. The latter is a consequence of

the former and is very important because mass is directly related to cost when it comes to spacecraft, which is discussed more in subsection 2.2.1. At the moment 3D printed parts are mostly used in static applications, such as struts. This type of loading also applies to some mechanisms and the idea of leveraging the design freedom of AM for fabricating ad-hoc components for more dynamic applications is beginning to be considered a reality, there is an example of a mechanism being developed for deployment of satellite solar panels that will be discussed later. The lack of understanding of how springs produced via AM behave when subjected to loading is the main driver for this research, in an effort to advance the understanding mainly for the benefit of the space industry.

During the research, a phenomenon was also observed and further investigated, which is the presence of localized strain oscillations observed during slow tensile loading. Since this phenomenon lies outside the scope of this research, the chapter about strain oscillations can be found in Appendix A.

1.3 Scope and objectives

The main focus of this research was to model the behaviour of 3D printed springs for use in mechanisms employed on spacecraft. They can be used in, for example, novel Cold Gas Thruster (CGT) designs or telescopic antennae and AM lends itself particularly well to these types of applications since the springs can be designed to be of any shape or size. The main material used was Polylactic Acid (PLA) printed with a Fused Filament Fabrication (FFF) printer because both are cheap, readily accessible, and printed PLA has a high degree of material anisotropy, making the results of this research easily applicable to other material types. A comparison was also done with springs printed with ULTEM 9085, a high performance thermopolymer that has been used in space-flight already. As mentioned before, an unusual phenomena was also observed and explored in the course of the research, the observations made can be found in the appendix.

A series of five sub-objectives was employed to achieve the main objective, listed below.

1. *Build a model for use in simulations and for reference.* This was done via:
 - identification of the most appropriate model for 3D printed materials
 - determination of the most accurate way of measuring the strain during testing
 - measurement of the material constants that were required for the model
 - comparison of the material constants based on the type of in-fill
2. *Variation of the number of perimeters for samples subjected to tensile loading,* achieved via:
 - simulation of tensile coupons with various numbers of perimeters and the most commonly used in-fill
 - printing and testing of tensile coupons with the same characteristics
 - comparison of the simulations and experimental results
3. *Using a novel thruster design or deployable helical antennae as possible applications, investigate the performance of 3D printed springs* by:
 - determining the spring wire cross-section that will print best
 - printing and testing a variety of helical springs, both compression and tension
 - testing the springs to explore differences and similarities between in-fill and types
 - perform cyclical loading in the post-deformation region
4. *To reduce the time needed for design and testing, derive an equation that calculates the spring constant of 3D printed springs:*
 - identify a derivation method

- perform the derivation
- compare the calculated and experimentally measured spring constants

5. *Develop methods for reducing the cost of printing springs by:*

- determining the material/support ratio of springs printed with UL-TEM 9085
- calculating the manufacturing time and cost of single and batches of springs
- leveraging the design freedom of AM to reduce the cost

1.4 Structure

The next chapter, chapter 2, will review the research that has been currently done on 3D printed springs and in AMFS in an effort to highlight the knowledge gaps. Following this, chapter 3 will discuss in more detail how the objectives will be achieved. Then chapter 4 will cover the methodology for measuring the material constants for PLA, the plastic used in this research. The simulation and physical testing of samples with varying numbers of perimeters is explained in chapter 5. This is followed by chapter 6 where the findings of tests done on compression and tension springs are discussed. Chapter 7 describes the derivation of an equation for predicting the spring constant of 3D printed springs. The final of the main chapters is concerned with costs of 3D printed springs, manufacturing time, and methods for reducing the cost. This thesis will then conclude with chapter 9, conclusions and future work. Each of the chapters apart from this and the last one will have a short summary at the end. Appendix A is about the exploration of localised strain oscillations that have been observed.

CHAPTER 2

LITERATURE REVIEW: 3D PRINTING FOR THE SPACE SECTOR

This chapter will discuss the research and developments that has been made in 3D printed springs and AM for use in the space industry. For AMFS, the discussion is going to be specifically about the accomplishments and gaps in AM research whose end goal is use in some aspect of space related applications, from launchers to habitat building on extraterrestrial planets.

2.1 3D printed springs

There is very little literature that applies AM to mechanical springs. Most authors make use of the following equation,

$$k = \frac{Gd^4}{8D^3N_a} \quad (2.1)$$

where k , the stiffness of the spring, can be calculated from the spring parameters shown in Figure 6.1 and the shear modulus of the material, G . This equation will be discussed in more detail in chapter 7 but has been stated here to emphasize that most research assumes that 3D printed springs are made of isotropic material, hence there is only one shear modulus.

In Saleh and Ragab [1], the authors studied the effects of geometry on the shear modulus of helical springs manufactured with Ti-6Al-4V via SLM. They solved Equation 2.1 for G then printed various springs with different pitches, examples shown in Figure 2.1, to verify if changes in the geometry of the material affected the shear modulus. The results revealed that the shear modulus ranges from 60 to 85% of the rated value (38 ± 3.8 GPa) and that springs with a smaller pitch were closer to the rated shear modulus. Interestingly the springs show no signs of supports, likely due to their small size (42.04 mm in length and 22.14 mm in diameter), something which could be a problem with bigger springs.

Figure 2.1: Springs with four different pitches, four samples were manufactured per pitch value [1].

He et al. created an interactive tool that allows users to create and control 3D printed deformable objects with embedded springs and joints [2]. First they tested tensile samples made of tough PLA [62] to obtain the material properties. Like Saleh and Ragab, they used Equation 2.1 to calculate the shear modulus of the material and verified that it gave them good results when varying spring parameters, see Figure 2.2b.

Hoa used 4D printing to manufacture and test leaf springs [3]. 4D printing is a manufacturing method that combines 3D printing together with the ability

(a) The Ondulé spring design tool interface [2].

(b) Results showing that 3D-printed helical springs have similar twisting performance to theoretical predictions with varied d , D , N , and L values [2].

of the part to reconfigure itself upon activation of some mechanism such as heat, light, or the absorption of moisture. The author used this manufacturing method to produce curved leaf springs using flat moulds and the results showed that it is possible to make composite springs with practical stiffnesses, like the one shown in Figure 2.3, and strengths comparable with composite springs that are currently used.

There is also some literature on composite material springs dealing with optimization of spring performance [63, 64], substitution of metal springs with composite ones [65], and tubular helical spring whose structure is made from multiple laminae of composite material [66]. None of these works are relevant to this research, though, because the manufacturing processes are very different from AM.

Other research that has been found is on the application of 3D printing to compliant mechanisms, which are flexible mechanisms that transfer an input

Figure 2.3: Example of a leaf spring created using 4D printing. When first produced the spring was flat but it became curved when the right conditions were met [3].

force and displacement from one point to an output force and displacement at another point through elastic body deformation. Only one source was found that discussed 3D printed mechanisms and their application to space: a primer produced by Merriam et al. on 3D-printed titanium compliant mechanisms for aerospace applications made with Electron Beam Melting (EBM) [67]. There is other research on compliant mechanisms outside of the space industry [68, 69, 70, 71, 72] but it is not relevant to this research since the focus is specifically on springs.

The work by Saleh and Ragab, He et al., and Hoa were the only instances of published literature that could be found that made use of AM to produce springs. None of the studies had as an objective the in-depth investigation of 3D printed springs, though, and made simplifications such as assuming that only one shear modulus was necessary, implying that 3D printed material is isotropic. This is an oversimplification of the material properties that will be discussed in more depth in subsection 4.1.3. Due to the sparsity of published literature on the subject, the conclusion can be made that there is a definite research gap when it comes to the application of AM to 3D printing. Only simple models are proposed in the literature and no detailed study has been made that develops guidelines for

springs manufactured via AM.

2.2 Research in AM for space

An attempt has been made to make this literature review as comprehensive as possible, but it is very difficult to cover all AMFS because to the sparsity of details when it comes to research in this specific area due to various reasons. Firstly governmental agencies like National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) are at times not able to release sensitive information to the public so cannot go into much detail. Then there is the fact that private companies such as Space-X, Boeing, Thales Alenia Space (TAS), and Airbus usually release even less details, most research news coming in the form of press releases and finished products whose details are protected by intellectual copyrights. Finally, there are relatively few research institutions such as universities that specialize in AMFS, most of the research is in general AM. More specific review papers on general AM can be found for example on processes [73, 57], materials [74, 75], simulation and modelling [76, 46], and cost models [77, 78].

2.2.1 The importance of mass reductions for spacecraft and launchers

Spacecraft are composed of many materials including various types of plastics, metals and alloys, ceramics, composites, and glass [79]. Some, like plastics, do not weigh much but metals such as aluminium, steel, and inconel that are used for large parts of spacecraft are the main source of weight. As previously mentioned, one of the main ways that 3D Printing (3DP) can substantially help to reduce costs is making parts lighter, which comes from the manufacturing processes' inherent design freedom. This short section discusses in simplified terms the main way that 3D printing reduces costs and aids the space industry. An

example spacecraft moving in a circular orbit with speed v has velocity

$$v = \sqrt{\frac{GM}{r}} \quad (2.2)$$

where $G = 6.67 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}$ is the universal gravitational constant, M is the mass of the planet being orbited, and r is the radius of the circle. For the spacecraft to stay in a stable orbit, v is the velocity required.

Getting a spacecraft into space or altering its orbit requires changing its velocity. When going from the surface of the Earth to space a launcher is used to achieve this. The equation that governs the basic operation of any spacecraft is called the Tsiolkovsky equation or the ideal rocket equation,

$$\Delta v = v_e \ln \left(\frac{m_0}{m_f} \right) \quad (2.3)$$

It relates Δv to the exhaust velocity v_e of the spacecraft's thruster (the velocity at which the fuel is being ejected), the initial mass m_0 (which includes the spacecraft and the fuel before the burn), and the final mass m_f (which is smaller because fuel has been used up during the burn). Equation 2.3 is simplified in ways that are sufficient for the purposes of this thesis. It can be rewritten as

$$\frac{m_0}{m_f} = \exp \left(\frac{\Delta v}{v_e} \right) \quad (2.4)$$

where $\frac{m_0}{m_f}$ is called the mass ratio. The plot of Equation 2.4 is shown in Figure 2.4, which illustrates that the greater the mass ratio, the greater the change in velocity. If the mass of the spacecraft is small, the mass ratio increases and therefore the Δv budget increases for a given amount of fuel and the overall cost of the mission is lowered. Lighter spacecraft have bigger Δv budgets and therefore longer ranges and/or lifetimes.

Figure 2.4: Final velocities as a function of launch vehicle mass ratios calculated using equation Equation 2.4.

2.2.2 Usage of new technologies in the space sector

The National Research Council (NRC) summarises the ways in which the space industry can benefit from AM in the following three points [59, 80]:

- The creation of new materials and parts that may one day be made in microgravity only and may only function there, i.e. they would be truly space based
- Given the previous point, there would be a shift in the logistic and planning of space missions since in-space construction would be a reality
- Lastly, given the previous two points, there is the possibility that AM could change the space market by allowing construction of spacecraft directly in space

The space industry is very conservative so new technologies are introduced very slowly. This happens for two main reasons. Firstly, a long approval process means that many years may pass until a mission's actual implementation. For example the Origins, Spectral Interpretation, Resource Identification, Security,

Regolith Explorer (OSIRIS-REx) mission was approved in 2011 and launched by NASA in 2016 [81]. Considering the high rate of development of new technologies, especially in a fertile field such as AM, the time gap from the approval to launch of the mission means that it is difficult to implement any new technologies or developments on the OSIRIS-REx spacecraft made in the interim.

Secondly, space missions are very expensive. Table 2.1 shows the rough costs of launching to Low Earth Orbit (LEO) using SpaceX’s Falcon Heavy (FH) and NASA’s Space Launch System.

Table 2.1: Cost to launch to LEO using the Space Launch System and FH [39], all costs are in USD.

Launch vehicle	Mass to LEO	Cost to LEO	Cost/tonne	Cost/kg
Space Launch System	70 tonnes	600M	8.67M	8570
FH	53 tonnes	158M	2.97M	2970

Several costs are omitted from Table 2.1 such as development, construction, testing, and certification of the payload before the launch. This can bring the cost to 290 million USD for a satellite that can track hurricanes [82]. Constant monitoring is also required once the spacecraft is in orbit which means further expenses in the order of millions of USD per year for communication satellites [82]. Given these high costs, and in some cases potential for the loss of human life, it is no surprise that many entities in the space industry prefer to rely on tried and tested methods and parts.

But AM has huge potential so there is a strong push to investigate this printing technology for use in the space industry. For example, efforts have been made to use 3DP to reduce the mass, complexity, part count, and welds of parts [54, 52, 83, 80]. 3DP is now being considered of paramount importance for human exploration of space and the space sector in general [54, 84, 85].

2.2.3 In-space AM

Currently there is only one way to print in space, using the FFF printer on the International Space Station (ISS), therefore most AMFS is still ground based. AM research conducted in orbit will be referred to as In-Space Additive Manufacturing (ISAM), which is a part of but separate from In-Space Manufacturing (ISM). The latter includes also more traditional forms of manufacturing. ISM and ISAM are closely connected therefore this section discusses both. Most of the ISAM research has been performed as part of NASA's In Space Manufacturing Initiative [43].

The first in-space 3D printer was an FFF developed by California based Made In Space (MIS) as part of the 3D Printing in Zero-G Experiment (3DPrint) [86, 42]. It was launched in September 2014 and fit in the ISS's Microgravity Science Glovebox (MSG). Several calibration objects and test coupons were manufactured, Figure 2.5 shows some of the objects printed at this time. The samples were then sent back to Earth to NASA's Marshall Space Flight Center (MSFC). There their properties were investigated and compared to a set of identical objects printed using the flight printer prior to launch. Tests included visual inspection, mass and density calculation, x-ray and Computer Tomography (CT) scanning, destructive mechanical testing (done following ASTM standards for tensile [87], flexural [88], and compression [89] testing) the results of which are shown in Table 2.3 [90, 4, 41, 91].

The printer launched as part of the 3DPrint project was only the beginning since as of 2016 there is a new FFF on the ISS: the Additive Manufacturing Facility (AMF) [40] shown in Figure 2.6, the specifications for which can be seen in Table 2.2. The new printer has an expanded selection of materials including Acrylonitrile Butadiene Styrene (ABS), Polyethylene (PE), and Polycarbonate (PC).

Just like with the previous printer, the AMF was calibrated by performing

Figure 2.5: Some of the objects printed on the ISS [4].

Figure 2.6: The AMF mounted in an EXPRESS Rack Mid-Deck Locker in the ISS (Image credit: NASA).

Table 2.2: AMF system specifications [40].

Attribute	Value
Print volume	14x10x10cm, 1400 cm ³
Material	ABS, Green PE, PC
Resolution	0.1 - 0.44 mm
Height Resolution	≥ 75 microns
Maximum wall thickness	1 mm

tensile, compression, and flexural tests using ASTM guidelines [30, 89, 88]. For consistency the ABS used in these tests was the same as that used for the first printer. Table 2.3 shows the test results of the two generations of printers both in microgravity and on the Earth.

Table 2.3: Results from tests on samples prepared in orbit (0 g) and on the ground (1 g) [41, 42].

Environment		0g		1g	
Test type		AMF	3DPrint	AMF	3DPrint
Ultimate strength (MPa)	Tensile	38	27.9	37.8	23.9
Elastic Modulus (GPa)		3.1	1.7	2.2	1.5
Ultimate strength (MPa)	Compressive	51.1	38.5	52.9	51.4
Elastic Modulus (GPa)		1.7	1.1	1.5	1.7
Ultimate strength (MPa)	Flexural	58.9	45.1	62.3	35.9
Elastic Modulus (GPa)		1.9	1.7	2.1	1.4

Being a newer printer, the AMF produced better quality parts, which is an expected result. Compared to the samples printed on the ground, the flight samples had worse compressive and flexural properties but were better in tension. MIS also investigated the phase distribution of the samples and found no significant differences [42].

The ability to manufacture custom tools in space will be invaluable to astronauts, as shown by the Multipurpose Precision Maintenance Tool (MPMT) in Figure 2.7. It is a tool that allows wire cutting and bolt tightening all in one and was the winner of the “Future Engineers Space Tool Challenge” [5]. Thanks to AM’s design freedom and the type of research exemplified by the AMF, astronauts will be able to manufacture ad-hoc tools for any situation.

The first of only two references found that apply 3D printed springs to the space sector is shown in Figure 2.8. These are a pair of small springs printed on the ISS using the FFF printer there, called the AMF. The springs are made of ABS but unfortunately no further information could be found on the dimensions or if post-manufacturing testing was successful or not.

Figure 2.7: The MPMT, created by a university student as part of the “Future Engineers Space Tool Challenge”, printed on the ISS [5].

Figure 2.8: Springs printed on the ISS [6].

The future of ISAM

The ultimate goal of ISM is to manufacture and assemble large structures in orbit. The obvious advantage of this is that it is far easier to launch raw materials rather than pre-built delicate structures. Thus the cost of space missions would therefore be lowered. An added benefit is that new spacecraft designs can be developed because there will be no need to launch them [8]. There are many challenges to implementing ISM though, these include:

- recycling of materials
- ability to move large structures during construction
- robotic dexterity in fabricating complex parts
- manufacturing of electronics
- being limited to materials that can resist the space environment

The biggest issue is that currently there is no ISM infrastructure, meaning that it would have to be built. This entails a large up-front cost that most agencies and companies are not ready to pay for, therefore resorting to traditional Earth based manufacturing [8], something that is discussed in more detail in subsection 2.2.2.

Closing the manufacturing cycle is also an important aspect of ISM. Just like manufacturing on Earth, recycling of unwanted parts would help to reduce the amount of raw resources needed. Recycling is especially important in manned space exploration since it would lead to significant mass savings. ISAM, like any other manufacturing technology, would also greatly benefit from this.

Tethers Unlimited, Inc. (TUI) has developed a *“combination 3-D printer and plastic recycler”* called Refabricator to NASA for testing in flight [92]. Typically when recycling polymer parts on Earth they are ground, which is not possible on the ISS because the dust poses a health hazard to the astronauts. The Refabricator instead uses a system called Positrusion, which does not involve grinding, to recycle old polymer and print new parts[93]. The process has already been demonstrated on Earth with FFF and ABS [94]. Interlog Corp., Techshot, and TUI are also developing a system that can recycle multiple types of materials, including metal and polymer [95]. NASA will then decide which company produced the best prototype and will continue the project with them.

Another important aspect of ISM is the ability to manufacture electronics. Ultra-capacitors made with AM have already been developed, tested, and patented [43] on Earth and the next step is to test this technology in flight.

An example of a solution to build large structures in space is TUI’s SpiderFab, shown in Figure 2.9. It uses a combination of 3DP and on-orbit robot assembly to create structures such as antenna reflectors, solar concentrators, solar sails, and manned habitats. This achieved by a combination of two systems, Trusselator and OrbWeaver. The former is a machine able to assemble large trusses through a combination of AM and robotic assembly, while the latter is used to *“manufacture large, high-precision antenna reflectors on-orbit and then robotically integrate them with*

a phased-array RF system” [96].

Figure 2.9: A concept art of SpiderFab Bot creating a truss in orbit [7].

Another project that is developing a similar technology is Dragonfly. This is a system by Space Systems Loral for in-space reconfiguration and installation of large RF reflectors [43]. MIS are also throwing their hat in the ring with Archinaut, a system similar to SpiderFab. It is a “free-flying space manufacturing and assembly capability that enables advanced spacecraft and structures to be produced in the space environment” [97]. Orbital ATK are developing the Commercial Infrastructure for Robotic Assembly and Services (CIRAS), another candidate system of in-space hardware assembly technologies for performing ISM [98].

All the above technologies tend to focus on construction of large metal structures. McGuire et al. [8] instead proposed an architecture for a spacecraft equipped with a large FFF to print polymers instead. The advantage is that plastic requires less power than metal to print due to the lower temperatures involved. Metals also typically require post-processing in order to achieve their full properties and this also requires a lot of power. The proposed spacecraft architecture uses concentrated solar energy to melt the polymer. In order to ensure a consistent source of light, the spacecraft would likely be in a sun-synchronous orbit, which also helps to reduce the amount of temperature fluctuations and simplifies the thermal systems.

Figure 2.10: System architecture for in-space 3DP spacecraft [8].

2.2.4 Ground based AMFS

Gone are the days when AM used to be called rapid prototyping, nowadays it is considered a valid manufacturing method for aerospace parts. In the many facilities present on Earth, numerous techniques that allow the printing of an increasingly wide range of materials [99] and of increasing complexity have been developed. As a consequence, AMFS research can be broadly divided into three categories based on the material used for printing: metal, polymer, and others. These categories can be further divided into manned and unmanned according to the type of mission that the printed parts would be used for. Research in AMFS has been classified in this way in the following sections, an attempt has been made to classify research under ‘manned’ only if it is specifically targeted for this use. A brief description of satellite classification and what is special about CubeSats follows.

Satellite classifications

Satellites come in many shapes and sizes but they are generally categorized based on mass as follows [100]:

- *Large*: > 1000 kg
- *Medium*: 500 - 1000 kg

- *Mini*: 100 - 500 kg
- *Micro*: 10 - 100 kg
- *Nano*: 1 - 10 kg
- *Pico*: 0.1 – 1 kg
- *Femto*: < 100 g

CubeSats are a particular type of nano-satellites that come in units of $10 \times 10 \times 10$ cm (1U) and can be configured into spacecraft of up to 12U in size, shown in Figure 2.11. They are very small, simple, and cheap to make, so much so that institutions such as universities [101] and even elementary schools [102] can build and launch them. There has also been a case of an individual building and launching his own CubeSat [103]. They are mostly built with commercial off-the-shelf components and are launched in tandem with other CubeSats in the fairings of bigger satellites, thus sharing the cost of launch.

Figure 2.11: Examples of different configurations of CubeSats [9]. Left - 1U “Phonesat”; top right - 1.5U “EDSN Spacecraft”; bottom right - 6U “EcAMSat”.

Metal AMFS research

Manned missions AM can produce very particular geometries, which is one of its main advantages. In [104], the oxygen system study, a comparison was made between wrought Inconel 718 and SLM printed In718 with post heat treatment to determine the differences in material flammability for components printed for the ISS's urine processor assembly and oxygen systems. Fire is a major concern on the ISS so the project's goal is to investigate the flammability of printed parts. It was found that printed In718 with heat treatment and Hot Isostatic Pressing (HIP) burnt more than printed In718 with only heat treatment and wrought In718.

Unmanned missions Most AMFS research with metals is focused on propulsion systems using Powder Bed Fusion (PBF) techniques, especially SLM, since this technology is reliable, among the most well understood, and most consistent. Werkheiser [43] and Clinton [105] discuss an on-going project that NASA has to develop a printed rocket engine prototype in 2.5 years by leveraging the advantages of AM to reduce part count, cost, and fabrication times, further details can be found in Table 2.4. The developed engine prototype will then be used as a basis for creating a new engine which will receive certification to use on missions.

Carter et al. [106] presents a summary of the findings of NASA's Glenn Research Center (GRC) with regards to metal AM, which helps to give an overview of the activities in this agency. Various fields were investigated and the findings presented in the paper.

The first study took a replica RL-10 combustion chamber made of AM copper alloy with the injector made of AM Ni alloy and subjected it to hot fire testing [55]. 19 tests were performed in total with 4 different engine configurations and the results were used to implement requirements for the AM parts. This work also identified ways that AM's design freedom could be used to improve perfor-

Table 2.4: Developing a prototype rocket engine with AM versus conventional manufacturing [43].

	State of the art for typical engine developments	Prototype AM engine
Design, development, test and evaluation time	7-10 years	2-4 years
Hardware lead times	3-6 years	6 months
Testing	Late in the DDTE cycle	Early in the DDTE cycle
Cost	Engine: 20-50 million USD	Prototype: 3-5 million USD
Applicability	Design specific to mission and often proprietary	Provide relevant data to multiple customers and flexible test bed can accommodate changes in hardware or design concepts

mance and reduce cost.

Another study mentioned by Carter et al. [106] is the creation of a material database for Ti-6Al-4V printed with EBM [107, 108]. HIP was performed after printing to close any porosities and to achieve the desired microstructure. Detailed analyses of the chemical and structural changes in the material were performed throughout the process. High-Cycle Fatigue (HCF), CT, and tensile testing were also performed. Ti-6Al-4V parts printed via EBM were found to possess mechanical properties comparable or superior to conventional Ti-6Al-4V [109]. The database that was created for this material and process combination contains details such as micro-structure, mechanical properties, fatigue crack growth, and fracture toughness as well as thermal properties that were observed from cryogenic to elevated temperatures.

GRCop-48 is a copper alloy developed by GRC for rocket engine main combustion chamber liners and has excellent mechanical and thermal properties [110]. Like EBM Ti-6Al-4V, GRCop-48 printed using Laser Beam Melting (LBM) [111]

has been found to produce parts whose properties are better than those made with traditional means [112, 106].

Similar to the project discussed by Werkheiser [43] and Clinton [105], GRCop-48 is also being used in the Low Cost Upper Stage-Class Propulsion (LCUSP) project to reduce the cost and time taken to manufacture rocket engines [113]. Here two materials and two printing technologies were used together, GRCop-84 was used to print a combustion chamber liner with SLM then Inconel 625 was used with Electron-Beam Freeform Fabrication (EBF³) [114] to manufacture a structural jacket on the inside of the liner [108]. This was done in an effort to develop processes for the rapid manufacture of reliable advanced engine parts.

EBM typically has one beam but a multi-agency team has investigated Ni-based super-alloys using multi-beam EBM [108, 115]. The objective of this project is to expand the capabilities of AM, specifically by developing alloys that leverage 3DP's unique manufacturing methodology.

Large scale metal AM is one of the biggest areas of research worldwide due to the fact that 3D printers are currently quite limited in size. NASA is also investing in this field with technologies such as LENS, EBF³, Laser Freeform Manufacturing Technology (LFMT), and various forms of Direct Energy Deposition (DED) because, as shown in Figure 2.12, the build volumes of metal printers is too small to be useful for large rocket engine manufacturing.

Not all research in large scale metal AMFS is done by governmental agencies. Relativity Space is developing new launchers using the Stargate system, a proprietary, automated, large scale metal 3D printing system developed by its founders shown in Figure 2.13. Parts are manufactured thanks to robotic arms that perform laser sintered metal printing [116]. Similar to other projects discussed, Relativity Space plans to simplify and reduce the cost of building launchers by reducing the part count and development time. Terran 1, the company's first launch vehicle, is slated to have its inaugural launch in 2020 with a capacity of 1,250 kg to LEO [117].

Figure 2.12: Comparison of SLM build volumes to rocket engines [10]. Dimensions in SI starting from the left are $25.4 \times 25.4 \times 25.4$ cm (16387.064 cm³), $39.37 \times 60.96 \times 48.26$ cm (115823.768 cm³), 228.6 cm, 116.84 cm, 177.8 cm, and 142.24 cm.

Figure 2.13: Tim Ellis, co-founder of Relativity, holding a printed nozzle in front of the Stargate printing system [11].

Stepping away from large scale metal AMFS, Goddard Space Flight Center (GSFC) has been conducting research into spacecraft instruments, components, electronics, sensors, and coatings using technologies such as Direct Metal Laser Sintering (DMLS) [57] and Atomic Layer Deposition (ALD) [118]. To manufacture electronics, they have been making use of printers such as the Aerosol Jet [80]. GRC (with Aerojet Rocketdyne) and MSFC have also 3D printed and tested several injectors [80].

Unlike chemical propulsion rockets, whose energy source is the chemical reaction that occurs in the combustion chamber, rockets that use Nuclear Thermal Propulsion (NTP) employ a nuclear reaction to heat the fuel and then eject it out through the nozzle, a schematic of which can be seen in Figure 2.14. It is an extremely efficient form of propulsion i.e. the mass ratio (defined in equation 2.4) is very small. Mireles et al. [119] discusses the potential to use AM for NTP because some of the parts needed are very difficult to produce otherwise.

Figure 2.14: Schematic of a NTP rocket [12]. Fuel is pumped into the combustion chamber where a nuclear reactor provides the heat for combustion. This is much more efficient than traditional rockets due to the far greater amount of thermal energy provided by the nuclear reactor.

In Europe the Additive Manufacturing Aiming Towards Zero Waste and Efficient Production of High-Tech Metal Parts (AMAZE) project (cordis.europa.

[eu/project/rcn/105484_en.html](http://eu.project.rcn/105484_en.html)) was a multi-disciplinary effort to improve several key areas of metal AM for the aerospace, space, energy, and automotive sectors. It was the largest project of its type and had many objectives which included increasing print volume and productivity, cost reduction compared to traditional processes, improve dimensional accuracy, and reducing scrap rates [120]. Two printing methods were investigated, PBF and DED performed with powder and wire. The AMAZE project lead to many developments. The ones that directly pertain to AMFS include [120, 121, 122]:

- Wire and powder feedstock specifications and test protocols to aid in development of a robust supply chain
- Software for rapid and reliable design of 3D printed parts
- Build strategies and processes which enabled build times to be reduced by a factor of 10
- Novel materials including aluminium alloys and composites which better utilize the AM process
- New finishing procedures and flexible fixtures
- In-process monitoring methods to capture key process variables during printing
- Improved process models
- A new benchmarking process, further discussed in section 2.3
- Many demonstration parts which have reduced cost, part count, weight, and improved performance

Private companies also have a vested interest in metal AM. Apart from the aforementioned Relativity Space, SpaceX has also been doing a lot of research in AM which led to, for example, the launch of a Falcon 9 rocket with a 3D printed

Main Oxidizer Valve (MOV) [123]. Airbus Defence and Space used DMLS to print the brackets shown in Figure 2.15 for their Eurostar E3000 telecommunications satellites [124]. NASA's 2011 JUNO spacecraft also had printed brackets, this time made by Lockheed Martin [121].

As mentioned before, one of the main research areas is the development of topology optimization to create lightweight structures for space. An example is shown in Figure 2.15, by Thales Alenia Space, who has launched 79 3D printed parts spread across various missions, namely Telkom 3S, SGDC, and KOREASAT-8 [121]. Other examples of this type of research include developing and using a process flow for additive manufacturing of topology-optimized metallic components suitable for use on satellites [125, 126, 127, 128].

Figure 2.15: Titanium brackets manufactured using an EOSINT M 280 for use on Eurostar E3000 satellites [13].

Universities also perform metal AM research and it sometimes extends to AMFS. In Deepak et al. [52] the authors tested a novel liquid bi-propellant rocket engine designed by the Students for the Exploration and Development of Space at the University of California San Diego (SEDS UC) student association. Knowing of the design freedom granted by 3DP, the group used their ability to change the design at any stage throughout the project. They were able to design a regenerative cooling system that was embedded in the combustion chamber's walls and has optimized channel cross-sections. The prototype rocket was printed using DMLS In718. The group designed a new version of their rocket and in 2018

they printed a liquid oxygen and kerosene engine again using In718 with DMLS [129].

As previously mentioned, only two references were found that looked into 3D printed springs and the space industry. The first one used ABS printed on the ISS while the second one uses metal. TAS has done some work on 3D printed springs: they developed the Adel'Light hinge for deploying solar panels, shown in Figure 2.16. The coil springs push against each other to generate torque and open the solar panels and once in position the hinge locks in place. The prototype shown in Figure 2.16 is made of titanium and would be very difficult to fabricate without 3D printing. No published work could be found on this hinge.

Figure 2.16: The Adel'Light hinge for deployment of solar panels [14].

Polymer AMFS research

Manned missions As stated before, AM is extremely useful for long term human space exploration. The main advantage being that astronauts can manufacture ad-hoc tools when needed rather than having to carry them all the way from Earth. In this spirit Wong et al. [85] carried out an investigation into the quality of ABS surgical tools printed with FFF. Several surgeons were asked to perform simulated prepping, draping, incision, and suturing using 3DP forceps, hemostats, and clamps. The consensus was that the printed tools were adequate even if they were printed with ABS. Nonetheless, the usefulness of AM for long

duration manned missions is greatly highlighted by this study.

Unmanned missions Injectors are an integral part of rocket engines and Catina et al. [130] used FFF with ABS to print various configurations of injector plates to test if an acceptable flow would be possible. The liquid used was water and no hot fire testing was performed, which is understandable given the polymer used. Although crude, the experiments showed that adequate flows could be obtained. They also performed simulations of the injectors, compared them to the real samples, and found that the two were quite different. This is to be expected since there is a lack of software that is able to accurately represent materials produced with AM and will be further discussed in section 2.3.

The design freedom that AM has is again cast into the light by Marshall et al. [9] discussing how AM could aid designers of CubeSats by allowing embedded wiring, electronics, and propulsion systems. They incorporated a commercial Busek micro Pulsed Plasma Thruster (PPT) into a structure printed with FFF. Prior to this the team had tested whether printed PC, the material used, had a high enough dielectric strength and results showed that the material could withstand the voltage without breaking down. The μ PPT was fired while embedded in the PC and the material again performed well as there were no signs of degradation from the firing apart from some colouring on the casing due to arcing.

Plastic is not as strong as metal so creating stronger polymers is an area of research in AM. NASA had a study performed in this field where simple PLA and PLA mixed with bronze, copper, iron, and stainless steel were compared [131]. Tensile, wear, fracture, and microscopy testing was performed at different layer heights and it was found that higher concentrations of metals lowered the strength of the printed material but increased the stiffness and porosity while Poisson's ratio stayed about constant. What was likely happening is that the plastic did not properly bond with the metal particles, thereby weakening the material [131].

Although not a written rule, CubeSats have been designed from the start to be simple and cheap so a printed micro-thruster fabricated with AM for use on nano-satellites should follow these guidelines. Gagne et al. [15] outlined the development of a micro-thruster for use as either primary propulsion or for attitude control, shown in Figure 2.17. The thruster respects the launch rules for CubeSats [132] so only “green” propellants were considered. Printed with SLA using Clear V2 resin, the thruster brought hydrogen peroxide (the mono-propellant) into contact with different catalysts, resulting in an exothermic reaction whose products are expelled through a converging-diverging nozzle. AM helped by allowing the removal of a catalyst bed and the designing of an optimized nozzle size.

Figure 2.17: Artist's impression of the thruster in a 3U CubeSat [15].

Figure 2.18 shows the schematic of another proposed thruster design by Stevenson et al. [16]. Unlike the one by Gagne et al., this one is designed for attitude control of an interplanetary 6U CubeSat. Once again made with SLA, which produces the smoothest surface finish of all polymer printers, the printed portion of the thruster includes the main propellant tank and plenum, seven nozzles, and the propellant feed pipes. Fuel flow was regulated by solenoid valves and testing in a thermal vacuum chamber showed that the thruster generated 50 to 60 mN of thrust with $I_{sp}=31.7$ s and total impulse of 62.2 Ns [16].

Polymers can also be used to print CubeSat structures therefore Slejko et al. [133] investigated the feasibility of printing modular, non-metallic CubeSat buses

Figure 2.18: Diagram showing the tanks, pipes, nozzles, and valves for the thruster [16].

using Polyetheretherketone (PEEK) HP3, WINDFORM XT, and DuraForm PA. PEEK turned out to be the strongest and since it has already been qualified for use in space NASA [43], they decided to proceed with this material. The modular nature of the bus was achieved by printing and combining several elements (bars, panels, etc.) to produce the size needed. A prototype 1U structure was printed using SLS and is being tested to ascertain its mechanical properties.

There are also private companies that have an interest in developing polymers for use in AMFS. For example Stratasys had partnered with NASA/Jet Propulsion Laboratory (JPL) to print 30 polymer antenna array supports to be used directly in space on the FormoSat-7/COSMIC-2 constellation [134].

Other AMFS research

Manned missions In-Situ Resource Utilization (ISRU) is the practice of using locally sourced materials for construction and manufacturing. As humanity expands into space, ISRU will become increasingly important because it is much

cheaper and easier to build a habitat on Mars or the Moon than carrying one all the way from Earth. NASA, along with the United States Army Corps of Engineers, was developing two sister modules for performing ISRU: Automated Additive Construction System (ACES)-3 for terrestrial applications, shown in Figure 2.19, and Additive Construction with Mobile Emplacement (ACME) for extraterrestrial ones (using lunar or Martian regolith) [135].

Figure 2.19: Overview of ACES-3 [17].

When on Mars or the Moon, the best option is to use local regolith as aggregates for cement when constructing buildings. ACES 3 has been used with lunar (JSC-1A) and Martian (JSC Mars-1A) regolith simulants to make both normal and “waterless” concretes. These concretes were then used with contour crafting [136] to fabricate habitats to test the mechanical properties of the deposited materials, investigate various types of binders, and how the ACES coped with the various concrete mixtures [17, 137, 138].

Another study tested four cement samples [17, 137, 44], three made with casting and one with additive construction, whose constituents are shown in Ta-

ble 2.5. Testing included simulated micrometeorite impacts, compression, and visual inspection, which showed that cement with Lunar regolith had shallower penetration depth than that with Martian regolith [44, 17].

Table 2.5: Constituents of the samples investigated in the ACME study [44].

Sample	Simulant	Cement	Additives
1	JSC Mars-1A	Portland	Stucco mix
2	JSC Mars-1A	Portland	Stucco mix, Navitas 33
3	JSC Mars-1A	Sorel	Boric acid
4	JSC-1A	Portland	Stucco mix

Similar to the sun-powered FFF discussed in section 2.2.3, Meurisse et al. [18] propose a sun-powered printer for making bricks on the Moon. This is an interesting solution given the extremely thin atmosphere on the Moon and subsequent strength of solar illumination. As can be seen in Figure 2.20 the printer is basically an SLS that uses concentrated solar energy for printing instead of a laser.

Results from 23 printed samples produced an average compressive strength of 2.48765 ± 0.71097 MPa and an average Young's modulus of 0.20601 ± 0.1519 GPa. The surface finish of the samples was very rough and they were also very porous. Given that there are still many limitations, this is a promising AM technique since it is being developed to be completely self-sufficient and does not require powder sieving, making it ideal for ISRU.

Figure 2.20: Solar powered 3D printer with xenon lamps for testing [18].

A study by ESA looked into the feasibility of using ISRU to build habitats by using D-shaping [139] and Sorel cement [19]. Two developments were made in the course of the study: the novel habitat design shown in Figure 2.21, and a new lunar regolith simulant based on volcanic material. The habitat design developed has a printed outer wall to offer protection against micrometeorites while an inflated module inside provides atmosphere. Demonstration building blocks were printed to test the mechanical properties of the lattice and the printer's accuracy, both of which were found to be satisfactory.

Figure 2.21: Outpost structure (top) and wall profile (bottom left) with detail (bottom right) [19].

It is not unfeasible that astronauts may have to use locally sourced materials to make objects. A study used sieved lunar regolith simulant JSC-1AC in a LENS printer to manufacture dense cylindrical parts and test their mechanical properties, which were found to be satisfactory [58].

This work was later expanded by using SLM to study how scanning speed, hatch spacing, laser power, beam diameter, and layer thickness affected the micro-

structure, surface roughness, and mechanical properties of various types of lunar regolith samples manufactured via AM [140]. In this paper the authors also discussed how PBF printing processes would suffer in environments with reduced gravity [140].

The studies discussed so far focus on solid objects whereas Jakus et al. [141] instead investigated the feasibility of making a plastic-like material. They used FFF to print inks made by combining sieved JSC MARS-1A and JSC-1A regoliths mixed with elastomeric binders and a solvent mixture to make elastic materials that were similar to polymers.

Asteroid mining is a potential source of vast amounts of resources [142] but setting up the infrastructure is challenging. ISRU makes the task less daunting therefore Lietaert et al. [143] used Direct Metal Printing (DMP) to print objects using an iron meteorite as the source of the powder.

Unmanned missions As discussed in section 2.2.4, CubeSats are very small so reducing the volume occupied by components is a must. AM's design flexibility would allow for great mass and volume savings so there are projects such as as "3D Printing the Complete Cubesat" whose goal is to advance 3DP for CubeSat applications [144]. Kief [144] also mentions that AM could enable the development of new structures where several subsystems like power, propulsion, and communications are incorporated directly into the structure. This would require printing of various types of materials hence why this research has been put in this subsection.

The final form of printing that does not involve metals or polymers is ceramics and ceramic based composites. Because there is a wide variety of printing techniques, there is the possibility of developing new materials that have unique properties. For example ceramic parts with fibre reinforcements are considered to be possible with Laminated Object Manufacturing (LOM) [145] and Binder Jet Printing (BJP) [146]. Other AM techniques can be used though, and have

been demonstrated on gas turbine components using both ceramics and polymers [147, 55].

There is also research in a more general field that is not necessarily material specific: Design for Additive Manufacturing (DFAM) applied to the space sector. Dordlofva et al. [148] proposed developing “Design for Qualification” guidelines for AM components by considering qualification as a design factor in the early phases of product development, instead of more traditional approaches, thus reducing cost and lead time for development and qualification as products are designed to be qualified. Borgue et al. studied how the introduction of 3DP in space applications impacts the design phases [149]. They found that most of the literature agrees that there is need to better understand the constraints and behaviour of AM so as to take full advantage of its increased design freedom and that there are few studies on systematic and generic modelling approaches for DFAM for space, unlike in other industries. Also, a constraints replacement strategy for the redesign of components to be manufactured with AM based on Enhanced Function-Means modelling has been proposed as a basis for re-design of products using AM applied on a case study featuring a satellite sub-component [150, 151].

2.3 Research in AMFS and 3D printing of springs: gaps and directions

One of the main problems, which affects all AM and not just the space sector, is that there are many factors that determine characteristics and therefore the behaviour of printed parts. Because of this, their interaction and effects still not well understood. For example SLM can have as many as 130 different factors affecting the quality and performance of the final object [152]. Many factors are semi or fully random, such as powder distribution or the flow of melt pools, making AM difficult to predict. Even two objects printed together may have

large feature variations [153] and this is a fact that cannot be avoided, simply mitigated. Ghidini [54] summarises the challenges in widespread adoption of AM in the space industry very well:

- the need to change the approach to design in order to take full advantage of the capabilities of AM, in other words more research into DFAM;
- the need to ensure reproducibility, accuracy, and reliability;
- the need to develop new standards and verification methodologies for 3D printed parts since classical standards do not apply, also mentioned by [53].

Most of the issues facing widespread adoption of AM can be mitigated by the adoption of standards. Fortunately, there is a lot of activity in AMFS and slowly standards are being introduced. Outside of the space industry, ASTM International and ISO have published a structure for their future standards regarding AM which are general and not specific to the space industry. ASTM F3122 [154] provides guidelines on how to evaluate the mechanical properties of materials made using AM and references several existing standards among which ASTM A370-16 [155], ASTM B565-04(2015) [156], ASTM E132-04(2010) [157], and ASTM E290-14 [158]. Similar to ASTM F3122 the American Society of Mechanical Engineers Additive Manufacturing Standardization Collaborative (AMSC) is a cross-sector coordinating body whose objective is to accelerate the development of industry-wide additive manufacturing standards and specifications consistent with stakeholder needs and thereby facilitate the growth of the additive manufacturing industry. The AMSC published its Standardization Roadmap for Additive Manufacturing (Version 2.0) in June 2018 [159]. This identifies existing standards and specifications, as well as those in development, assesses gaps, and makes recommendations for priority areas where there is a perceived need for additional standardization. The AMSC roadmap describes 93 gaps [160] where no published standard or specification currently exists to respond to a particular industry need, which have been compiled in an interactive, online portal [160].

Space entities are also developing standards. NASA's Additive Manufacturing Structural Integrity Initiative (AMSII) project aims to establish a qualification method for SLM parts to be used in space-flight applications. Two documents have so far been produced: Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware (MSFC-STD-3716) [161] and Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes (MSFC-STD-3717) [162]. The first contains the overall guidelines while the second provides details for design process, part classification, pre-production and production, manufacturing, qualification, and acceptance [163]. Together MSFC-STD-3717 and MSFC-STD-3716 provide a framework for standardization of laser PBF of metals.

As can be seen in this literature review, there is great interest in the space industry for AM. Many areas have ongoing research including rockets, CubeSat structures, surgical instruments, habitats, and electronics. Although the main issue affecting AM in the space industry, and in other industries, is the lack of established standards, for the purposes of this research this is not relevant.

There is a lot of work underway for the development of 3D printing standards for the space industry but, as previously mentioned, there is very little literature about the application of 3D printing to springs, and what little there is superficial. There are many potential applications for springs in spacecraft mechanisms therefore the main objective of this research was the investigation of springs manufactured via AM with the targeted application being, but not limited to, use in the space sector.

Summary

This chapter discussed the literature reviewed for this research and the gaps. While there is a lot of work being done in many areas of AMFS, there is very little when it comes to 3D printed springs. Only three published papers were

found that investigated springs made via AM and the research performed in them was superficial. Also, no published literature could be found that applies AM to springs in spacecraft. Therefore a research gap has been identified and this research will attempt to remedy it.

CHAPTER 3

PROPOSED RESEARCH METHOD

So far most AMFS has been used mainly for static parts such as combustion chambers, piping, brackets, or buildings. But the design freedom afforded by AM should also be considered when developing mechanisms like the aforementioned compliant mechanisms. Modelling parts for mechanisms will allow AM to be used in unconventional ways, taking full advantage of its design freedom.

There are many types of springs, examples of which can be seen in Figure 3.1. The most common is the helical spring, either compression or tension. Springs are a complicated system to model and creating equations to predict their behaviours is not easy but they are widely used in mechanisms and therefore the potential application of AM should be investigated. For this reason, a hypothetical application of springs has been developed for this research, detailed in the next section.

Figure 3.1: Examples of types of springs [20].

3.1 Novel CGT design for small spacecraft

3.1.1 Cold gas thrusters

CGTs are simple thrusters used for attitude control in spacecraft and have been hugely successful [164]. They work on the principle of ejecting pressurised gas from a nozzle so, unlike in a chemical rocket, the gas pressure is not created via a chemical reaction, it is simply stored under pressure. If the propellant tank was directly connected to the nozzle the thrust would drop proportionally to the drop in pressure due to the expulsion of propellant. By instead storing gas in plena like in Figure 3.2, the pressure can be regulated and therefore the thrust produced is more consistent.

3.1.2 Using AM to increase the dynamic range of CGTs

When CGTs are used in small spacecraft such as CubeSats, where space is a valuable commodity, the inclusion of plena reduces the amount of propellant available. They could be removed if there was a way to keep the propellant pressurised throughout most of the thruster's lifetime. A hypothetical solution is shown in Figure 3.3. This is a new CGT design that foregoes the plena and uses

Figure 3.2: Example CGT module design schematic showing the main components: propellant tank, plenum, valves, and nozzle [21].

springs to keep the fuel under pressure. When the thruster is empty, the panel rests on the left side and the springs are in a their rest configuration. As fuel is introduced, the panel moves and pulls the springs, pressurising the gas. The valve is then activated when needed and the fuel is expelled. As the propellant is used the pressure drops but the force generated by the springs helps to keep it constant.

Figure 3.3: A hypothetical CGT that uses 3D printed springs.

The thruster is assumed to fit in a CubeSat so has the following restrictions [83]:

- dimension of 1U, see section 2.2.4
- mass: 1.3 kg per 1U
- the spacecraft is not allowed to have any pressure vessels, which NASA defines as vessels that have pressures above 100 psia, which is about 689

kPa

This means that the force generated by the springs will have to be tailored to not exceed the tolerances or the thruster will be considered a pressure vessel and thus will be subject to greater testing. The dimensions give a starting point for sizing the thruster and therefore how much pressure the panel generates based on the force of the springs.

3.1.3 The problem with linear springs

Cylindrical helical springs obey Hooke's law,

$$F = kx \quad (3.1)$$

which relates the force F needed to displace a spring from its initial position by an amount x via k which is called the spring constant or stiffness and has units of N/m. When the spring is behaving according to Hooke's law it is said to be elastic. Figure 3.4 shows how the force and the displacement are defined for a tension spring.

Figure 3.4: The spring at rest position is defined as $x = 0$. When a force is applied the displacement from the initial position is called x .

As can be seen, Equation 3.1 is a linear equation so springs in the thruster will produce less force the closer they come to their original position. In reality springs can be stretched beyond their elastic limit but that will be discussed in

chapter 6. A solution is development of a non-linear spring, one who's equation is

$$F = f(x) \quad (3.2)$$

where F is a function of x . In this case

$$k = \frac{dF}{dx} \quad (3.3)$$

Here the force is a function of displacement from the equilibrium position but unlike in linear springs k is not a constant. For example when a compression force is applied to the spring showed in Figure 3.5 the region with a smaller pitch will compress first followed by the region with more pitch. This results in a changing k and hence the name non-linear springs.

Figure 3.5: Example of a non-linear, dual pitch spring [22].

Although commonly used, non-linear springs have never been 3D printed. There are design limitations due to manufacturing difficulties, like for example it is not possible to vary the diameter or shape of the wire. This is instead not a problem with AM due to the fact that objects are built layer by layer. Therefore one of the objectives of this research was to derive an equation for the calculation of the spring constant of 3D printed springs. The derivation technique could also be extended to other types of springs such as spiral or conical. A series of linear springs could then be created similar to Figure 3.5 to provide a force that is as

tailored to the requirements of the mission. For example if a CubeSat is expected to tumble out of control after launch, a spring which initially generates a high force can be manufactured to provide high thrust to stop the unwanted motion. Once the spacecraft is under control, the spring can be tailored to provide less thrust for finer attitude adjustments.

3.2 Deployable helical antennae

Another example of a potential application of 3D printed springs is deployable helical antennae. The predominant antenna choice for CubeSats has been one or more monopole or dipole antennae, although they are low gain, naturally linearly polarized, inefficient and normally narrowband [165]. There are many types of deployable antennae available for CubeSats, shown in Figure 3.6a, but the ones of interest here are the helical type. Helical antennae are wider band, naturally circularly polarized, and may also have more than one helix to further increase their gain [24]. Figure 3.6b shows how a helical antenna is folded and stored.

Since helical antennae have the same shape as springs, it is possible, as will be shown later, to print hollow polymer springs and then thread conductive into them, even with several helices. There are two advantages to this method. First, the springs act as the supporting helices (see Figure 3.6a) so there is no need for dedicated support helices. Second, using the equation developed in this research it is possible to tailor the stiffness of the spring so as to avoid unwanted oscillations as a result of deployment. It is also possible to create compound springs, thereby providing a graduated extension.

3.3 Research method

Given the previous information and literature review the main goal of this research was to model a 3D printed helical spring by developing an equation that

(a) Packaging schemes for CubeSat antennae: (a) the helical pantograph, (b) coilable conductors, (c) dual-matrix composite shells, (d) hinged ribs, and (e) the wrapped mesh [23].

(b) Simulation of compaction of eight-helix pantograph antenna [24].

Figure 3.6

predicts their stiffness based on material properties and spring dimensions.

3.3.1 Material selection

The first step was determining which material to use for printing. This depended on several factors including cost, printing flexibility (when it comes to the slicing program), and ease of printing (because many samples of different types would have to be manufactured).

Metal printing was not considered for the following reasons. First there was the concern of support removal. Although Saleh and Ragab [1] showed that it is possible to print small springs with no supports on an Elctro Optical Systems (EOS) SLM printer, at the beginning of the research the need for supports for larger springs was considered to be inevitable. Since they would also be printed out of metal their removal would be very difficult and add a lot of time to the process, thereby slowing the whole research. Removal of supports from springs printed with metal could be investigated in a future study where techniques for printing metal springs in a way that was efficient in both time and cost are investigated.

Another reason for not using metal is because of the increased mass compared to polymers. Since the emphasis of this research was developing 3D printed springs for use in the aerospace industry, as subsection 2.2.1 explained weight reduction is always a great consideration. Also, since the loads that spacecraft are typically subjected to during flight are very small (being in microgravity) there is little need to make springs out of metal.

The final reason is that 3D printed metals and plastics are both quite anisotropic in their material properties [74, 166, 167, 168] therefore it makes little difference if one or the other is used for testing. Out of the two, polymers tend to produce materials that are more anisotropic therefore they were selected because they are a “worst case scenario”.

The research is focused on creating a spring that is useable in space with

FFF, therefore the filament that was the primary candidate was ULTEM 9085 by Stratasys, printed using Fused Deposition Modeling (FDM). This thermoplastic and printing technology is certified for use in space since ULTEM 9085 was used to manufacture the antenna array supports for COSMIC-2 [169]. Use of springs printed with ULTEM for space applications would automatically qualify them for flight. The only testing that would need to be performed is, for example, for the effects of cyclical loading on the springs, or how the temperature changes caused by the day-night cycle while in LEO affect the stiffness over time. These tests are different for every application so are not covered in this research.

There are two issues with using this filament though. ULTEM 9085 is expensive at 1320 SGD for a 1510 cm³ canister of material and 1320 SGD for a canister of support, to which need to be added a set of tips (450 SGD) and print sheets (1100 SGD for a packet of 20). Since this research includes a lot of experimental work, several canisters of ULTEM and support would have been needed so a cheaper alternative was sought. The other reason for not using ULTEM 9085 for the bulk of testing was that the printer used, a Fortus 450mc, requires the use of Stratasys' proprietary slicing software. This does not allow manipulation of layer height and temperature for ULTEM 9085, which ensures consistency but does not allow flexibility. Therefore at the beginning of the research the decision was made to use a material/printer combination that allowed more print settings to be changed.

Several plastics are available for FFF printers including PLA, ABS, PC, Thermoplastic Polyurethane (TPU), and Polyethylene Terephthalate Glycol (PETG). PLA was selected because it is a commonly used polymer [170] (the other most common one being ABS), it is easy to print [171], and has a higher rigidity, tensile strength, and layer adhesion compared to ABS [172]. While not being certified for use in space, PLA is cheap (at only a few tens of dollars per kg) and can be printed on a variety of FFF printers. There are many slicing programs available for PLA, all of which allow minute control of print settings, thus creating a larger

design space than with ULTEM 9085. This allowed the variation of layer height that was tested in chapter 6. By using PLA on an entry-level printer more samples could be printed faster and with more flexibility in the print settings. The equations derived in chapter 7 were tested with both PLA and ULTEM 9085 and can be used with any material as long as the necessary shear moduli are provided. It should be noted that PLA was only used for developing the equation. No intention is made to use PLA for functional space parts due to its high outgassing [173]. The material of choice for functional parts remains ULTEM 9085 since it has already been used in space.

3.3.2 Comparing springs made via AM and conventional means

The idea of plastic springs has been around since the middle of the 20th century [174, 175] and they find use in niche applications such as extending the life of hard disk drives by dampening vibrations [176], interferometers [177], and more commonly in suspension systems [166] and applications where corrosion resistance is necessary [178]. The materials used are usually PEEK, ABS, TPU, and proprietary polymers such as special formulations of Polyetherimide (PEI). It is therefore not possible to directly compare the springs printed in this research with commercially available ones because none could be found that are made of PLA or ULTEM 9085.

If the comparison were possible, due to the fact that print settings make a large difference to the mechanical properties of printed parts it would be difficult to gauge if springs made via AM are consistently better, worse, or the same without an in depth study. Future research could therefore be performed in this field, comparing the properties of printed and conventional springs in an effort to create printing guidelines that enable high quality printed springs to be manufactured. The objective of this research, though, is not to compare printed and existing springs but to enable new designs of springs to be manufactured via 3D printing and therefore direct comparison with existing springs is not part of the

scope.

3.3.3 In-fill selection

After the material had been selected, the in-fills were considered. Figure 3.7 shows the cross-section of an object printed with material extrusion, where two separate regions of material can be seen. The first is the contours or outline, which are the tracks of material deposited on the outside of the part to create smoother surfaces. Contour lines are always parallel to each other over all layers and follow the outline of the object. The contour width usually cannot be changed but the number of outlines N_{out} can, with the standard in most slicing programs being 2 or 3.

Figure 3.7: Cross-section of a part printed with FFF showing various features.

The other region is the in-fill, which is everything inside the contour. The in-fill is typically produced by laying parallel tracks of material in alternating directions so that one layer has raster angle (as defined in Figure 3.7) $+45$ and the next -45 . Theoretically there are infinite types of in-fill patterns (Archimedean spiral, gyroid, grid, honeycomb, Hilbert curve, etc...) and directions (± 45 , $30/60$, $0/90$, $0/45/90$, etc...) depending on the slicer used but most have ± 45 as their default setting.

Due to the different alignments, the in-fill and the perimeter can be defined as two different materials. That is because the perimeter is composed of mono-directional tracks that are parallel to the edges of the part while the in-fill is more similar to a sandwich of alternating fibres like a composite. This difference is very clear in Figure 3.7.

Users typically measure the mechanical properties of test objects printed with standard settings defined by the slicing program. They then measure the mechanical properties of those objects and perform simulations based on the recorded properties. The perimeter, being different materials, could have an effect on the mechanical properties of the part depending on how many there are. Two sets of PLA samples were therefore printed, one with in-fill in the $+45/-45$ directions (or ± 45) and the other with only $+45$ (or *mono-directional*, also shortened to *mono* in this thesis). These were used to simulate a tensile coupon using Finite Element Analysis (FEA). Since the effects of raster angle has already been extensively investigated in the literature [27, 166, 179, 180, 181, 167, 182], there are no further contributions that can be made in this research. Therefore the ± 45 in-fill was selected for the simulations because, as previously stated, it is the standard in-fill in most slicing programs.

Apart from the FEA simulations, the two in-fills were selected for other reasons. Adoption of the mono-directional in-fill is related to the mathematics of creating an equation that predicts the stiffness of printed springs. The derivation process will be discussed in more detail in chapter 7, for the moment it is enough to say that an in-fill had to be selected for the springs that was constant along the coils so as to not overcomplicate the problem. The ± 45 in-fill varies as shown in Figure 3.8a, at position 1 the in-fill has one configuration while at position 2 it is different. Logically this means that the shear moduli would change with the in-fill, making them dependent on the angle at which the cross-section is taken. All in-fills that are deposited in straight lines, like 30/60 or 0/90, would cause the shear moduli to change along a coil, making the derivation more complex. Figure 3.8b shows that the mono in-fill does not suffer from this problem because it is consistent throughout the coil, hence why it was the main in-fill for the springs manufactured in in this research.

Figure 3.8: Comparison of ± 45 and mono-directional in-fills.

3.3.4 Procedure

After selection of the material and in-fills, the model that was best suited for 3D printed objects was determined. Then all the constants needed for Equation 4.11 were measured for PLA using the two types in-fills. This was done in order to better understand the material and for future simulations and modelling. It was during this part of the research that the localised strain oscillations were first observed thanks to the particular strain measuring technique employed. More details can be found in Appendix A.

Once the constants had been measured the simulations of samples with various numbers of perimeters was performed, followed by testing of samples with the same number of perimeters. Most users of AM use pre-determined printing parameters with little care for the effects of variables such as the number of perimeters because they are typically interested in printing high quality and consistent parts. The perimeters and in-fill can be considered separate materials though, due to the way they are printed, therefore changing the number of perimeters might have an effect on the tensile properties of the part. Simulating the material as orthotropic with 1 to 5 perimeters and with different materials for the in-fill and perimeters then verifying the results experimentally allowed this question to be answered.

In order to derive an equation for 3D printed springs, samples had to be manufactured to determine if the calculated values corresponded to reality, therefore in this part of the research several springs were printed and their spring rates measured. First a comparison of the printing quality of round and square springs was made. Then three spring characteristics were varied: the pitch, coil diameter, and wire diameter. k , the spring stiffness, was measured for all the springs printed, both compression and tension, and for the different types of infill. Cyclical testing was also performed on springs that had been stretched past plastic deformation and into the second region to test their response.

Lastly, once all the data had been gathered, derivation of the equation for calculating k was done. This involved the creation of a new formula since, as explained earlier, 3D printed springs are very unusual. In fact the only equations known are for isotropic materials, not even composites. The energy stored by a stretched spring was equated to the energy stored by a shaft of equal length subjected to torsion. A correction was included to account for the fact that the equivalent shaft does not have a constant cross-section then the spring constants were calculated and compared to the measured ones. Finally, the cost of printing springs with ULTEM 9085 was calculated and some methods were developed for reducing the amount of material needed, print time, and therefore cost.

Figure 3.9 shows a summary of the main objective and the sub-objectives presented in section 1.3. For each step of the sub-objectives the section and page numbers where the relevant details can be found are provided.

Summary

In this chapter, although ULTEM 9085 has been used in space already, due to the cost it was determined that PLA was better for this research. Two in-fills, ± 45 and mono ($+45$), were then chosen for testing. Finally the testing procedure was outlined, involving first choosing a material model, then measuring the material

Figure 3.9: Thesis roadmap.

constants, followed by comparison of simulated and experimental tensile testing with varying numbers of outlines. Then 3D printed springs are to be investigated in depth, and finally two equations for calculating the spring stiffness are to be derived and verified.

CHAPTER 4

CREATION OF AN ORTHOTROPIC MODEL FOR PLA

The objectives for this chapter was the following: build a model for use in simulations and for reference. This was done via:

- identification of the most appropriate model for 3D printed materials
- determination of the most accurate way of measuring the strain during testing
- measurement of the material constants that were required for the model
- comparison of the material constants based on the type of in-fill

4.1 Determination of material model

4.1.1 Reference axis and coordinate origin

In this research the reference axes for the printer (shown in Figure 4.1) are defined following ASTM standards [183]:

- **Z-axis:** runs normal to the build platform;
- **X-axis:** runs parallel to the front of the machine and perpendicular to the Z-axis;
- **Y-axis:** perpendicular to both X and Z axis so the right hand rule is satisfied.

The origin of the coordinate system is defined as the point where all three of the coordinate systems intersect. Unless otherwise stated, this is assumed to be the centre of the build platform.

Figure 4.1: Definition of printer axes and coordinate origin [25].

4.1.2 Road angle

The road angle, also called raster angle for FDM, is defined as the angle the printer makes with respect to the X-axis in the bottom layer while looking along the -Z direction, shown in Figure 4.2.

Figure 4.2: Cross-section of a part printed with FFF showing various features including road angle [26].

4.1.3 Anisotropic materials

In order to create a model for 3D printed springs it is necessary to first discuss the nature of materials fabricated via AM. A short discussion of the mathematical models used for anisotropic materials will now be given. Stress (compressive or tensile) is defined as the amount of force F exerted over an area A ,

$$\sigma = \frac{F}{A} \quad (4.1)$$

Strain (compressive or tensile) is typically a measure of the deformation of an object where L_0 is the initial unstressed length and L_f is the length after stress has been applied,

$$\varepsilon_{eng} = \frac{L_f - L_0}{L_0} = \frac{\Delta L}{L_0} \quad (4.2)$$

ε_{eng} is known engineering strain and is used in most applications. Logarithmic or true strain was instead adopted in this research due to the ductile nature of PLA and because it is required by Abaqus CAE [184], the FEA software used. The derivation of true strain begins with an infinitesimal strain increase $d\varepsilon_t = \frac{dL}{L}$. The true strain is then obtained by integrating from L_0 to L_f

$$\int_0^{\varepsilon_t} d\varepsilon_t = \int_{L_0}^{L_f} \frac{1}{L} dL \quad (4.3a)$$

$$\varepsilon_t = \ln \left(\frac{L_f}{L_0} \right) \quad (4.3b)$$

Stress and strain are related by a form of Hooke's law:

$$\sigma = E\varepsilon \quad (4.4)$$

where E is Young's modulus or the modulus of elasticity. Poisson's Ratio (ν) is the ratio of transversal strain (ε_{trans}) to axial strain (ε_{axial}) in response to stress applied in the axial direction,

$$\nu = -\frac{\varepsilon_{trans}}{\varepsilon_{axial}} \quad (4.5)$$

Referring to Figure 4.3, the shear modulus or modulus of rigidity (G), is defined as the ratio of shear stress τ_{xy} (the component of σ that is coplanar to A) to the shear strain γ_{xy} (the component of ε parallel to A),

$$G = \frac{\tau_{xy}}{\gamma_{xy}} = \frac{Fl}{A\Delta x} \quad (4.6)$$

Here F is a force applied parallel to and area A , $\gamma_{xy} = \frac{\Delta x}{l} = \tan(\theta)$ is the shear strain, Δx is the transverse displacement, and l is the initial length.

Figure 4.3: Definition of shear strain.

E , ν , and G are related in an isotropic material because the molecules inside are uniformly distributed, allowing the calculation of one property from the other two. Domingo et al. [185] suggested an equation for calculating the in-plane shear modulus,

$$G_{ij} = \frac{E_i}{2}(1 + \nu_{ij}) \quad (4.7)$$

where i is the loading direction and j is perpendicular to i . To calculate the shear modulus using this method a type I tensile coupon is printed in the ij plane oriented in the i direction but rotated by 45° . This method was not used here because not enough literature could be found that confirmed if the method produced reliable results; so it was deemed more accurate to measure the shear constants directly. A future study could be made where Domingo et al.'s method is compared to the results obtained using ASTM standards.

3D printed materials, especially those produced via material extrusion (which is the printing method used for this research), act anisotropically for of three reasons [27]. First, during printing the molecules in the plastic align themselves to the direction of deposition, thus responding to stress differently depending on the direction. Secondly, this is also true of inter-layer bonding compared to bonding between tracks, where the former is stronger than the latter. Finally gaps and porosities can form between tracks like in Figure 4.4, creating areas where the stress response is dissimilar from that of the surrounding plastic.

(a) Scanning Electron Microscope (SEM) image of material extrusion printed plastic that shows the gaps between tracks [27].

(b) Cross-section of material extrusion printed ABS that shows the air gaps produced during the printing process [28].

Figure 4.4

When tested AM materials will produce a standard stress-strain curve like the one in Figure 4.5. Only the elastic portion of the curves is considered for measuring the material properties. When in this regime, the generalized form of

Figure 4.5: Typical stress-strain curve for a material. From A to B the material obeys Hooke's law (elastic behaviour). At C it starts to yield, from C to D it undergoes necking, and finally at E the material breaks.

Equation 4.4 for a material undergoing elastic transformation is

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix} \quad (4.8)$$

where the C_{ij} constants form the the stiffness matrix and can be determined experimentally. Solving Equation 4.8 for the strains gives the following compliance matrix where the S_{ij} s are known as compliances,

$$\begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ & & S_{33} & S_{34} & S_{35} & S_{36} \\ & & & S_{44} & S_{45} & S_{46} \\ & & & & S_{55} & S_{56} \\ & & & & & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} \quad (4.9)$$

Since both the stiffness and compliance matrices need to be symmetrical along the main diagonal, only 21 out of 36 constants are needed to characterize the material. A further simplification was made by modelling the material as orthotropic.

Feng et al. [186] printed several blocks of concrete using essentially material extrusion and performed simple compressive and flexural tests to determine strength, Poisson's ratio, and elastic modulus. As previously discussed the results were that there was a difference in the responses in all three axis, meaning the blocks were best represented as orthotropic [186]. These have 3 material directions, which are (from strongest to weakest) [37]:

- the forces that hold the particles together in the same track
- the binding force between adjacent tracks in the same layer
- inter-layer forces

The regions that produce these forces are shown in Figure 4.6.

Figure 4.6: Microstructural details of a 3D printed material.

The orthotropic model, which is assumed to be true under linear elastic de-

formations, has been successfully used in the literature [187, 188, 185, 189, 190]. Therefore since 3D printed parts are similar to Figure 4.6 the stiffness matrix for an orthotropic material is simpler than that for fully anisotropic,

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ & C_{22} & C_{23} & 0 & 0 & 0 \\ & & C_{33} & 0 & 0 & 0 \\ & & & C_{44} & 0 & 0 \\ & & & & C_{55} & 0 \\ & & & & & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} \quad (4.10)$$

Inverting and introducing E , ν , and G into Equation 4.10 the result is

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{13}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{12}} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} \quad (4.11)$$

Here 1, 2, and 3 represent the material directions. E_1 is the stiffness in direction 1 so if only tension is applied in direction 1, Equation 4.11 will reduce to Equation 4.4. Figure 4.7a shows the labelling convention of normal and shear stresses that has been used as a basis for this research. The material directions have been defined as shown in Figure 4.7b. 1 and 2 are parallel to the tracks and 3 is perpendicular to the layers. As can be seen in Equation 4.11, there is no shear coupling, Rodríguez et al. [191] found that it is present but they concluded that it is weak and negligible therefore it will be ignored.

(a) Labelling of normal stresses, shear stresses, and material directions from ASTM standard 5379 [29].

(b) Definition of material directions used in this research, where 1 and 2 are aligned to the tracks and 3 is parallel to the deposition direction.

Figure 4.7

4.2 Material properties

Equation 4.11 requires the knowledge of the following material properties:

- E_1 , E_2 , and E_3
- ν_{21} , ν_{13} , and ν_{32} (the assumption is that Equation 4.11 is a symmetrical matrix)
- G_{23} , G_{13} , and G_{12}

Although not specifically designed for AM, existing ASTM testing procedures were used to measure the constants and are described in the following sections. Each test was performed by printing the relevant coupon in several orientations to test the various material directions. The average and sample standard deviation s of all the samples in a particular orientation were used to calculate the material properties and their errors.

4.2.1 Young's modulus E

This parameter is measured using coupons made according to ASTM standard D638-14, shown in Figure 4.8 [30], using first type IV then type I coupons, whose detailed dimensions can be found in Table 4.1. The reasons for changing from type IV to I will be explained later.

Table 4.1: Dimensions of type I and IV coupons [30].

Parameter	Type I (mm)	Type IV (mm)
W	13	6
L	57	33
WO	19	19
LO	165	115
G	50	25
D	115	65
R	76	14
RO	...	25
T	4	4

Figure 4.8: ASTM tensile coupons used [30].

Stress-strain curves such as the ones shown in Figure 4.15a were produced for E_1 , E_2 , and E_3 . The elastic modulus for each constant was calculated by taking the slope of the linear portion of the curve for each sample then averaging the slopes. The standard deviation was used for the error.

4.2.2 Poisson's ratio ν

The basic equation for calculating ν is as follows [30],

$$\nu = \frac{-d\varepsilon_t}{dP} \frac{dP}{d\varepsilon_{ax}} \quad (4.12)$$

$$= \frac{-\varepsilon_t}{\varepsilon_{ax}} \quad (4.13)$$

where ε_t is the transverse strain, ε_{ax} is the axial strain, and P is the load applied. Like for E , the test procedure is also outlined in ASTM standard D638-14 [30] and uses the same samples. It involves measuring axial and transverse strain as described in section 4.3. A plot was made of transverse versus axial strain and the linear portion identified. A linear regression was then performed on the linear portion of each sample's plot and then the average was calculated to give the final ν .

Table 4.2: Dimensions of shear sample [29].

Parameter	Size (mm)
d_1	19
d_2	3.8
h	4
L	76
r	1.3
w	11.4

4.2.3 Shear modulus G

To calculate G , the following equation from ASTM standard D5379 was used [29]:

$$G_{chord} = \frac{\Delta\tau}{\Delta\gamma} \quad (4.14)$$

Here G_{chord} is equivalent to G , $\Delta\tau$ is the change in shear stress, and $\Delta\gamma$ is the change in shear strain. Like E and ν , G is equivalent to the slope of the linear portion of the plot of shear stress against shear strain.

The two options for measuring this constant were ASTM standard D5379 (Iosipescu test) [29] and D4255 (rail shear method) [192]. The Iosipescu test [29] was selected because it is specifically designed for composite materials, which materials fabricated via AM are most similar to, and it provides accurate results [187]. The sample shown in Figure 4.9a, whose dimensions can be found in Table 4.2, is placed in the fixtures shown in Figure 4.9b which have been mounted on the testing machine.

A shear force P is then applied to the sample and stress and strain data is collected. The shear strain is calculated with the following equation [29]

$$\gamma_i = |\varepsilon_{+45}| + |\varepsilon_{-45}| \quad (4.15)$$

where γ_i is the strain at the i -th data point while ε_{+45} and ε_{-45} are the normal strains at the same data point. A plot of shear stress against strain is then made as shown in Figure 4.10. The linear portion marked “Chord Modulus Region”

(a) Sample used for shear testing [29].

(b) Testing fixtures used to apply shear stress [29].

Figure 4.9

is used to obtain the shear modulus. The average of the shear moduli of all the samples is then calculated.

Figure 4.10: Shear stress against shear strain showing important features from ASTM standard D5379 [29].

4.3 Methodology for measuring material properties

4.3.1 Sample orientation and naming convention

Figure 4.11b shows the orientations in which samples were printed, which were developed using Figure 4.11a from ASTM standard D5379 [29]. They are named according to the constant the samples were used to measure. Some orientations can be used to measure two constants like E_2 is used to measure ν_{21} . The material directions have been defined so that 1 is aligned to the +45 track, 2 is aligned to the -45 track, and 3 is parallel to the layer deposition direction.

A naming convention was devised, an example of which is ± 45 -E1-01, which

(a) Orientation of material planes used to develop coupon orientations [29].

(b) Diagram of sample orientations naming system. The white axes shows the printer coordinate system while the blue axes show the material directions. Although type IV samples are shown here, type I were also printed in the same orientations.

Figure 4.11

refers to the first (01) sample in the E_1 orientation (E1) for the set with the ± 45 in-fill. Another example is +45-v31-04, which describes the fourth sample (04) printed in orientation ν_{13} (v31) for the set with mono-directional in-fill +45.

4.3.2 Procedure

Two Shimadzu Autograph AGS-X Series Universal Testing Machine (UTM)s were used for testing, one with a 50 kN load cell and the other with a 10 kN load cell. The maximum values for the load cells are quite high and if the forces generated during testing are too small, the load cell would be unable to measure them accurately. The rule of thumb is divide the load cell rating by 500 to obtain the minimum force necessary for the reading to be considered valid [193]. For the 10 kN machine that is $\frac{10000}{500} = 20$ N while the minimum force for the 50 kN UTM is $\frac{50000}{500} = 100$ N. All experiments for measuring the material constants produced forces much greater than these values so they can be considered accurate. There were instances during spring testing where not enough force was generated therefore a slightly different approach was used which will be discussed in subsection 6.2.6.

A problem was quickly discovered when it came to measuring Poisson's ratio and the shear moduli. The UTMs were equipped with cameras to measure strain and therefore calculate Poisson's ratio. The normal procedure was to draw two parallel lines as shown in Figure 4.12 that were orthogonal to the gauge area. Trapezium X, the program that was used to control the UTMs and take data, was able to track these lines as well as the edges of the sample in order to calculate ν .

Figure 4.12: Type I tensile coupon ready with black lines for measuring axial strain.

Sometimes the changes in the sample's width (the transverse strain) were so small that Trapezium X could not detect any change, especially with the type

IV samples because of their smaller size. Due to the layered nature of 3DP, the in-built strain detector would also get confused because different parts of the sample shrunk at different times, creating incorrect data. Therefore another more accurate method was used as explained below.

4.3.3 GOM Correlate

Digital Image Correlation (DIC) is the technique employed to measure strains in this research, which has also been used by the literature [194, 38]. The specific software used here was GOM Correlate, a free DIC package [195]. This program allowed much greater precision than the video extensometers on the UTMs and even strain gauges (since it allowed the tracking of individual parts of the sample's surface) therefore was used for all testing.

Before testing all coupons were sprayed with a stochastic speckle pattern as shown in Figure 4.13c. Measurements of the cross-sectional area of the gauge length were entered into the software then coupons were placed in the UTM and the test was then started.

Stress, force, and displacement data was recorded at 10 Hz. A video of the test was taken for strain analysis using the cameras mounted on the UTMs, which was subsequently converted to 10 frames per second to match the rate at which data was collected. This was necessary because the frame-rate of the raw footage varied from 22 to 25 frames per second and was not controllable. Conversion was performed so as to not compromise the resolution of the video, only the frame-rate was changed.

An external camera with a higher frame-rate and better resolution could have been used in lieu of the cameras already mounted on the testing machines but there was the chance of introducing alignment errors because the optical axis of the camera has to be orthogonal to the surface of the sample. It would also have also been difficult to match the start of the strain data, which come from GOM, and the stress data, recorded by the UTM. The mounted cameras were correctly

aligned and Trapezium X ensured that the video started at the same time as the stress measurements, thereby guaranteeing that the stress and strain data were synchronised.

After conversion the video was analysed in GOM Correlate. First the area for analysis had to be selected, as shown in Figure 4.13a. GOM would automatically verify if the speckle pattern quality was satisfactory by displaying a legend with different colours representing the quality of the pattern and special attention was taken to ensure that all samples used in this research had a satisfactory pattern. The facet size and point distance were values that would be adjusted according to guidelines provided by GOM. The high accuracy computation method was used for all analyses, which used a bicubic interpolation method. Figure A.1 shows the analysis of a tensile coupon while shear data was collected as shown in Figure 4.13c.

In the DIC method, first the pixels in each image are mapped relative to their neighbours. Then by comparing blocks of pixels from one image to the other, programs like GOM Correlate are able to build up full field 2D and 3D deformation vector fields and strain maps [196]. More specifically, the program minimizes the zero-mean normalized sum of squared difference criterion in gray intensity between images to find correspondences between the subsets in the spatial domain [197]. Many shape functions are used to track the changes in the initially square subset and various software techniques have been developed that allow sub-pixel resolution. GOM is able to track changes on the surface of the sample that are smaller than the pixels of the video file, thus it is said that it has sub-pixel accuracy, which was important for the work done in Appendix A. For DIC to work effectively, the subdivisions need to be random and unique with a range of contrast and intensity levels, which is simply achieved by using spray paint [196].

Axes for strain measurement could be created in any orientation in GOM. For the shear samples, the x and y axes were rotated to match the orientation of

the strain gauges described in ASTM standard D5379. Regardless of which type of sample was being analysed the output of the DIC process was true strain as defined in Equation 4.3b, an example of which can be seen in Figure 4.13b.

The strain plot shown in Figure 4.14 is the arithmetic mean of the displacements of each subdivision in the selected area calculated at each frame of the video using the first frame as a reference. Using the mean produces smoother plots than looking at individual subdivisions for reasons that are discussed in more detail in Appendix A.

The strain and stress data are then combined and plotted in MATLAB to produce the necessary graphs for calculating material properties, Figure 4.15a shows an example for determining E_1 . For all E , ν , and G the linear part of the plot for each sample is selected and an iteratively re-weighted least squares regression is performed to calculate the slope with a bi-square weighting function to produce the regression lines seen in Figure 4.15b. The data points on which to perform the regression were identified by eye. In the last step the slopes of all the samples are averaged and the sample standard deviation s is used as a measure of accuracy. For the example shown in Figure 4.15b the average slope is 3751 ± 512 N/mm² or GPa.

Some strain softening was found to occur after the linear region during tensile testing of PLA, which is consistent with Letcher et al. [31], as can be seen in Figure 4.16a. They also observed no strain hardening after plastic deformation during tensile testing.

Since only one camera was used for DIC, the resulting strain analysis can only be 2D, meaning that GOM Correlate was unable to detect any out of plane strain. This is a potential source of error but there is no way of determining its effects using this technique. If two cameras were used, 3D DIC could be performed and so out of plane strains detected and accounted for. Due to the fact that only 2D DIC can be performed, special care had to be taken to ensure that the samples were aligned correctly so as to avoid errors in strain measurements caused by

(a) Example of selection of the area for analysis with pattern quality legend on the right.

(b) Simplified view of the analysis of sample $\pm 45\text{-E3-07}$ in GOM Correlate indicating significant features.

(c) Strain analysis for sample +45-G13-02. The measurement area can be seen in between the two notches. The x and y axes have been rotated to produce the required shear strain as described in ASTM standard D5379.

Figure 4.13

Figure 4.14: Output from the strain analysis in GOM Correlate of a tensile coupon showing the average axial (blue) and transverse (black) strains over time.

out of plane strain. Using the cameras that were already mounted on the UTMs ensured accurate measurements.

4.3.4 Print settings

An original Prusa i3 MK3, shown in Figure 4.17, was the material extrusion printer used for the PLA samples. The print settings are shown in Table 4.3.

Table 4.3: Print settings

Feature	Setting
Nozzle diameter (mm)	0.4
Extruder temperature (°C)	210
Bed temperature (°C)	65
Layer height (mm)	0.15
Infill (%)	100
Top and bottom solid layers	0
N_{out}	1

The slicing program used was Simplify3D (<https://www.simplify3d.com/>). To create a smoother surface, most slicing programs will create solid top and bottom layers, which are printed with modified parameters such as different raster widths [185]. In order to prevent these layers from affecting the mechanical prop-

(a) Complete stress-strain plots for all samples.

(b) Plots of linear portions of stress-strain curves showing average.

Figure 4.15: Plots of data used to calculate E_1 .

Figure 4.16

Figure 4.17: Original Prusa i3 MK3 [32].

erties, they were set to 0.

4.4 Results

4.4.1 Reasons for switching from type IV to type I coupons

Type IV coupons were first used because they were smaller than type I, resulting in less material usage and shorter printing times. In the course of the research the decision was made to change to type I because it was found that type IV samples were too weak in the vertical orientations ν_{13} and E_3, ν_{32} , resulting in plots such as those shown in Figure 4.18. When plotted independently against time, the axial (Figure 4.18a) strain has an overall linear region. The transverse strain, on the other hand, has a less clear linear region, as can be seen in Figure 4.18b, which is generally true of all samples. When plotting the transverse strain against the axial strain (Figure 4.18c) the data becomes very noisy and it is difficult to identify a clear linear region. The results in subsection 4.4.2 further discuss this fact.

ASTM standard D638 recommends setting the testing speed to either 5 mm/min or to a speed where breakage occurs at least 30 seconds after the start of the test [30]. The first samples had a testing speed of 5 mm/min but because the coupons were very weak, they broke too quickly and few data points were produced so the testing speed was lowered.

Samples 07 to 09 were tested at a speed of 0.1 mm/min, resulting in plots that had more data points as can be seen in Figure 4.19a. Taking all samples into account, ν_{32} was measured to be 0.510 ± 0.383 , where the standard deviation is close to 75% of the measured value. Such a high standard deviation is unacceptable so the switch was made to type I samples. Type I samples took longer to print and used more material but produced better data, like that shown in Figure 4.19b. These were tested at a rate of 0.5 mm/min because like the type IV coupons they broke too quickly when using the recommended rate. Table 4.4 shows the experimentally measured constants for in-fill with raster patterns +45

(a) Time versus axial strain.

(b) Time versus transverse strain.

(c) Transverse versus axial strain.

Figure 4.18: Plot for measuring Poisson's ratio using sample ± 45 -E3-03, a type IV coupon.

and ± 45 using type I and shear coupons. The latter were measured at a rate of 1 mm/min except for the G_{31} orientation, where the samples were breaking too fast so the loading rate was slowed to 0.5 mm/min.

4.4.2 Measured constants

Table 4.4 shows the material constants measured using type I and v-notch coupons printed with PLA. At least 4 coupons were tested for each orientation. Figure 4.20 compares the measured constants for the two in-fills.

Table 4.4: Measured orthotropic constants for +45 and ± 45 in-fill using type I and shear coupons made with PLA.

Material Constant	+45	s	± 45	s
E_1 (MPa)	3111	183	3011	124
E_2 (MPa)	3003	43	3326	189
E_3 (MPa)	2725	250	2301	149
ν_{21}	0.327	0.013	0.329	0.009
ν_{31}	0.334	0.033	0.236	0.035
ν_{32}	0.356	0.050	0.243	0.036
G_{12} (MPa)	1159.1	49.1	1125.5	54.9
G_{13} (MPa)	974.3	62.3	1006.5	67.3
G_{31} (MPa)	856.7	59.9	891.2	44.6

As can be seen in Figure 4.20a, the trend for the ± 45 in-fill is that E_3 is lower than E_1 and E_2 , which is expected. E_2 for the +45 in-fill is within two error bars from E_1 , whereas the expectation would be that, since in the E_2 coupon the strength comes from the bonding of neighbouring rasters, E_2 should be significantly lower than E_1 but that is not the case. On the other hand, E_2 and E_1 for ± 45 are very similar, which is expected.

The E s and ν s have small errors in some cases, 1% in the case of +45- E_2 while the largest is about 15% for ± 45 - ν_{13} . Compared to He et al., who gave the elastic modulus value as 2400 MPa for samples with 100% infill [2], the elastic moduli measured here were higher. The large errors are most likely due to the sensitivity of PLA to variations in print parameters and conditions [?], and the relatively poor resolution of the cameras on the UTMs. For both in-fill types, some coupons

displayed a strange behaviour where they expanded slightly in the transverse directions before contracting as normal. A possible explanation is that this is a form of stabilization before responding to the stress in the expected way. The +45 in-fill produces higher Poisson ratios in the vertical orientations most likely due to a smaller amount of air gaps as opposed to the ± 45 infill; so material in the +45 samples has less empty space to expand into when under stress thereby resulting in more visible changes compared to the ± 45 samples. Tronvoll et al. [198] found that the effect of voids on tensile strength is very significant, much more so than the effect on compressive strength. ABS specimens printed with FFF were found to have a tensile strength that was 68% lower than that of samples made out bulk material.

The shear moduli have consistently low errors for all samples and the +45 in-fill is higher in two out of three cases indicating that this in-fill is stronger when subjected to shear stresses, a result which can be explained with polymer weld theory [37]. In the +45 infill all material is deposited in the same direction, resulting in adjacent layers that are in continuous contact, as shown in Figure 4.21a, and thereby leading to stronger welds being created. In comparison the roads in the ± 45 in-fill have discontinuous contact regions, resulting in a weaker material (Figure 4.21b). For this and other reasons which will be discussed in chapters 6 and 7, the +45 in-fill was selected for the springs printed as part of this research. The values obtained are similar to those from He et al., around 1000 MPa for the 100% infill samples [2].

The results in Table 4.4 are comparable to those of bulk PLA, where the elastic modulus is 3500 MPa, Poisson's ratio is 0.36, and the shear modulus is 1287 MPa [199], with some differences. Firstly, none of the values are as high as those of the bulk material indicating that this combination of material and printing technique is detrimental to the mechanical properties. G_{12} is closest to the bulk material and G_{31} is the furthest because in this orientation the shear is applied along the layers, the weakest bond. The elastic moduli produce a similar result where the

vertical orientations are the furthest from the bulk modulus. ν_{32} for the +45 infill is the closest to the bulk material's ν because this is the only orientation where roads are perpendicular to the camera during testing, meaning that what is being measured is the resistance of the deposited roads to stress applied along their length. Since in this orientation there is the greatest amount of uninterrupted bulk PLA resisting contraction, i.e. no air gaps or tracks in different directions, it is reasonable that this orientation has the greatest Poisson's ratio. Conversely the ± 45 in-fill suffers because in the vertical samples half the tracks are deposited perpendicular to the camera and the other half radially, thus offering a much lower resistance to contraction.

Summary

In this chapter the material properties and material model were discussed. Then the techniques used for measuring each material constant were explained, along with the reason for the adoption of DIC and the switch from type IV to type I samples. The measured constants confirm the pattern found in the literature: the bonding between layers is the weakest.

(a) Transverse versus axial strain for all ± 45 -E3 samples using type IV coupons.

(b) Transverse versus axial strain for all ± 45 -E3 samples using type I coupons.

Figure 4.19

(a) Elastic modulus.

(b) Poisson's ratio.

(c) Shear modulus.

Figure 4.20: Comparison of measured mechanical properties for ± 45 and $+45$ in-fill using PLA.

Figure 4.21: Comparison of contact regions between layers in +45 and ± 45 in-fills.

CHAPTER 5

MULTI-MATERIAL FINITE ELEMENT SIMULATION OF 3D PRINTED MATERIALS

As a reminder, the objective of this chapter is to vary the number of perimeters for samples subjected to tensile loading and it was achieved via:

- simulation of tensile coupons with various numbers of perimeters and the most commonly used in-fill
- printing and testing of tensile coupons with the same characteristics
- comparison of the simulations and experimental results

5.1 Modelling of 3D printed materials

3D printed objects are composed of the various parts shown in Figure 5.1. First to be printed is usually the perimeter, tracks that mark the edges for the object

in that layer. There can be any number of perimeters although normally there are two or three. Then the printer will print the in-fill, which is the inside of the part and is made according to the specifications of the user. The user can set the printer to print solid, i.e. with 100% in-fill, layers at the top and bottom of the object, usually two to three layers at both ends. It is important to note that the layer height and nozzle temperatures do not usually change while printing the in-fill or the perimeter.

Figure 5.1: Cross-section of sliced object with various parts coloured in. The grey cylinder on the right represents the nozzle head.

Objects manufactured via FFF have at least two distinct parts, the perimeter and in-fill. Due to their different geometries, they will behave differently to stress. Therefore the objective in this part of the research was to investigate the effects of N_{out} on the mechanical properties of tensile coupons and see if FEA simulations reflect this.

5.2 Experimental procedure

There are three steps in this series of experiments. The first step is to characterize the properties of both the in-fill and the perimeter, the results of which have already been presented in subsection 4.4.2. These can be used with Equation

4.11 to create the two compliance matrices necessary for the simulations. The second step was to perform simulations of tensile coupons in Abaqus/CAE with various N_{out} values and to calculate E_{sim} and ν_{sim} according to the simulations. The third and final step was to print tensile coupons with the same number of perimeters as the simulations, measure E_{exp} and ν_{exp} , and compare them to E_{sim} and ν_{sim} . The print settings were those stated in subsection 4.3.4. To measure the mechanical properties of the perimeter and the in-fill as accurately as possible, N_{out} should be 0 when printing samples. Since Simplify3D does not have this option, N_{out} was set to 1, the smallest number possible.

5.3 Simulation and experimental verification

As previously mentioned, the FEA software used was Abacus/CAE. Two materials were created, one for the in-fill and the other for the perimeter using the results of the experimental characterization. Figure 5.2 shows an example of a coupon in Abaqus with $N_{out} = 5$. The in-fill region was a separate part from the perimeters, that were mirror images of each other and the inside surfaces of the perimeter regions were tied to the sides of the in-fill. The end tabs of the coupons were not simulated. The thickness of the perimeter regions was the width of the printer's nozzle, 0.4 mm, which is also the width of the printed tracks.

Figure 5.2: Abaqus assembly showing the in-fill and perimeters.

Figure 5.3 shows the local material directions for the two regions. Since the printer deposited the in-fill material in only two directions, the in-fill material directions 1 and 2 were aligned to the global axes as shown. The perimeters, on the other hand, change their alignment depending on the shape of the object. Therefore material direction 1 was set to follow the curve of the perimeter, with direction 2 defined orthogonally to that and direction 3, which was aligned to the direction of layer deposition. This means that 1 and 2 can change as stress is applied in the simulation, which is more realistic.

Figure 5.3: Top down of sample to show material directions for the perimeter (red) and the in-fill (blue). Direction 3 for both is out of the page.

Five simulations were conducted with $N_{out} = 0, 1, 2, 3, 5$. The boundary conditions of the FEA simulations were determined by the experimental setup, one end of the simulation samples was fixed while the other end moved at 0.5 mm/min. C3D8R elements were used in the mesh with a size of 0.4 mm, which was chosen because that is the width of the nozzle. The elastic modulus and Poisson's ratio was calculated by extracting the stress and strain data for one of the surface elements in the middle of the gauge area. A simulation was done with $N_{out} = 0$ for comparison.

The last step was to print tensile coupons and measure E_{exp} and ν_{exp} . Samples with $N_{out} = 1, 2, 3, 5$ were printed, $N_{out} = 4$ was skipped because most users do not use more than 3 perimeters so 5 was considered enough. 5 samples were printed and tested for every N_{out} . They were tested on the same Shimadzu UTMs as in section 4.3 using the same speed as for the simulated samples. Stress

data was obtained from the machines while strain was measured using GOM Correlate.

5.4 Results

The results are shown in Table 5.1. Figures 5.4a and 5.4b show how E and ν change with N_{out} .

Table 5.1: Elastic moduli and Poisson's ratios from simulations and experiments.

N_{out}	Simulation		Experiments			
	E (MPa)	ν	E (MPa)	$\pm$	ν	$\pm$
0	3011	0.3279				
1	3013	0.3252	3011	124	0.3378	0.0045
2	3013	0.3265	2900	11	0.3499	0.0307
3	3014	0.3262	2869	25	0.3492	0.0196
5	3013	0.3266	3040	12	0.3405	0.0282

As can be seen in Figure 5.4a, N_{out} has an effect on the E of printed samples since it drops from $N_{out} = 1$ to $N_{out} = 3$ but then goes back up at $N_{out} = 5$. The drop is very small and indicates that adding perimeters slightly weakens the part. With 5 perimeters the part is slightly stronger than with 1 perimeter because the perimeters are aligned to the direction of the stress and as explained in subsection 4.1.3 the strongest bond is that between the molecules in the plastic.

The simulated samples, on the other hand, are not affected by the number of perimeters. The characteristics of the sample with $N_{out} = 0$ are the same as those of the material, which is to be expected. There is a tiny increase in the elastic modulus from $N_{out} = 0$ to $N_{out} = 1$ due to the reinforcement provided by the perimeter but after that E remains constant. Although there is a difference, E_{exp} for $N_{out} = 2$ and $N_{out} = 3$ are only about 4% and 5% smaller than their simulation counterparts.

ν on the other hand is not as affected. Figure 5.4b shows that the simulated Poisson's ratio changes slightly from $N_{out} = 0$ to $N_{out} = 1$ but then remains

(a) Elastic modulus.

(b) Poisson's ratio.

Figure 5.4: Comparison of simulated and printed samples.

consistent. Printed samples show some variation in ν but not as great as the change in E . The most notable difference between the two sets of results is that the simulations consistently return a Poisson ratio that is slightly smaller than the experimental one.

As shown in Table 5.2, the data differ by only a few percentage points. This indicates that even though the number of perimeters does make a slight difference in the mechanical properties, it is not very significant. Most users print objects using manufacturer settings, which set $N_{out} = 2$ or $N_{out} = 3$ in most cases. Unless the part is very small, meaning the amount of in-fill is comparable to the amount of perimeter, the conclusion of this experiment is that FEA tensile simulations can be performed using only the properties of the in-fill without compromising the results.

Table 5.2: Percentage differences between the experimental and simulated elastic moduli and Poisson ratios

N_{out}	$\left(\frac{E_{exp} - E_{sim}}{E_{exp}} \right) \times 100$	$\left(\frac{\nu_{exp} - \nu_{sim}}{\nu_{exp}} \right) \times 100$
1	0	4
2	-4	7
3	-5	7
5	1	4

Summary

A comparison of Young's modulus and Poisson's ratio measured using simulations and printed samples was made in this series of experiments. The number of outlines was varied to verify if the simulations agreed with the experimental results and it was found that they do.

CHAPTER 6

EXPLORATION OF 3D PRINTED SPRINGS

6.1 Springs and AM

The aerospace industry is drawing great benefits from AM and will do so even more in the near future as has been explained in chapter 2. Chapter 3 has explained the potential advantages that mechanisms such as springs have for the space industry, they can operate in many environments and with harsh conditions for a long time without maintenance.

Springs also come in many shapes and sizes and are very adaptable, they can be modified to meet very specific needs and their only true limitation is manufacturing. As a reminder the objective for this section of the research was to compare springs with different in-fills and investigate the plastic region, in which a permanent deformation remains after a load is removed. This was done by:

- determining the spring wire cross-section that will print best

- printing and testing a variety of helical springs, both compression and tension
- exploring the differences and similarities between in-fills and types
- performing cyclical loading in the post-deformation linear region

In a broader sense this section is about how AM affects the properties of springs. This includes changing the cross-section of the spring material, circle vs square, since 3D printers can do either. Force-displacement plots were produced in order to measure the springs' elastic constant k and were used to determine how AM affects the springs. Springs were printed with ULTEM 9085 and PLA and were compared. An interesting result was found which will be discussed later.

6.2 Methodology

6.2.1 Spring types

There are many types of springs, classified based on their structure and load types which are axial, transverse, and torque. As described before they can also have non-linear responses to loads. The axially loaded helical or coil spring is the most common type and is the one chosen for this research as explained in section 3.1. Loading in tension and compression were both tested in order to investigate the widest possible range of springs. Compression springs are slightly easier to print but have limited pitches and displacements whereas tension springs are more difficult to print. Figure 6.1 shows the important spring parameters or dimensions that apply to this research.

6.2.2 Spring wire cross-section

An initial study was performed to see which cross-section printed better. Two tension springs were printed with identical dimensions: $d = P = 7$ mm, $D = 35$ mm, and $N_a = 5$. The springs had different cross-sections where one was a

Figure 6.1: Spring parameters, N_a refers to the active coils of the spring, those are coils that are not part of either end of the spring.

circle, Figure 6.2a, and the other a square, Figure 6.2b. The circular cross-section printed slightly teardrop shaped and required many more supports so the square was chosen instead since it had smoother sides and higher print quality. Springs with a square wire cross-section have existed for many years [200] but there is a further reason for selecting it which is related to the derivation of the spring stiffness equation. In short, having round wire simplifies the derivation of spring equations but since 3D printed springs are made of layered material, a circular cross-section would make the derivation more difficult. This will be discussed in greater detail in chapter 7.

When switching from the spring with the circular cross-section (Figure 6.2a), which has a mass of 58 grams, to the square cross-section (Figure 6.3a), with a mass of 74 grams, the difference is only 16 grams. Smaller springs would have smaller mass increases when switching from a circular to a square cross-section so this was considered to be suitable even for the space industry, where mass is limited and closely monitored, and subsection 8.3.4 discusses a method for fur-

ther reducing the mass of springs. A potential way to solve the inaccurate circle printing would be to make the spring much bigger but this was not considered since it would have required a lot more material and time to print and the mass increase would have been too great.

Figure 6.2: Comparing the print quality of circular and square wire cross-sections.

This is already an example of the design freedom that 3D printing can bring to spring design. Changing the cross-section from circle to square did not require a major re-working of the production method, just a change in the Computer Aided Design (CAD). The final printed spring had the exact square cross-section as wanted.

Another re-design is shown in Figure 6.3a where the tension springs were originally designed to have printed grips where to attach the clamps of the UTM. The grips were at the end of an extension arm so that the tension force was applied at the centre of the helix. The grips were found to be inadequate since excessive tightening of the jaws could damage or break them. On the other hand, if the jaws were not tightened enough the spring could slip out. Therefore the tension springs were re-designed to have holes at the top and the bottom for the insertion of screws. This allowed the clamps of the UTM to pull the springs without directly making contact with the spring material, as shown in Figure 6.3b.

Figure 6.3

6.2.3 Printing orientation and in-fill direction

All the springs in this study, both tension and compression, were printed vertically, with the axis around which the coils processed parallel to the layer deposition. A simple FEA analysis of the springs was performed in an effort to determine the stress distribution inside the coils. Using the constants measured in subsection 4.4.2, two FEA simulations were done of a single coil of a tension spring in Abaqus CAE. The normal material produced by 3D printers is shown in Figure 6.4a, which, like in chapter 4, is referred to as ± 45 in-fill. The other material orientation tested was where all the tracks printed were in the direction of the coil, shown in Figure 6.4b and referred to as mono-directional in-fill or mono. The coils were subjected to a constant upwards velocity of 0.5 mm/min to simulate the testing that was going to be done later.

When analysing the result of the FEA, the shear stress in Figure 6.5a is evenly distributed along the length of the coil. Figure 6.5b, on other hand, shows that there are areas of higher stress concentrations. This indicated that the ± 45 in-fill

Figure 6.4: Material orientations of a single coil for FEA.

might fail before the mono-directional in-fill therefore springs with both in-fills were printed and tested to verify the results of the FEA simulations.

Figure 6.5: Stress distributions generated by a constant upwards velocity of 0.5 mm/min.

6.2.4 Spring index and naming convention

An important parameter in the design on springs is c or the spring index

$$c = \frac{D}{d} \quad (6.1)$$

c gives an indication of how difficult or easy it is to stretch or compress a spring. A spring index of 3 or lower means that the spring is hard to manufacture con-

ventionally. Indices higher than 15 produce springs that buckle and tangle easily so the optimal range is usually about 4 to 12, which was the range chosen for this study.

Three sets of springs were printed and tested. The first set was composed of all PLA tension springs, the second all PLA compression springs, and the third was composed of ULTEM 9085 compression springs. Springs with mono-directional in-fill are referred to as mono springs, as previously discussed. The spring dimensions were chosen to be as varied as possible while at the same time being fast to print. For the tension springs only d and D were varied while P was kept constant, so as to reduce the number of variables. For the compression springs all three were instead varied. Figure 6.6 shows an example of a compression spring. As can be seen they have circles at the top and bottom, referred to as closed ends, which give the testing machines a surface on which to apply pressure.

Figure 6.6: Example of a PLA compression spring.

Springs are labelled according to their characteristics and what type of in-fill they have. For example a spring with $d = 5$ mm, $D = 20$ mm, and $P = 15$ mm is labelled as d5D20P15. Since the tension and compression springs have different dimensions, it is not necessary to add an extra term to the label to indicate what type of spring it is. The only exceptions are a few springs that will be discussed

later.

6.2.5 Printer settings

For the tension springs a Cubicon Single 3DP-110F was used but with the same settings as in subsection 4.3.4. The compression springs were instead printed on the same Prusa i3 MK3 and with the same settings as in subsection 4.3.4. The ULTEM 9085 springs were printed on a Fortus 450 mc with factory settings, except for the in-fill.

The equation to calculate the pitch P is based on the angle θ between the horizontal and a coil is

$$P = \pi D \tan(\theta) \quad (6.2)$$

so for $D = 20$ mm, which is the smallest compression spring, and $\theta = 50$ then $P \approx 150$ mm. This would mean that a spring with that pitch and having $N_a = 5$ would not fit in any of the printers so P was kept low and supports were used.

The mono-directional in-fill was achieved by instructing the slicing programs to create a number of outer walls that were at least bigger than $\frac{d}{2}$. This resulted in the in-fill shown in Figure 6.7a. Figure 6.7b instead shows one layer of the normal ± 45 in-fill for comparison.

6.2.6 Testing equipment and data generated

The springs were tested using the same UTMs as for subsection 4.3.2. As already mentioned if a load cell with a capacity much greater than the forces generated during testing is used, unreliable data might be produced. During the course of testing some of the springs generated very small forces, especially the compression ones, therefore the UTM with a 10 kN load cell was used, which was the smallest available. Testing was performed at various speeds, usually in the range of 50 to 80 mm/min and a series of experiments were done to verify that the change in speed did not affect the results and will be discussed later.

Figure 6.7: Compression springs in the slicing program.

The data generated by the UTMs was different from that in chapter 4. Force F was plotted against stroke or displacement, which are the same thing i.e. x in Equation 3.1. The slope of the linear portions of the F - x graphs would give k as per Hooke's law. Tests to breakage and cyclical testing were both performed.

Compression springs could not be broken but they were tested to maximum compression and also cyclically. The cyclical testing was done over two or three cycles and only for a small displacement, enough to measure the spring constant. The objective was to stay in the elastic region and to not break the samples so that they could be used again. As will be shown later, some of the more compliant springs showed that they were greatly affected by creep while undergoing cyclical testing.

6.2.7 Tension spring testing

This section will discuss the testing procedure for the tension springs. The emphasis here was the ± 45 in-fill but mono springs were still tested.

Test to fracture for ± 45 springs

The first set of springs tested were tension springs with ± 45 in-fill. The dimensions and spring indices can be found in Table 6.1.

Table 6.1: Dimensions of PLA tension springs.

d (mm)	D (mm)	P (mm)	c
4	25	7	6.3
	30		7.5
	45		11.3
5	25	7	5.0
	30		6.0
	45		9.0
6	25	7	4.2
	30		5.0
	45		7.5

As previously mentioned, the pitch was not varied for these springs so that the effects of d and D could be observed separately. The first loading rate used was 10 mm/min with 4 springs per spring index and they were stretched to breaking, thus revealing the full F - x curve. A second linear region after plastic deformation was observed, a phenomenon that is known and not limited to helical springs but is not typically explored because once a spring has reached the plastic region, it is considered not functional any more [33, 200, 201]. In this research the plastic region was instead investigated and the results are presented in section 6.3.1.

Variation of loading rate for ± 45 springs

In this test the two least stiff springs from the previous experiments, i.e. the two that had the lowest k , were tested at various loading rates to verify the effects of using a load cell with a rating much higher than what it measured. The loading rate was slowly increased from 10 to 120 mm/min or until the gradient of the elastic region became relatively constant. The springs were loaded within the

Figure 6.8: Monotonic and cyclic stress-strain curves for SAE 5160 spring steel [33].

linear region from the previous tests so that they could be re-used. This testing revealed the relationship between loading rate and k .

Cyclic testing of ± 45 springs

After breakage, the spring that showed the most stable behaviour was reprinted to test the plastic region. The springs were cyclically loaded at different points in the F - x curve in order to observe their behaviour under cyclic loading after deformation.

Mono springs: test to fracture and cyclic loading

Two more sets of springs were printed with mono-directional in-fill for comparison with ± 45 springs. The first set of mono springs were loaded to breakage at 10 mm/min and their k s measured. The second set of mono springs were loaded cyclically as with the springs in the previous section.

Comparison of tension and compression mono springs

A last set of tension springs was printed and compared to an equivalent set of compression springs. They were tested at a higher loading rate of 80 mm/min

which was used in the testing of the compression springs.

6.2.8 Compression spring testing

Unlike with the tension springs in subsection 6.2.7, P was varied and the mono-directional in-fill was the emphasis.

± 45 in-fill

Only a few were tested in compression since this in-fill was already investigated in subsection 6.2.7, therefore the compression springs with this in-fill were a subset of those tested in this section and had the dimensions shown in Table 6.2.

Table 6.2: Dimensions of PLA ± 45 compression springs.

d (mm)	D (mm)	P (mm)	c
3	20	10	6.7
		15	
	40	10	13.3
		15	
5	20	10	4
		15	
	40	10	8
		15	

Only one spring per combination of dimensions was printed and tested since it was only a surface study. More extensive testing was performed on a particular combination of parameters as shall be explained later. All the ± 45 springs were tested to failure, i.e. maximum compression where the coils were almost touching.

Compression mono springs

The dimensions of the compression springs with mono-directional in-fill are shown in Table 6.3. Once again one spring per combination of parameters was tested.

The exception was spring d5D20P15, of which 5 samples were printed for comparison with similar springs made with ULTEM 9085.

Table 6.3: Dimensions of PLA mono compression spring.

d (mm)	D (mm)	P (mm)	c
3	20	10	6.7
		12.5	
		15	
	30	10	10.0
		12.5	
		15	
	40	10	13.3
		12.5	
		15	
4	20	10	5.0
		12.5	
		15	
	30	10	7.5
		12.5	
		15	
	40	10	10.0
		12.5	
		15	
5	20	10	4.0
		12.5	
		15	
	30	10	6.0
		12.5	
		15	
	40	10	8.0
		12.5	
		15	

Three springs were tested to maximum compression to see if the plastic region could be reached. The results showed that the force-displacement plots remained in the elastic region therefore all subsequent testing was cyclical and only to measure the spring constant. The cyclical testing consisted of two cycles of loading and unloading at between 50 and 80 mm/min since preliminary test-

ing on the tension springs had demonstrated that in this speed range the stiffness of the springs did not change. Most testing was done at the higher speed though to ensure that the force data collected by the UTM was as reliable as possible.

ULTEM 9085 compression mono springs

The final set of springs to be printed were made of ULTEM 9085, whose dimensions can be seen in Table 6.4. They also underwent cyclical testing like the PLA compression springs and are differentiated by a U at the end so their label is d5D20P15U.

Table 6.4: Dimensions of compression ULTEM 9085 springs

d (mm)	D (mm)	P (mm)	c
5	20	15	5.0

6.2.9 Analysis of test data

The collected data was analysed in MATLAB. After plotting the force against the displacement, linear regressions were performed to obtain the spring constants. The Curve Fitting Toolbox (CFT) and a custom MATLAB script were used to produce the linear fits. The same robust bi-square regression formula as in chapter 4 was used to produce the fits.

For the springs that were stretched to breakage, the R-squared value was used to judge the goodness of the fit when performing linear regressions. Several trials were done to attain an R-squared value as close as possible to 1, then the highest one was used. This was done for both the linear and the post-plastic deformation regions. The compression springs did not need this procedure since the displacement was within the elastic region, therefore a linear fit was performed by removing the data at the beginning, end, and turnaround points of the cycles.

6.3 Results

6.3.1 Tension springs

± 45 tension springs to failure

The springs were stretched at a rate of 10 mm/min until breakage. 4 different springs were used for each spring dimension combination. Table 6.5 show the results along with the average and the sample standard deviations s . k_1 is the spring constant of the elastic region and k_2 is the constant for the plastic region.

Figure 6.9 shows the F - x plot for all ± 45 tension springs that were stretched to breakage. In the figure springs with the same dimensions have the same colour. As can be seen some springs broke before they reached the second linear region so were not considered in the calculation of k_2 .

Figure 6.9: F - x plot for all ± 45 tension springs. Sets of four springs with the same dimensions have the same colour.

The second region was shown to exist in all samples, as is expected, although it was found to not be completely linear. Figure 6.9 shows that at the end of the plastic region there is a small rise before breakage on several samples, suggesting that PLA printed with FFF exhibits strain hardening before rupture. Berzal et al. [34] observed a similar behaviour in their testing, as can be seen in Figure 6.10, where two out of the three torsion tests showed a slight rise in the moment gen-

Table 6.5: Measured spring constants, average and standard deviations for ± 45 tension springs stretched to breakage. All springs have $P = 7$ and so it has been omitted.

d (mm)	D (mm)	k_1 (N/m)	$\bar{k}_1$ (N/m)	s (N/m)	k_2 (N/m)	$\bar{k}_2$ (N/m)	s (N/m)
4	25	641.6	629.35	23.53	132.4	113.88	12.47
		604.8			107		
		655.9			110.1		
		615.1			106		
	30	317	356	30.26	47.7	82.39	23.31
		387			95.98		
		370.8			89.81		
		349.2			96.06		
	45	109.5	108.68	5.24	59.17	54.42	3.76
		114.1			55.63		
		109.6			50.87		
		101.5			52		
5	25	1446	1533.3	110.81	204.9	206.43	12.17
		1643			219.3		
		1614			195.1		
		1430					
	30	839.6	897.13	74.60	141.8	155.58	11.49
		976.2			159.8		
		945.1			168.8		
		827.6			151.9		
	45	274	268.33	17.56	90.22	95.36	4.17
		284.3			94.5		
		271.7			96.58		
		243.3			100.2		
6	25	3181	3076.3	256.14	259	282	16.03
		3388			285.5		
		2837			296.2		
		2899			287.3		
	30	1791	1844	104.55	247.5	241.5	20.57
		1895			218.6		
		1962			258.4		
		1728					
	45	538.4	528.73	35.68	135.9	131.63	15.39
		574.7			132.1		
		495.3			110.8		
		506.5			147.7		

erated by cylindrical samples undergoing torsion. On the other hand, no strain hardening was observed during the shear testing in chapter 4, which indicates that the spring shape is what causes the strain hardening.

Figure 6.10: Comparison between torsion tests and FEA simulations in various test pieces [34]. The plots of the torsion tests are grey in colour.

From Table 6.5 it is possible to see that the k_2 s were always smaller than the k_1 s since the spring had already passed the point of plastic deformation. The k_2 s also tend to be less varied than the k_1 s and roughly in the same order of magnitude indicating that after plastic deformation the spring shape stops being the main source of stiffness since they are permanently deformed. The relative consistency of k_2 s compared to k_1 s indicate that the stiffness in the plastic region is more a consequence of material properties rather than the shape.

As indicated by Equation 6.1, increasing D for a given d reduces k_1 , which is expected and in line with what the spring index indicates. On the other hand, the springs become less brittle as the mean diameter grows so they break at greater extensions. For example the d6D45 springs broke between 0.4-0.5 m whereas the d6D30 group broke at about 0.225-0.3 m. The d6D25 springs broke even earlier, clustered around 0.2 m (ignoring the one that failed prematurely).

Another behaviour observed is that as D for a given d increases the ultimate strength decreases, which can be explained by the reduction in stiffness of the springs. When the base area of the tension springs, characterized by D , becomes bigger or the coils are made thinner, the stiffness decreases, leading to a lower resistance to elastic deformation and therefore ultimate strength.

Related to the previous point is the fact that specimens with similar indices

had different F - x curves, for example springs d5D25 and d6D30 which both had $c = 5$. Although c is a linear factor, the results indicate that D has a stronger influence on the spring's response to stress since d6D30's curve is shallower and longer than that of d5D25. This is due to the fact that when going from d5D25 to d6D30, d increases by 1 while D by 5, which is much greater.

Table 6.6 shows all the springs ranked according to their k_1 . As expected c and k_1 have an inverse relationship. The springs with $D = 45$ mm tend to be the weakest while the smaller $D = 25$ mm are located more towards the top of the table. As indicated by Equation 6.1, a spring with $D = 45$ mm would need a bigger d than 6 mm in order to have a higher k_1 .

Table 6.6: ± 45 tension springs ranked according to their measured k_1 .

Rank	d (mm)	D (mm)	c	k_1 (N/m)
1	6	25	4.17	3076.25
2	5	25	5	1533.25
3	6	30	5	1844.00
4	5	30	6	897.125
6	4	25	6.25	629.35
5	6	45	7.5	523.26
7	4	30	7.5	356.00
8	5	45	9	268.325
9	4	45	11.35	105.594

The last observation was regarding the consistency of the measurements made. The trend is that the error for k_1 is smaller than or roughly equal to that for k_2 and the standard deviation for k_1 never becomes greater than 10% of the average whereas k_2 for d6D45 is close to 12%. This is to be expected because the second linear region occurs after plastic deformation and therefore the material becomes less consistent than during the linear region. AM, and FFF in particular, has an intrinsic process variability that is very hard to completely eliminate therefore having standard deviations in the range of 5-8% of the average can be considered acceptable. Out of 36 springs, 4 failed during plastic deformation so that gives a $(4/36) \times 100 = 11\%$ failure rate. This is most likely due to the fact that

PLA and the printer (Cubicon) are relatively low grade, compared to ULTEM 9085 and the Fortus 450mc, and therefore are more likely to produce flaws that lead to part failure. Conversely, 100% of the springs fractured after the first linear region and since most spring applications involve operation in this range, the material and printer performed in a satisfactory way.

Varying the load rate on more compliant ± 45 springs

After the first round of testing, the least stiff springs were selected to verify the effects of loading rate on k_1 , which were d4D45 and d5D45. Since they produced forces much smaller than the load cell of the UTM, it was necessary to verify if changing the load rate affected the forces they generated.

Two new d4D45 and d5D45 springs were printed and loaded at a rate of 10, 20, 30, 50, 70, 90, and 120 mm/min or until the effect of the loading rate was verified to be insignificant. Testing was performed in the elastic region only, 0-0.006 m range, which was derived from the $F-x$ curves in the first round. The length of the spring was also measured before each test to verify that it had not been stretched. The results can be seen in Table 6.7 and Table 6.8.

Table 6.7: Results of load rate verification tests for ± 45 tension spring d4D45

Loading Rate (mm/min)	k_1 (N/m)	Length of spring before testing (m)
10 (Round 1)	103.3	0.038
10 (Round 2)	105.8	0.04
20	106.1	0.041
30	105.5	0.041
50	106	0.041
70	107.5	0.041
90	107.1	0.041
120	107.4	0.041

During testing there seemed to be some noise at low loading rates in the form of small, irregular bumps, shown in Figure 6.11. They were found also at high loading speeds for d4D45 and during testing in chapter 4, which indicates that they might be caused by instability in the material of the springs themselves,

Table 6.8: Results of load rate verification tests for ± 45 tension spring d5D45

Loading Rate (mm/min)	k_1 (N/m)	Length of spring before testing (m)
10	253.1	0.039
20	258.9	0.041
30	259.8	0.041
50	261.8	0.042
70	263.4	0.042
90 (Round 1)	262.5	0.042
90 (Round 2)	263	0.042
120	263.1	0.042
180	265.4	0.042

perhaps due to 3D printing. This phenomenon was not further investigated since it lays outside the scope and it was not detected in all samples.

Figure 6.11: Noise present in the testing.

Even with the noise bumps, the overall straightness of the lines was not affected. Tables 6.7 and 6.8 show that although increasing the loading rate did have an effect on k_1 , it was very small. The increase from the smallest to the biggest k_1 for d4D45 was about 3.6% of the maximum k_1 and about 4.6% for d5D45. It is therefore reasonable to conclude that low testing speeds did not greatly affect the results from section 6.3.1 and they can be regarded as accurate.

Cyclic testing in post-deformation region for ± 45 springs

In this part of the research two springs with dimensions d5D25 underwent cyclic testing in the plastic region to increase the understanding of the post-deformation behaviour of 3D printed springs.

For the first spring, which will be referred to as d5D25-k2-1, the second linear region was estimated to lie within the range of 0.1-0.14 m according to the values attained in section 6.3.1. The spring was therefore first stretched to 0.14 m then 8 cycles between 0.14 m and 0.1 m were carried out at a consistent loading rate of 10 mm/min.

d5D25-k2-2 also underwent 8 cycles but in a smaller range: 0.125-0.115 m, which was close to the midpoint of the second linear region. The results of the two tests can be seen in Figure 6.12.

Figure 6.12: Results of the cyclical testing in the pseudo-linear region.

The slope between two consecutive cyclical end points is roughly equal to k_1 , which suggests that PLA behaves like an elastic, perfectly plastic material [202]. During loading and unloading, a hysteresis loop was formed for both spring specimens where, as can be seen from the decreased distance between successive hysteresis loops, the deformation due to cyclic loading reduces after multiple cycles due to work hardening [203]. This occurred quicker with the

shorter stroke than with the longer because a smaller displacement results in a small change in the material and faster work hardening.

Yet deformation has not completely eliminated the effects of the spring's structure. The fact that the hysteresis loops stabilize and that their slopes are similar to k_1 indicates that these springs can still function roughly like they are supposed to even after plastic deformation. This could be used as a safety feature so that if the springs are stretched too far, assuming they have not broken, they will roughly behave as intended until replaced. Further testing is needed, though, to characterize the load bearing behaviour of 3D printed springs with ± 45 in-fill after plastic deformation.

Test to breakage of mono-directional springs

Using spring d5D25 as a basis for comparison, the effect of changing the in-fill was investigated in this experiment. As explained in subsection 6.2.5, the springs had the dimensions d5D25 but were printed with several outer walls so that they substituted the normal in-fill. Figure 6.13 shows the result of printing and testing 4 d5D25 mono springs and the measured k_s can be found in Table 6.9.

Figure 6.13: Force-displacement curves of d5D25 mono spring to breakage.

Since the mono springs have a longer section after deformation, k_2 was mea-

Table 6.9: Measured k_1 s and k_2 s for d5D25 mono spring to breakage.

Test	k_1 (N/m)	k_2 (N/m)
1	1567	288.1
2	1567	279.1
3	1498	271.2
4	1503	271.4
$\bar{k}$	1533.75	277.45
s	38.44802	7.996041

sured right after the deformation zone. This was done in order to be consistent with the springs with the ± 45 in-fill. Figure 6.14 is a screenshot of MATLAB's CFT showing an example of the area where k_2 was measured for one of the samples. Further analysis of these results will be done in section 6.3.1.

Figure 6.14: Screenshot of the CFT in MATLAB to show where k_2 was measured. The red portions of the plot are ignored by the straight line fitting.

Cyclical testing of mono springs in the post-deformation region

Two d5D25 mono spring were printed and tested in this experiment. From Figure 6.13 the plastic region was estimated to lie within the range of 0.08-0.12 m. For the first round of cyclic testing the spring was first extended to 0.12 m then 8 cycles between 0.12 m and 0.08 m were carried out. The second spring was placed under 8 cycles of loading between 0.095 m and 0.105 m. Both tests were

conducted at a consistent loading rate of 10mm/min. The resulting F - x plots can be seen in Figure 6.15.

Figure 6.15: Cyclical testing of d5D25 tension mono spring. Small displacement: 0.12 - 0.08 m, large displacement: 0.095 - 0.105 m.

The results obtained for the mono springs closely resembled the trends for the ± 45 springs. The hysteresis loops were present and the changes in deformation became increasingly stable as more cycles were completed due to strain hardening. Therefore, the conclusion can be made that infill orientation does not play a significant role in determining the post-deformation properties of 3D printed PLA.

Comparison of ± 45 springs and mono springs stretched to failure

The average k_1 of the mono springs, see Table 6.9, is almost exactly the same when compared to the ± 45 d5D25 springs from Table 6.5, therefore it would seem that the spring constant is mainly affected by the inter-layer bonding and not the in-fill, otherwise there would have been a more pronounced difference. The k_2 s are also relatively close, 277 against 206, but that is to be expected since deformation can have unpredictable effects.

The standard deviation for both k_1 and k_2 is lower for the mono spring, 38 and ≈ 8 respectively, than for the ± 45 springs, 110 and 12. Since both types of springs

were loaded in the same way, it would seem that having all deposited material aligned in the same direction leads to a more consistent behaviour, which is corroborated by Figure 6.16. As can be seen there, the mono springs follow the same curve more closely and for longer than the ± 45 springs.

Figure 6.16: *F-x plot of all d5D25 springs tested to fracture.*

As discussed in subsection 4.4.2, polymer weld theory [37] and the amount of voids present in the springs helps to explain why the mono spring had a higher ultimate yield strength than the ± 45 ones. Since the mono springs have in-fill that is aligned to the direction of the helix, voids are going to be created between concentric rings of material. When stacked one on top of the other the tracks of deposited filament lay almost exactly one on top of the other, like in Figure 6.7a, thus the bonding between roads is continuous and such that the inter-layer bonding is mainly dependent on the bond between roads since each road is bonded to at least 4 neighbours.

The ± 45 in-fill instead does not promote a continuous bonding and introduces new voids in the slicing process, like the ones in Figure 6.17, because circular shapes are not always compatible with the raster pattern. The extra voids are places where the rasters do not have neighbours so there is no bonding. Overall the criss-crossing pattern of the rasters makes the ± 45 in-fill more susceptible to

shearing stresses, which are the main types in springs and this is why the mono springs were more resistant to failure.

Figure 6.17: Example of ± 45 in-fill resulting in a greater number of voids.

The ± 45 springs failed at an ultimate tensile strength of 80-100N which corresponded to a stroke of approximately 0.23-0.27m. The mono spring, on the other hand, fractured and broke after almost twice the amount of load was applied, 180-240N, and at a greater displacement, 0.3-0.35m. Figure 6.18 shows the stark difference between the two in-fills.

The way the springs broke is indicative of their stiffness. The ± 45 springs typically broke between layers, seen in Figure 6.19a, while the mono ones broke almost perpendicularly to the filament orientation, shown in Figure 6.19b. This further proves that the mono springs had stronger inter-layer bonding and so were able to withstand greater loads.

The mono in-fill pattern is very regular and the cross-section of a mono spring at any point is also fairly regular, except for the points where one layer ends with a transverse shell printed perpendicular to the direction of filament. In chapter 7 the assumption is that the direction of the filaments are uniform throughout the

Figure 6.18: Breakage comparison between a ± 45 spring (left) and a mono spring (right).

entire cross-section and across all points of the active coils. On the other hand the ± 45 in-fill produces a range of cross-sections depending on where it is taken along the helix. Both of these features will be further discussed in chapter 7.

Comparison between tension and compression mono springs

In this experiment a comparison was made between tension and a compression springs with the same dimensions: d5D20P15, with a spring constant of 4. Four tension and five compression springs were printed, an example of a compression spring is shown in Figure 6.20. The tension springs were printed using the Cubicon printer while the compression springs were printed on the Prusa. Identical settings were used for both printers to ensure consistency.

The tension springs were tested to fracture while the compression springs underwent 4 cycles with a constant speed of 80 mm/min. The spring constants measured for both types can be found in Table 6.10.

As can be seen, the two are very similar. The tension springs have a slightly lower k but they are within a standard deviation of the compression springs. The discrepancy is likely due to slight differences in the printers or caused by small imperfections during the printing process or while removing the supports. This

(a) ± 45 spring, the indicated lighter areas are fractures along the layers.

(b) Mono spring, where the fracture plane is perpendicular to the coil.

Figure 6.19: Fractured ends of springs.

Figure 6.20: One of the d5D20P15 compression mono springs tested to compare to the tension springs with the same dimensions.

Table 6.10: Comparison of tension and compression d5D20P15 springs.

	Tension	Compression
Test	k (N/m)	k (N/m)
1	2779	2785.85
2	2753	2777.04
3	2743	2810.76
4	2705	2774.73
5	-	2745.64
$\bar{k}$	2745	2779
s	31	23

experiment confirms for 3D printed springs what is already known for conventional helical springs: that within the linear region the behaviour of the springs is going to be the same whether in compression or tension.

6.3.2 Compression springs

Effects of in-fill on compression springs

As previously mentioned, when testing compression springs all 3 dimensions were varied: d , D , and P . A single spring with each dimension and in-fill combination, showed in Table 6.11, was printed on the Prusa. A single spring per dimension combination was printed for two reasons. First because the main objective in this study was to obtain an estimate of various spring constants to com-

pare to the spring constants calculated in chapter 7 and not to study the springs' behaviour in depth. Secondly because the low standard deviations in Table 6.5 showed that one spring per dimension combination was enough.

Spring d5D20P15 was an exception and 5 samples were printed and tested, as has been discussed. The higher accuracy was necessary because this was the spring that was compared to the ULTEM 9085 springs and it was also used as a case study in section 6.3.2.

The ± 45 springs were tested to maximum compression, i.e. where adjacent coils touched. Since none of the the springs left the linear region before reaching maximum displacement, it was then deemed unnecessary to compress the springs all the way, so the mono springs all underwent 4 cycles with a displacement of 1 cm instead. Table 6.11 shows the results of testing and the difference between the two in-fills.

Table 6.11: *ks for compression springs with ± 45 and mono in-fills.*

Spring	Spring dimensions				k (N/m)	
	d (mm)	D (mm)	P (mm)	c	± 45	Mono
d3D20P10	3	20	10	6.7	318	363
d3D20P15			15		286	320
d3D40P10		40	10	13.3	44	41
d3D40P15			15		38	42
d5D20P10	5	20	10	4.0	2813	2779
d5D20P15			15		2359	2746
d5D40P10		40	10	8.0	384	343
d5D40P15			15		367	338

As with the tension springs, the ks are very similar confirming that the in-fill does not play a significant role in determining the spring constant. The d5D20P15 spring stands out because there is a difference of about 400N/m between the two in-fills. This is likely due to an imperfection in the printing process that caused a weakness in the ± 45 spring but is of little consequence when considering the rest of the springs.

Variation of mono compression spring parameters

In this experiment the d , D , and P were each given three levels instead of two like in Table 6.11 to broaden the investigation. The objective was to verify if the mono in-fill produced any unusual results. A single spring was printed per dimension combination and the results from section 6.3.2 were re-used for this series of testing too. The mono springs underwent 4 cycles with a displacement of 1 cm from rest and the results can be found in Table 6.12.

Table 6.12: Measured stiffness for mono compression springs.

Spring	d (mm)	D (mm)	P (mm)	c	k
d3D20P10	3	20	10	6.7	363
d3D20P12_5			12.5		346
d3D20P15			15		320
d3D30P10		30	10	10.0	108
d3D30P12_5			12.5		109
d3D30P15			15		108
d3D40P10		40	10	13.3	41
d3D40P12_5			12.5		46
d3D40P15			15		42
d4D20P10	4	20	10	5.0	1122
d4D20P12_5			12.5		1112
d4D20P15			15		1142
d4D30P10		30	10	7.5	350
d4D30P12_5			12.5		344
d4D30P15			15		353
d4D40P10		40	10	10.0	143
d4D40P12_5			12.5		154
d4D40P15			15		149
d5D20P10	5	20	10	4.0	2779
d5D20P12_5			12.5		2985
d5D20P15			15		2746
d5D30P10		30	10	6.0	892
d5D30P12_5			12.5		873
d5D30P15			15		870
d5D40P10		40	10	8.0	343
d5D40P12_5			12.5		371
d5D40P15			15		338

The findings are not surprising given that they are similar to those for the tension springs. Like before higher indices gave lower spring constants and vice versa. Also, two springs with the same spring index have different k_s , d3D30 series and d4D40 series. Finally, the variation in pitch does not appear to have a significant effect but this is likely because the change is small.

The most interesting result from this experiment can be seen in Figure 6.21. The F - x plots of two springs with low c are shown and the most obvious feature is the large amount of viscoelastic creep. These two are just an example and other weak springs displayed this behaviour. As the stiffness of the springs increased, the hysteresis became less evident.

Figure 6.21: Viscoelastic creep during cyclical testing of two weak mono PLA compression springs.

Comparison of ULTEM 9085 and PLA springs

This experiment was composed of two series of tests. In the first three d5D20P15 springs were printed using ULTEM 9085 and compared to 5 springs with the same dimensions fabricated with PLA. In the second 4 types of springs were printed and compared, one with ULTEM 9085 and one with PLA for every parameter combination. A Fortus 450mc was used for printing the ULTEM springs so, as discussed in subsection 3.3.1, the layer height (0.254mm) and other print

settings such as nozzle temperature and deposition speed were fixed. The in-fill type could be changed and so the ULTEM springs (reminder: identified with a U in their name) were printed using the mono in-fill.

The two sets of d5D20P15 springs were compressed by 1 cm from rest over 2 cycles with a displacement rate of 80 mm/min. Table 6.13 shows the results of the testing and, as can be seen, the PLA springs have a greater spring constant than the ULTEM ones, which is an unexpected. Figure 6.22 shows the F - x plots for all the springs, with the creep removed, and as can be seen the PLA springs have a steeper slope.

Table 6.13: Spring constants measured from cyclical testing of 5 d5D20P15 and 3 d5D20P15U springs.

Spring	Sample	k	s
d5D20P15	1	2786	0.005
	2	2777	0.007
	3	2811	0.005
	4	2775	0.006
	5	2746	0.003
d5D20P15U	1	1906	0.005
	2	1943	0.005
	3	1937	0.005

Figure 6.22: Plot of cyclical testing of ULTEM and PLA springs with creep removed.

Further testing was therefore performed on two sets of springs, one printed

with ULTEM and the other with PLA, the results of which are shown in Table 6.14. The new tests confirmed what had been found previously: the PLA springs are stiffer than the ULTEM ones. The difference in print settings could explain this phenomenon but a direct comparison is not possible because PLA cannot be printed with ULTEM settings and vice-versa. Rodriguez et. al. [?] found that the tensile strength of PLA and ABS samples fell when increasing the layer height from 0.1 mm to 0.2 mm, thus it is possible that the different layer heights, 0.254 vs 0.15 mm, might be one of the factors that weakens the shear properties of the material. A further experiment was performed to verify this hypothesis and the results are presented in section 6.3.2.

Table 6.14: Comparison of ULTEM 9085 and PLA springs.

Spring	k (N/m)		$k_{PLA} - k_U$ (N/m)
	PLA	ULTEM 9085	
d3D40P10	41.0	31.3	9.7
d3D40P15	42.0	33.3	8.8
d5D40P10	343.1	213.5	129.6
d5D40P15	337.9	239.1	98.8

The last comparison made is shown in Figure 6.23a, where the full cyclical testing of a PLA and ULTEM spring are shown for comparison. Both materials are equally affected by creep during cyclical testing, therefore ULTEM springs can be considered overall worse than PLA springs because they are affected by creep in the same way and are less stiff. Figure 6.23b shows the full testing of all the ULTEM springs and all are affected by creep.

Effects of layer height on PLA springs

The layer height cannot be changed for ULTEM so the PLA springs were varied instead. It was not possible to print PLA springs with layers comparable to the ULTEM ones because above 0.15 mm the quality of PLA becomes inconsistent with the print settings used in this research, which are designed for 0.15 mm,

(a) Comparison of ULTEM 9085 and PLA springs.

(b) ULTEM 9085 springs.

Figure 6.23: Viscoelastic creep in cyclical testing.

and therefore reliable results cannot be guaranteed. On the other hand, it was possible to print shorter layers therefore two new d5D20P15 springs were manufactured with 0.05 mm and 0.10 mm layer heights and tested like in section 6.3.2. Table 6.15 compares the stiffness of the two new springs to the ones with 0.15mm layer height.

As observed by Rodriguez et al. [?] and hypothesised in section 6.3.2, increasing the layer height does seem to weaken the shear properties of the springs, causing them to become less stiff. The difference is bigger between 0.05 mm

Table 6.15: Effects of layer height variation on the stiffness of PLA springs, first round of testing with one d5D20P15 per layer height.

Layer height (mm)	k
0.05	2761.71
0.10	2706.32
0.15	2703.56

and 0.10 mm than between 0.10 mm and 0.15 mm suggesting that layer heights greater than 0.15 mm would result in lower stiffness losses but the difference is small and might be due to slight imperfections in the springs. Therefore a new experiment was carried out where three springs were printed per layer height. Their dimensions are d7D20P15 with $N_a = 2$, resulting in the stiffest springs tested in the entire research. This was done in an effort to make the stiffness differences more pronounced. They were tested for 2 cycles at a speed of 100 mm/min and a displacement of 0.5 cm, the results of which can be found in Table 6.16. This smaller displacement was used to avoid deforming the springs.

Table 6.16: Effects of layer height variation on the stiffness of PLA springs; second round of testing with three d7D20P15 springs per layer height.

Layer height (mm)	k (N/m)	$\bar{k}$ (N/m)	s (N/m)
0.05	25051.20	25804.87	816.70
	26672.60		
	25690.80		
0.10	25082.20	25016.60	923.45
	24062.10		
	25905.50		
0.15	24983.20	25009.50	351.09
	25373.00		
	24672.30		

As with the previous round of testing, the difference is bigger between 0.05 mm and 0.10 mm than between 0.10 mm and 0.15 mm. The average stiffnesses for 0.05 mm and 0.10 mm are within one standard deviation of each other but combined with the results of the d5D20P15 springs it can be posited that increas-

ing layer height causes a lowering of the spring stiffness, likely caused by a weakening of the shear modulus of the material. This is unlikely to be the only factor to create the difference between the PLA and ULTEM springs in Figure 6.22, but this experiment has shown that layer height does at least play a part and has lead to the design guideline whereby smaller layers produce stiffer springs.

Summary

In this chapter a thorough investigation of 3D printed helical springs was carried out. The two in-fills were compared, mono and ± 45 , and although the difference in stiffness was not significant, the mono springs ruptured at much greater extensions than the ± 45 springs, which makes this infill the superior choice. Varying the spring parameters produced stiffnesses that were in line with what the spring index predicted. Weaker springs were strongly affected by viscoelastic effects leading to large hysteresis loops during cyclical testing, but the stiffness was unaffected. Tensions and compression PLA springs were compared and found to be similar. Stretching into the post-deformation region followed by cyclical testing revealed that the springs behave semi-elastically even after undergoing plastic deformation. PLA were found to be stiffer than ULTEM springs and further testing revealed that layer height is inversely proportional to stiffness, i.e. bigger layers produce weaker springs.

CHAPTER 7

DERIVATION OF AN EQUATION FOR CALCULATING THE SPRING CONSTANT OF 3D PRINTED SPRINGS

In this chapter the objective was to derive an equation that calculates the spring constant of 3D printed springs. This was achieved via the following sub-objectives:

- identify a derivation method
- perform the derivation
- compare the calculated and experimentally measured spring constants

7.1 Existing equation for springs

Helical springs with a square cross-section, also called rectangular wire springs, when manufactured using conventional means cause the cross-section of the wire to distort during winding due to uneven stresses, as shown in Figure 7.1. Fabricating a keystone profile can help to promote a rectangular cross-section after coiling but a better solution would be to use AM since, as shown in chapter 6, it is very easy to change the cross-section.

Figure 7.1: Change in wire cross-section after coiling for rectangular wire springs [35].

As discussed in subsection 6.2.2, the square cross-section has been chosen for this research since it results in higher quality prints. The equation that will be discussed in this section applies to circular springs but is relevant to rectangular cross-section springs too.

Springs are widely used in many fields and although there are many different types of springs, the most common one is the helix so that is the one that has been covered in this research. The existing equations for helical springs have two assumptions:

1. The material is isotropic
2. The wire's cross-section is a circle

Isotropic materials are the standard for springs because they are mostly made with steel that is extruded through a die. There are also polymer springs but they are relatively rare. The circular cross-section is typical of helical springs but the rectangular cross-section is usually found in leaf, spiral torsion, and volute springs.

Springs can also be machined out of metallic tubes using CNC machines to produce the required helical path and provide the desired elasticity [36]. These closer resemble 3D printed springs because they can be modified with features such as threads, clamps and fixing holes, resulting in simpler parts like the example shown in Figure 7.2. Although more flexible than traditional springs, machined springs cannot achieve the shapes that 3D printed springs can like hollow wire springs, which will be discussed later.

Figure 7.2: Example of simplification of parts using machined springs [36].

7.1.1 Calculating the stiffness of isotropic springs

Elasticity is the ability of a material to return to its original shape after a stress has been applied, springs are no different and they obey Hooke's law: $F = kx$. As mentioned in section 2.1, it is possible to derive an equation to calculate k from the spring parameters shown in Figure 6.1,

$$k = \frac{Gd^4}{8D^3N_a} \quad (7.1)$$

The derivation method for Equation 7.1 will be used as a basis for deriving an equation for 3D printed springs and will now be explained.

Derivation of the shear modulus from the torsion constant for an isotropic helical spring

The assumption throughout this derivation is that the displacements and rotations are small enough that the spring behaves elastically. When a spring of radius R is stretched by a force F the wire that the coils are composed of is twisted along its entire length. There is going to be some stretching along the length of the wire but that is negligible compared to the twisting.

The spring can be considered to be composed of many identical elements like the ones in Figure 7.3. When the spring is stretched by an amount dx due to F , all elements of the spring are twisted by an angle $d\theta$ [204].

Figure 7.3: Distance that coils move when a spring is stretched.

dx is the length of the arc subtended by $d\theta$ so

$$\begin{aligned}
 dx &= R d\theta \\
 \int_0^x dx &= R \int_0^\theta d\theta \\
 x &= R\theta \\
 \theta &= \frac{x}{R}
 \end{aligned} \tag{7.2}$$

The energy stored by a spring can be written in two ways. First, from Fig-

ure 3.4 there is the classic expression

$$U = \frac{1}{2}kx^2 \quad (7.3)$$

The second expression uses the fact that, as discussed, the wire in the spring twists and therefore gains torsional energy U_t . There are various versions of this equation but the one used here is

$$U_t = \frac{1}{2}\kappa\theta^2 \quad (7.4)$$

Here κ is the torsion constant and is defined as

$$\kappa = G \frac{\pi r^4}{2L} \quad (7.5)$$

Here G is the shear modulus of the material, r is the radius of the wire, and L is the total length of the wire that the spring is composed of which can be roughly calculated using

$$L = 2\pi RN_a \quad (7.6)$$

The derivation of Equation 7.5 can be found in Appendix B.

The two expressions for energy can be equated

$$\frac{1}{2}kx^2 = U_t = \frac{1}{2}\kappa\theta^2 \quad (7.7)$$

Plugging equations 7.5, 7.2, and 7.6 into Equation 7.7 and solving for k gives an equation which allows the calculation of the spring constant using the springs'

parameters and the material's shear modulus,

$$\frac{1}{2}kx^2 = \frac{1}{2}\kappa\theta^2 \quad (7.8)$$

$$kx^2 = \left(G \frac{\pi r^4}{2L}\right) \left(\frac{x}{R}\right)^2$$

$$k = G \frac{\pi r^4}{2LR^2}$$

$$k = G \frac{\pi r^4}{2(2\pi RN_a) R^2}$$

$$k = \frac{Gr^4}{4R^3N_a} \quad (7.9)$$

Substituting $r = \frac{d}{2}$ and $R = \frac{D}{2}$ into Equation 7.9 results in Equation 7.1, both of which assume an isotropic material and hence why there is only one shear modulus. The material produced by 3D printing, especially FFF, has been modelled as orthotropic in this research therefore equations 7.1 and 7.9 are not useable and k s have to be measured rather than calculated, hence the extensive testing in this study.

Obviously this is not the most efficient way of creating a springs for applications discussed in sections 3.1 and 3.2, or in general. It is possible to keep testing until an appropriate spring is found but having the ability to estimate the stiffness would greatly reduce the design time. Therefore as stated in section 3.3 one of the objectives of this research was to find an equation similar to Equation 7.1 that predicts the spring constant for a 3D printed spring.

7.2 Derivation method

The two assumptions made about the wire material are:

1. The material is orthotropic
2. The cross-section is rectangular

As previously discussed, modelling 3D printed materials as orthotropic is appro-

priate given the high degree of anisotropy that result from the AM process itself, especially in material extrusion. The cross-section is assumed to be rectangular for two reasons, one physical and the other mathematical. The physical reason is that, following the results of the initial samples printed in subsection 6.2.2, square wire springs were of a higher quality which favoured their adoption in lieu of the circular ones. Since the springs are made of plastic and given their small size, increases in mass caused by the square cross-section are minimal and not considered consequential.

The second reason is that a circular cross-section would not eliminate warping from the derivation of the stiffness equation like with isotropic materials [205, 206, 207], see Appendix B. Warping torsion occurs when the cross-section of a member under torsion is subjected to axial stresses and so displaces axially along the member [207]. Since the warping function, which describes mathematically the distortion of the cross-section, has to be found for both cross-sections it makes no difference which is used. Using a circle would lead to more complex integrals because the shear moduli, which are assumed to be aligned in the directions shown in Figure 7.5, would have to be defined in polar coordinates or the boundaries would have to be defined in Cartesian coordinates. Therefore the square was adopted in the end because the region over which the integration has to be performed is simpler, described only by four straight lines.

The basic idea in the derivation is to find a form of U_t to plug into Equation 7.7 that is appropriate for the assumptions made above. The derivation begins with a rectangular prismatic bar of height $2a$ and width $2b$ that undergoes torsion like the diagram shown in Figure 7.4, which is the basis for all the work in this chapter.

Numerical solutions to torsional problems can be found using methods such as FEA and this is usually the easiest way, for example using a p -version FEA [208]. This was not practical for this research, though, since Abaqus/CAE does not output the torsional constant and anyway the problem was simple enough

Figure 7.4: Rectangular prismatic bar under torsion at one end.

that an analytical solution should have been possible.

As explained in subsection 3.3.3, the mono in-fill was selected for testing since it is deposited tangentially to the coils. It should be noted that this in-fill is not perfectly regular, though, there are variations caused by the layering that will be discussed later. For now the assumption will be that the beam in Figure 7.4 is homogeneous and looks like Figure 7.5, where the shear moduli correspond to the +45 values from subsection 4.4.2.

Figure 7.5: Shear moduli for ideal mono in-fill where 1 is the direction tangential to the coils, 3 is parallel to layer deposition, and 2 is orthogonal to the other two.

7.2.1 Warping function vs stress function approach

Generally there are two analysis methods for the type of mathematical problem in this chapter [209]. The first was introduced by Saint-Venant, which uses displacement components and associated warping functions. This method is gov-

erned by the formulation of displacements, from which all other quantities are derived and the shear strains are represented using the warping function [210].

The second method is by Prandtl and uses stress functions along with the same displacement formulations that are used for Saint-Venant's method. The stresses are formulated using another function, called the stress function, which allows the elimination of the warping function from the derivation [210].

Both methods were used in this research and require solving of Partial Differential Equation (PDE)s of either Laplace or Poisson type. Saint-Venant's approach leads to the former while Prandtl's method yields the latter. Torsion problems, therefore, are typically a form of Boundary Value Problem (BVP) and can be solved numerically and sometimes analytically.

If the cross-section of the beam is regular, an analytical solution can usually be found otherwise numerical solutions are easier. Darilmaz et al. [211] have developed a method for dealing with arbitrarily shaped orthotropic beams and will be discussed later. When dealing with rectangular cross-sections Prandtl's stress function is usually easier, like in Timoshenko et al. [212]. This is because the stress function produces Dirichlet (or first-type) boundary conditions, where the values that a solution needs to take along the boundary of the domain are specified. Saint-Venant's method, used in Srinath [213], leads to Neumann (or second-type) boundary conditions which define the normal derivative of the function at a boundary. Regardless of which approach is used, the method for solving the torsion BVP for rectangular sections typically uses Fourier series but an attempt was made to find a solution without, which is presented in section 7.3.

7.3 Derivation using warping functions

This attempt was made using the method from Slaughter [214] with the starting equations from Rongqiao et al. [215] because the method in Slaughter derives the warping function for an isotropic beam, whereas the starting equations from

Rongqiao et al. are for an orthotropic beam. According to Saint-Venant's torsion theory the displacements are formulated as follows,

$$\begin{aligned}u &= -\theta zy \\v &= \theta zx \\w &= \theta \phi(x, y)\end{aligned}$$

where u , v , and w are displacements and θ is the twist angle per unit length. $\phi(x, y)$ is the warping function, which describes the out-of-plane displacements of the cross-sections of the beam. The strain-displacement relationships in terms of ϕ are

$$\gamma_x = \theta \left(\frac{\partial \phi}{\partial x} - y \right) \text{ and } \gamma_y = \theta \left(\frac{\partial \phi}{\partial y} + x \right) \quad (7.10)$$

Using these it is possible to write the following stress-strain relationships

$$\tau_x = G_x \theta \left(\frac{\partial \phi}{\partial x} - y \right) \text{ and } \tau_y = G_y \theta \left(\frac{\partial \phi}{\partial y} + x \right) \quad (7.11)$$

There are only two non-zero stress components and they are not dependent on z therefore the equilibrium equations in the x and y directions are immediately satisfied. The only equation left is the one that is dependent on the z direction and therefore the governing equation is obtained,

$$\frac{\partial}{\partial x} \left(G_x \left(\frac{\partial \phi(x, y)}{\partial x} - y \right) \right) + \frac{\partial}{\partial y} \left(G_y \left(\frac{\partial \phi(x, y)}{\partial y} + x \right) \right) = 0 \quad (7.12)$$

This is a second order PDE. The traction free Boundary Condition (BC)s on the lateral surfaces require that

$$\frac{\partial \phi}{\partial x} - y = 0 \text{ at } x = -a, a \quad (7.13)$$

$$\frac{\partial \phi}{\partial y} + x = 0 \text{ at } y = -b, b \quad (7.14)$$

which are Neumann BCs.

Now that the main equation and the BCs have been established, the solving process can begin using the method of variation of parameters. A new function $\psi(x, y)$ is introduced

$$\phi(x, y) = xy - \psi(x, y) \quad (7.15)$$

which when plugged into Equation 7.12 gives

$$-G_x \psi_{yy}(x, y) - G_y \psi_{xx}(x, y) = 0 \quad (7.16)$$

where $\psi_{yy} = \frac{\partial^2 \psi}{\partial y^2}$ and $\psi_{xx} = \frac{\partial^2 \psi}{\partial x^2}$. Plugging Equation 7.15 into Equations 7.13 and 7.14 gives new BCs

$$\psi_x = 0 \text{ at } x = -a, a \quad (7.17)$$

$$2x - \psi_y = 0 \text{ at } y = -b, b \quad (7.18)$$

The next step is to perform separation of variables. The assumption is made that $\psi(x, y) = f(x)g(y)$ so Equation 7.16 becomes

$$-G_x g(y) f''(x) - G_y f(x) g''(y) = 0 \quad (7.19)$$

This gets rearranged so that $G_x \frac{f''(x)}{f(x)} = -G_y \frac{g''(y)}{g(y)} = \lambda$. The cases where $\lambda > 0$ or $\lambda = 0$ give trivial solutions where the constants are 0 so $\phi = 0$. When $\lambda < 0$ let $\lambda = -k^2$ where $k > 0$ so this results in a system of second order differential equations

$$\begin{aligned} f''(x) + \frac{k^2}{G_x} f(x) &= 0 \\ g''(y) - \frac{k^2}{G_y} g(y) &= 0 \end{aligned}$$

Solving this system leads to

$$\begin{aligned} f(x) &= C_1 \cos\left(\frac{kx}{\sqrt{G_x}}\right) + C_2 \sin\left(\frac{kx}{\sqrt{G_x}}\right) \\ g(y) &= C_3 \cosh\left(\frac{ky}{\sqrt{G_y}}\right) + C_4 \sinh\left(\frac{ky}{\sqrt{G_y}}\right) \end{aligned}$$

Using the assumption that $\psi(x, y) = f(x)g(y)$ and applying the BC $2x - \psi_y = 0$ at $y = -b, b$ gives the following system of equations

$$\begin{aligned} 2x &= f(x) \frac{k}{\sqrt{G_y}} \left(C_4 \cosh\left(\frac{bk}{\sqrt{G_y}}\right) - C_3 \sinh\left(\frac{bk}{\sqrt{G_y}}\right) \right) \\ 2x &= f(x) \frac{k}{\sqrt{G_y}} \left(C_4 \cosh\left(\frac{bk}{\sqrt{G_y}}\right) + C_3 \sinh\left(\frac{bk}{\sqrt{G_y}}\right) \right) \end{aligned}$$

This is equivalent to saying that $f(x)g'(-b) = f(x)g'(b) = 2x$ so since $2x$ is odd, $f(x)$ must also be odd. Since cosine is an even function then $C_1 = 0$ so

$$f(x) = C_2 \sin\left(\frac{kx}{\sqrt{G_x}}\right)$$

so the system of equations becomes

$$\begin{aligned} 2x &= C_2 \sin\left(\frac{kx}{\sqrt{G_x}}\right) \frac{k}{\sqrt{G_y}} \left(C_4 \cosh\left(\frac{bk}{\sqrt{G_y}}\right) - C_3 \sinh\left(\frac{bk}{\sqrt{G_y}}\right) \right) \\ 2x &= C_2 \sin\left(\frac{kx}{\sqrt{G_x}}\right) \frac{k}{\sqrt{G_y}} \left(C_4 \cosh\left(\frac{bk}{\sqrt{G_y}}\right) + C_3 \sinh\left(\frac{bk}{\sqrt{G_y}}\right) \right) \end{aligned}$$

Subtracting these two equations from each other and solving for C_3 gives

$$\begin{aligned} f(x) &= C_2 \sin\left(\frac{kx}{\sqrt{G_x}}\right) \\ g(y) &= C_4 \sinh\left(\frac{ky}{\sqrt{G_y}}\right) \\ \therefore \psi(x, y) &= C_2 C_4 \sin\left(\frac{kx}{\sqrt{G_x}}\right) \sinh\left(\frac{ky}{\sqrt{G_y}}\right) \end{aligned}$$

Now set $C_2 C_4 = A$ and apply the BC $-\psi_x = 0$ at $x = -a, a$ to get

$$\psi(x, y) = A \sin\left(\frac{kx}{\sqrt{G_x}}\right) \sinh\left(\frac{ky}{\sqrt{G_y}}\right) \quad (7.20)$$

$$\begin{aligned} -\psi_x(x, y) &= \frac{Ak}{\sqrt{G_x}} \cos\left(\frac{kx}{\sqrt{G_x}}\right) \sinh\left(\frac{ky}{\sqrt{G_y}}\right) \\ -\psi_x(\pm a, y) &= \frac{Ak}{\sqrt{G_x}} \cos\left(\frac{kx}{\sqrt{G_x}}\right) \sinh\left(\frac{ky}{\sqrt{G_y}}\right) \end{aligned} \quad (7.21)$$

The only non-trivial solution to Equation 7.21 is when $\cos\left(\frac{ak}{\sqrt{G_x}}\right) = 0$ so that means that $k = \frac{\pi\sqrt{G_x}(2n+1)}{2a}$ therefore Equation 7.20 is a series:

$$\psi(x, y) = \sum_{n=0}^{\infty} A_n \sin\left(\frac{k_n x}{\sqrt{G_x}}\right) \sinh\left(\frac{k_n y}{\sqrt{G_y}}\right) \quad (7.22)$$

Applying Equation 7.18 again gives

$$\begin{aligned} \sum_{n=0}^{\infty} \frac{A_n k_n}{\sqrt{G_y}} \cosh\left(\frac{b k_n}{\sqrt{G_y}}\right) \sin\left(\frac{k_n x}{\sqrt{G_x}}\right) &= 2x \\ \Rightarrow \sum_{n=0}^{\infty} B_n \sin\left(\frac{k_n x}{\sqrt{G_x}}\right) &= 2x \end{aligned}$$

The orthogonality of terms in the sine series is defined as

$$\int_{-a}^a \sin\left(\frac{k_m x}{\sqrt{G_x}}\right) \sin\left(\frac{k_n x}{\sqrt{G_x}}\right) dx = \begin{cases} 0, & \text{if } m \neq n \\ a, & \text{if } m = n \end{cases}$$

and since $m = n$ in this case and $B_n \sin\left(\frac{k_n x}{\sqrt{G_x}}\right) = 2x$ it is possible to write

$$\begin{aligned}
 a &= a \\
 \int_{-a}^a \sin\left(\frac{k_m x}{\sqrt{G_x}}\right) \sin\left(\frac{k_n x}{\sqrt{G_x}}\right) dx &= \int_{-a}^a \sin\left(\frac{k_m x}{\sqrt{G_x}}\right) \sin\left(\frac{k_n x}{\sqrt{G_x}}\right) dx \\
 \int_{-a}^a \left[B_n \sin\left(\frac{k_n x}{\sqrt{G_x}}\right) \right] \sin\left(\frac{k_n x}{\sqrt{G_x}}\right) dx &= \int_{-a}^a [2x] \sin\left(\frac{k_n x}{\sqrt{G_x}}\right) dx \\
 B_n a &= \frac{16a^2(-1)^n}{(2\pi n + \pi)^2} \\
 \Rightarrow B_n &= \frac{16a(-1)^n}{\pi^2(2n + 1)^2} \tag{7.23}
 \end{aligned}$$

7.3.1 Final solution for the warping function without Fourier series

Now all the information is present to solve for the warping function. Equation 7.23 leads to the solution for A_n ,

$$A_n = \frac{32\sqrt{G_y}(-1)^n}{\pi^3\sqrt{G_x}(2n + 1)^3} \operatorname{sech}\left(\frac{\pi b\sqrt{G_x}(2n + 1)}{2\sqrt{G_y}}\right) \tag{7.24}$$

which is plugged into Equation 7.22 then into Equation 7.15 to give the solution for the warping function

$$\begin{aligned}
 \phi(x, y) &= \sum_{n=0}^{\infty} \frac{32\sqrt{G_y}(-1)^n}{\pi^3\sqrt{G_x}(2n + 1)^3} \operatorname{sech}\left(\frac{\pi b\sqrt{G_x}(2n + 1)}{2\sqrt{G_y}}\right) \\
 &\quad \sin\left(\frac{1}{2}\pi(2n + 1)x\right) \sinh\left(\frac{\pi\sqrt{G_x}(2n + 1)y}{2\sqrt{G_y}}\right) \tag{7.25}
 \end{aligned}$$

7.3.2 Verification of the solution

The next step is to verify the solution, setting $a = b = 0.0025$ (the width of the d5D20P15 springs), $G_x = G_y$ (which simulates an isotropic material) and going from $n = 0$ to $n = 50$ produces the plots in Figure 7.6a. Figure 7.6b shows the plots of the derivatives of the warping function which give the stresses.

Figure 7.6a shows that the limits from Equations 7.13 and 7.14 are correctly respected at the corners of the boundary. The derivatives in Figure 7.6b also

(a) Plot of the warping function $\phi(x, y)$ without using Fourier series.

(b) Plot of the derivatives of the warping function where orange is $\phi_x(x, y)$ and blue is $\phi_y(x, y)$.

Figure 7.6

follow the BCs. A problem occurs when trying to work out the torsional rigidity GJ , though. Rongqiao et al. [215] give the equation for calculating GJ over a region R as

$$GJ = \iint_R (G_y(\phi_y(x, y) + x)x - G_x(\phi_x(x, y) - y)y) dx dy \quad (7.26)$$

where R in this research is the limits of the rectangle defined by $\pm a$ and $\pm b$. Doing the integral gives a series GJ_n in terms of R , the shear moduli, and n . For the solution to be correct the series should be a horizontal asymptote so that

$$\lim_{n \rightarrow \infty} GJ_n = 0 \quad (7.27)$$

$$\therefore \lim_{n \rightarrow \infty} \sum_{1,3,5,\dots}^n GJ_n = c \quad (7.28)$$

where c is some value. Plotting the value of GJ_n for every n in the series produces Figure 7.7, where GJ_n does asymptote but not to 0. When plotting the sum of GJ_n the sum keeps increasing infinitely, which shows that this solution is not correct and therefore another approach is necessary.

Figure 7.7

7.4 Using Prandtl's stress function

After the previous attempt, a second method was tried which used Prandtl's stress function. As previously explained, this method differs from using warping functions because instead of solving for displacements the solution is sought in terms of stresses. It begins the same way as in section 7.3 with Saint-Venant's displacement, strain-displacement, and stress-strain relationships. The equilibrium relationship is given by the following equation [211]

$$\frac{\partial \tau_x}{\partial x} + \frac{\partial \tau_y}{\partial y} = 0 \quad (7.29)$$

Prandtl's stress function $\varphi(x, y)$ satisfies Equation 7.29 such that

$$\tau_x = \frac{\partial \varphi}{\partial y} \text{ and } \tau_y = -\frac{\partial \varphi}{\partial x} \quad (7.30)$$

Combining Equation 7.11 with 7.29 gives the governing PDE to be solved

$$\frac{\varphi_{xx}}{G_y} + \frac{\varphi_{yy}}{G_x} = -2\theta \quad (7.31)$$

and the traction free BCs are satisfied if

$$\frac{d\varphi}{dR} = 0 \quad (7.32)$$

or in other words $\varphi(x, y)$ is a constant along the boundary.

The method for finding the solution to $\varphi(x, y)$ was found in Hsieh [216]. The limits here are different, x goes from 0 to a while y has limits $-b/2$ to $b/2$. In this method the solution is assumed to be of the form

$$\varphi = \sum_{n=1,3,5,\dots}^{\infty} Y_n(y) \sin\left(\frac{n\pi}{a}x\right) \quad (7.33)$$

The right hand side of Equation 7.31 can be expanded as a Fourier series between

0 and a so that

$$-2\theta = \frac{4\theta}{\pi n} (\cos(\pi n) - 1) \sin\left(\frac{\pi n x}{a}\right) \quad (7.34)$$

and since $\cos(\pi n) = -1$ for $n = 1, 3, 5, \dots$ Equation 7.31 becomes

$$\frac{\varphi_{xx}}{G_y} + \frac{\varphi_{yy}}{G_x} = -\frac{8\theta}{\pi} \sum_{n=1,3,5,\dots}^{\infty} \frac{1}{n} \sin\left(\frac{\pi n x}{a}\right) \quad (7.35)$$

Substituting Equation 7.33 into Equation 7.35 and working out the differentials gives

$$\frac{1}{G_x} Y''(y) - \frac{\pi^2 n^2}{a^2 G_y} Y(y) = -\frac{8\theta}{\pi n} \quad (7.36)$$

This is a second order Ordinary Differential Equation (ODE) which when solved for $Y(y)$ gives

$$Y(y) = \frac{8a^2 G_y \theta}{\pi^3 n^3} + C_1 \exp\left(\frac{\pi \sqrt{G_x} n y}{a \sqrt{G_y}}\right) + C_2 \exp\left(-\frac{\pi \sqrt{G_x} n y}{a \sqrt{G_y}}\right) \quad (7.37)$$

The constants C_1 and C_2 are determined from the BCs at $y = \pm \frac{b}{2}$ which for a simply connected cross-section are $\varphi = 0 \forall (x, y)$ at the boundary of the region.

Therefore

$$C_1 = C_2 = -\frac{(4a^2 G_y \theta) \operatorname{sech}\left(\frac{\pi b \sqrt{G_x} n}{2a \sqrt{G_y}}\right)}{\pi^3 n^3} \quad (7.38)$$

Plugging Equation 7.38 into Equation 7.37 then the result into Equation 7.33 results in the final result for the stress function

$$\varphi = -\sum_{n=1,3,5,\dots}^{\infty} \frac{8a^2 G_y \theta}{\pi^3 n^3} \sin\left(\frac{\pi n x}{a}\right) \left(\operatorname{sech}\left(\frac{\pi b \sqrt{G_x} n}{2a \sqrt{G_y}}\right) \cosh\left(\frac{\pi \sqrt{G_x} n y}{a \sqrt{G_y}}\right) - 1 \right) \quad (7.39)$$

7.4.1 Verification of the solution

The shear stresses are given by [216]

$$\tau_x = \frac{\partial \varphi}{\partial y} \text{ and } \tau_y = -\frac{\partial \varphi}{\partial x} \quad (7.40)$$

Plotting the stress function and the shear stresses above with $a = 0.005$, $b = 0.0025$, $G_x = 1159113284$, $G_y = 974339096$, $\theta = 1$, and for $n = 1, 3, 5 \dots 99$ produces the graphs shown in Figure 7.8.

(a) Plot of the Prandtl stress function.

(b) Plot of the shear stresses.

Figure 7.8

The plot of ϕ is zero at the boundaries, as it should be, and the shear stresses seem reasonable but the real test was confirming if the stress function converges to a value for the torsional rigidity, which is obtained from the following equation

[216],

$$GJ = 2 \int_{-\frac{b}{2}}^{\frac{b}{2}} \left(\int_0^a \varphi(x, y) dx \right) dy \quad (7.41)$$

When combined with the fact that $\sin^2\left(\frac{\pi n}{2}\right) = 1$ for $n = 1, 3, 5, \dots$, Equation 7.41 results in the following expression for the torsional rigidity

$$GJ_n = \sum_{n=1,3,5,\dots}^{\infty} \frac{32a^3 G_y \theta}{\pi^5 \sqrt{G_x} n^5} \left(\pi b \sqrt{G_x} n - 2a \sqrt{G_y} \tanh\left(\frac{\pi b \sqrt{G_x} n}{2a \sqrt{G_y}}\right) \right) \quad (7.42)$$

The plots in Figure 7.9 were generated using $a = 0.005$, $b = 0.0025$, $G_x = 1159113284$, and $G_y = 974339096$. Compared to Figure 7.7, in Figure 7.9a the values of GJ_n become smaller as n increases which results in the expected converging behaviour towards an asymptote seen in Figure 7.9b for which the value is $GJ_{99} = 0.0198752$. The convergence behaviour shows that the stress function gives reasonable answers.

Figure 7.9

The next step is to work out the torsional rigidity constant κ which Hsieh [216] gives as

$$\kappa = \frac{GJ_n}{ab^3} \quad (7.43)$$

Setting $a = 4$, $b = 2$, and $G_x = G_y = \theta = 1$ in Equation 7.43 gives $\kappa = 0.228681$ and setting $a = b = G_x = G_y = \theta = 1$ gives $\kappa = 0.140577$. These are the same

values as those obtained by Hsieh, demonstrating that the stress function works.

7.4.2 Final derivation of the equation for k

There are three equivalent expressions for the energy stored by a beam under torsion,

$$U_t = \frac{1}{2} T_n \theta = \frac{1}{2} \frac{G J_n}{L} \theta^2 = \frac{1}{2} \frac{T_n^2 L}{G J_n} \quad (7.44)$$

Here θ is Equation 7.2 while T_n and β are given by

$$T_n = \frac{a b^3 G_x \theta \beta}{L}$$

$$\beta = \frac{G J_n}{a b^3 G_x}$$

Plugging θ , T_n , and β into Equation 7.44 results in the same thing for all three equations

$$U_t = \frac{G J_n x^2}{2 L R^2} \quad (7.45)$$

then setting this equal to the energy stored by a spring then setting $L = N_a \sqrt{(\pi D)^2 + P^2}$, which is the length of a helix, and solving for k gives the final equation

$$k = \frac{G J_n}{N_a R^2 \sqrt{(\pi D)^2 + P^2}} \quad (7.46)$$

Shear moduli correction

As mentioned before, close analysis shows that the cross-section of the spring's wire is not constant, even with the mono-directional in-fill. Figure 7.10a shows an idealized cross-section if the material was deposited in rectangles, which is unrealistic but adequate for demonstration. In Figure 7.10b it is possible to see what the cross-section taken on the right of Figure 7.10c looks like. Notice how at the bottom of the cross-section there is a continuous track. This is a consequence of the slicing shown in Figure 6.7a where there are parts of each layer that are deposited radially to the axis of the spiral. There are in fact radial sections with

different lengths so the cross-section will change throughout a single circle. It is theoretically possible to account for this changing cross-section but it overcomplicates the process of finding a numerical solution for the stress function so has not been considered here. As will be shown later, it was anyway not necessary to include this correction in Equation 7.46.

Figure 7.10

Figure 7.10c shows an approximation of what the spring would look like if it was uncoiled into a shaft. The layers are not aligned to the z axis of Figure 7.5 and therefore it is possible that the shear moduli of the material need to be rotated onto the shear moduli of the shaft in order to give better predictions. Since the rotation takes place around the x axis in Figure 7.5, $G_{12} = G_x$ and does not need

changing. The angle α in Figure 7.10c is related to P and D

$$\alpha = \tan^{-1} \left(\frac{P}{2D} \right) \quad (7.47)$$

and so G_y is

$$G_y = G_{31} \cos(-\alpha) - G_{13} \sin(-\alpha) \quad (7.48)$$

Two versions of Equation 7.46 can therefore be written, one that includes the shear re-alignment so G_y is calculated using Equation 7.48, and the other without, where $G_y = G_{13}$. Both versions were used and compared to the experimental results in the next section.

A manufacturing solution for the printing of springs that would eliminate the need for the shear re-alignment is shown in Figure 7.11. Using a robotic manipulator similar to that used in LENS the material could directly be deposited in the direction of the coil. The two main issues are: first, as can be seen in Figure 7.11, the deposition head would have to be small enough to fit in between the coils of the springs; second, the lack of supports could lead to the collapse of deposited material. Therefore this spring printing technique could be an avenue for future investigation.

Figure 7.11: Printing of springs using robotic arms.

7.4.3 Verification of the final equation for the stiffness of a 3D printed spring

A comparison of the calculated and experimental spring constants are shown in Figure 7.12, tables with the values can be found in Appendix C. As can be seen, the difference between the experimental and calculated spring constants is small with the biggest being the d3D20P15 spring, which is likely due to some imperfection during printing. This proves that the derivation method and the equation work and gives very accurate predictions of the spring constant. In fact the difference between the experimental and calculated stiffnesses is so small that it is not possible to determine if the shear realignment is necessary or not using Figure 7.12.

The average stiffness of the three d5D20P15 springs with a layer height of 0.15 mm from section 6.3.2 was 25,009.50 N/M. Using the equation without the shear realignment gives a theoretical stiffness of 24,361 N/M, which is about 3% smaller than the experimental value. This result has not been included in Figure 7.12 because the value is ten times greater than the next stiffest springs, thus making the bar chart difficult to read, but has been included in Table C.2.

The rightmost columns were added to Tables C.1 and C.2 to see the percentage difference between the calculated and measured k_s . The formula with the shear realignment has 7.6% average difference but the standard deviation is quite large, 5.1%, likely because of the random nature of 3D printing and especially FFF and PLA. On the other hand without the shear realignment the average difference is only 4.1% but the standard deviation is bigger than the average, 4.6%. This favours the shear realignment version of Equation 7.46 but there is a problem. The three levels for the pitch are 10, 12.5, and 15 mm and they seem to have little effect on the spring constant, whether experimental or calculated. Upon closer inspection the two versions of Equation 7.46 predict two opposite behaviours though: with the shear realignment k grows as the pitch is increased

(a) With the shear realignment.

(b) Without the shear realignment.

Figure 7.12: Plots of the measured and calculated spring constants.

whereas without the shear realignment the opposite is true. Comparison to the experimental data is inconclusive because it does not seem to follow a pattern so will be discussed further in subsection 7.4.4.

The equation was also used on the springs with ± 45 in-fill that were tested in chapter 6. Tables 7.1 and 7.2 compare the experimental stiffnesses to those calculated using Equation 7.46. As expected both versions of the equation have a higher average difference than with the mono in-fill indicating that a different version of the equation would need to be derived for the ± 45 in-fill. On the other hand, the results suggest that the version without the shear correction could be used to give rough estimates of the shear constant for printed springs with the ± 45 in-fill.

Table 7.1: Spring constants for ± 45 in-fill with shear correction.

Spring	k_{exp} (N/m)	k_{calc} (N/m)	$\frac{(k_{calc}-k_{exp})}{k_{exp}} \times 100$
d3D20P10	318	397.841	20.0
d3D20P15	286	406.006	29.5
d3D40P10	44	47.738	8.8
d3D40P15	38	48.863	22.4
d5D20P10	2813	3069.760	8.4
d5D20P15	2359	3132.760	24.7
d5D40P10	384	368.350	-4.2
d5D40P15	367	377.032	2.6
		Average	14.0
		s	11.8

A comparison has been attempted with the results of He et al. [2], discussed in section 2.1, but the results were poor because they did not measure the three shear moduli necessary for use of Equation 7.46. Table 7.3 shows the stiffness values calculated using Equation 7.46 with no shear correction. G_{12} and G_{13} were estimated to be 800 MPa for 100% infill from Figure 7.13a. Since He et al. did not include a table of their results, comparing Figures 7.13b and 7.13c is the only way to verify the calculated values. As can be seen, the calculated spring stiffnesses seem reasonably close to those measured by He et al., given the estimated shear

Table 7.2: Spring constants ± 45 in-fill without shear correction.

Spring	k_{exp} (N/m)	k_{calc} (N/m)	$\frac{(k_{calc}-k_{exp})}{k_{exp}} \times 100$
d3D20P10	318	379.066	16.0
d3D20P15	286	373.345	23.4
d3D40P10	44	47.8284	9.0
d3D40P15	38	47.6414	20.4
d5D20P10	2813	2924.89	3.8
d5D20P15	2359	2880.75	18.1
d5D40P10	384	369.046	-4.0
d5D40P15	367	367.603	0.1
Average			10.8
s			10.1

moduli. The shape of the plots are also similar, with a steep rise when going from $d = 6.2$ mm to $d = 7.6$ mm. He et al. also varied D , N_a , and L , see Figure 2.2b, but the calculations were not repeated since the exact shear moduli and the measured values are not known.

Table 7.3: Stiffness calculated using Equation 7.46 with no shear correction and $G_{12}, G_{13} = 800$ MPa.

D (m)	P (m)	N_a	d (m)	k (N/m)
0.032	0.01	5	0.002	14
			0.0034	116
			0.0048	462
			0.0062	1285
			0.0076	2901

7.4.4 ULTEM springs

The last verification was made on a set of springs printed with ULTEM 9085. The same procedure and samples as for the +45 (mono-directional) infill in subsection 4.3.2 were used to measure both shear moduli. G_{13} used the same thickness and testing speed as for PLA, whereas for G_{12} the samples were made 1 cm thick (see parameter h in Figure 4.9b) and the testing speed was increased to 2 mm/min, the recommended head speed from ASTM standard 5379 [29]. This

was done because when using the previous sample thickness and speed the samples would produce G_{12} values that had unacceptably large errors, in the range of 40-50%. Changing to the new thickness and speed resulted in much more consistent values, which can be seen in Table 7.4 compared the values for PLA.

As can be seen, ULTEM 9085 in the mono-directional configuration is significantly weaker than PLA and has a higher standard deviation, leading to the observations made in section 6.3.2. Also, G_{13} for ULTEM is greater than G_{12} , which is the opposite of PLA. Overall it would seem that, if not for the fact that ULTEM 9085 is certified for use in space, PLA is the better plastic for springs. Therefore, an integral part of future investigations into 3D printed springs should be the measurement of G_{13} , G_{12} , and G_{31} for various materials; so as to create a database from which the most appropriate material can be chosen.

Table 7.4: Measured shear constants for ULTEM 9085 compared to PLA.

Shear modulus	ULTEM 9085 (MPa)	$\pm$ (MPa)	PLA (MPa)	$\pm$ (MPa)
G_{13}	786.3	127.5	974.3	62.3
G_{12}	574.0	79.6	1159.1	49.1

Several springs were then printed with ULTEM, tested, and their stiffnesses calculated, a comparison between the experimental and calculated sets of k s is tabulated in Table 7.5. Included are the d5D20P15 springs used when comparing ULTEM and PLA springs (section 6.3.2). The version of Equation 7.46 without shear correction was used, since only G_{13} and G_{12} were measured for ULTEM.

There are two conclusions that can be drawn from the results in this table.

Table 7.5: Comparison of calculated and experimental stiffness of ULTEM springs.

Spring	k_{exp} (N/m)	k_{calc} (N/m)	$\frac{(k_{calc}-k_{exp})}{k_{exp}} \times 100$
d3D20P15	267.4	234.4	-12.4
d3D40P10	31.3	30.0	-4.0
d3D40P15	33.3	29.9	-10.1
d5D40P10	213.5	231.7	8.5
d5D40P15	239.1	230.8	-3.5
d5D20P15	1928.1	1808.3	-6.2
		Average	-4.6
		s	7.3

Firstly, the average error is comparable to those in Tables C.1 (7.6 ± 5.1) and C.2 (4.1 ± 4.6), indicating that the equation provides good estimates not only for PLA. The second conclusion is that since the stiffness increases with pitch, 31.3 to 33.3 N/m and 213.5 to 239.1 N/m with 10 to 15 mm pitch, the version of Equation 7.46 with shear correction provides better estimations. Although relatively few ULTEM springs were manufactured compared to PLA springs, it is possible to make this conclusion because ULTEM springs have a more consistent print quality than PLA springs thanks to the higher quality printer and material (Fortus 450mc and ULTEM 9085) compared to PLA on a Prusa. Therefore the way to make the most accurate predictions of the stiffness of 3D printed springs involves measuring the 3 shear moduli shown in Figure 7.5: G_{12} , G_{13} , and G_{31} . In lieu of this, just measuring G_{12} and G_{13} will still provide a close estimate of the stiffness.

Summary

Two equations were derived for calculating the stiffness of a 3D printed spring, the first uses only G_{12} and G_{13} as they are. The second also uses G_{31} to correct the shear moduli and align them correctly to the direction of the spring coils. Comparison with experimental data showed that the equations can predict the stiffness with about 5-7% error for PLA and 5% for ULTEM 9085.

CHAPTER 8

COSTS, MANUFACTURING TIME, MATERIAL USAGE, AND DESIGN FREEDOM

Springs are a well understood component in mechanisms and have been used for a long time so the following question can be asked: "Why use 3D printing for springs in lieu of established, reliable methods?". Like for most of the applications of AM the answer is the design freedom afforded by this novel manufacturing technique. For most applications a regular spring is adequate, but there are many situations where this is not the case and that is where AM may be considered. The cost, manufacturing time, material usage, and design freedom of AM applied to springs will now be discussed using the experience gained from this study.

8.1 Material usage

The amount of material used in 3D printing springs is going to be more than that used for conventional springs, with the exception of machined springs, which are manufactured from solid pieces of metal. Conventional springs are typically made via extrusion through a die then winding, resulting in no material wastage, while AM springs must be printed with supports, resulting in some material going to waste. In the case of PLA springs, the supports are made of the same material so the plastic can be recycled into new filament. On the other hand, printing with ULTEM 9085 always leads to some wasted material because the supports cannot presently be recycled into new filament.

Table 8.1 shows the material cost of various springs made with ULTEM 9085; as mentioned in subsection 3.3.1 the canisters of material and support both cost 1320 SGD for 1510 cm³, resulting in a cost of 0.87 SGD/cm³. The amount of ULTEM 9085 and support material was obtained from Stratasys' slicing program for the Fortus 450mc using SMART supports (which minimize the amount of supports). The cost of PLA springs is not calculated because, as previously mentioned, it was only used to develop the model.

Table 8.1: Ratio of support material to ULTEM 9085 used in printing cylindrical springs and resultant cost. The cost of both ULTEM 9085 and support used for calculations is 0.87 SGD/cm³.

Spring	ULTEM 9085 (cm ³)	Support (cm ³)	Support/ULTEM	Cost/spring (SGD)
d3D20P10	12.24	12.48	1.02	21.61
d3D20P15	15.53	16.35	1.05	27.87
d3D40P10	17.52	21.05	1.20	33.72
d3D40P15	20.89	27.41	1.31	42.22
d5D20P10	20.60	17.33	0.84	33.16
d5D20P15	23.43	18.78	0.80	36.90
d5D40P10	33.18	23.61	0.71	49.64
d5D40P15	36.27	31.23	0.86	59.01
Average			0.98	
s			0.21	

On average the amount of material and support needed is roughly the same,

meaning that each spring costs about twice as much as it would without supports. This can be mitigated somewhat by changing the wire cross-section and will be discussed in section 8.3. If the material used was instead PLA or ABS, the cost would of course be much lower, just a few dollars per spring. The cost per spring does not include labour or machine cost and will be discussed in more depth in the next section.

8.2 Cost and manufacturing time

The cost and manufacturing time of 3D printed springs are strongly connected so will be discussed together. Springs are typically not expensive components, even large ones used in trains are only a small fraction of the total cost [217]. As previously discussed, AM allows greater design freedom so the cost savings come from the ability to quickly and easily manufacture complex spring shapes, as well as the fact that there is no need to design and fabricate tools and fixtures [45].

Using the method from Atzeni et al. [45], an estimate was made of the total cost to print the biggest (d5D40P15) and smallest (D3D20P10) springs in Table 8.2, an exchange rate of 1 EUR = 1.49554 SGD was used to convert the prices. The higher machine cost per hour, 38 EUR/h, from Atzeni et al. was used so as to calculate a worst case scenario. The machine operator cost per hour was 14 EUR/h.

The set up and post-processing times were estimated from the experience gained in this research. ULTEM 9085 support material is not difficult to remove, since ULTEM is much stronger than the support material, but can be time consuming. If several prints of many springs were done, a tool could be developed and printed to allow quick separation of the springs from the supports. Such a tool was not developed in this research because most of the printing was done with PLA and the only way to remove the supports in this case is by breaking

them off.

The biggest and smallest springs were chosen so as to calculate the cheapest and most expensive springs, the others fall between these two. Since D determines how many springs can fit on one print sheet, a max of 132 can be printed for all those with $D = 20$ mm and 42 for those with $D = 40$ mm. Therefore the springs considered are: 132 d3D20P10 springs, and 42 d5D40P15 springs. Foundation sheets, which are placed on the platform, come in packets of 20 costing 1100 SGD so 55 SGD each. The cost of the foundation sheet was not added to the cost of a single spring since they can be re-used depending on the part arrangement and come in packets of 20, meaning that they add a fractional amount to the total cost.

Table 8.2: Estimated cost of printing springs with ULTEM 9085 using the method from Atzeni et al. [45].

	d3D20P10		d5D40P15	
No. of springs per print	1	132	1	42
Machine cost/hour (SGD/h)	56.90		56.90	
Build time (h)	2.83	374.43	4.32	181.27
Machine cost (SGD)	161.22	21,305.26	245.62	10,314.07
Machine cost/part (SGD)	161.22	161.40	245.62	245.57
Machine operator cost/hour (SGD/h)	20.96		20.96	
Set-up 1 post-processing time per build (h)	1	10	1	6
Machine operator cost (SGD)	20.96	209.6	20.96	125.76
ULTEM 9085 used (cm ³)	12.24	1616.09	36.27	1523.35
Cost of ULTEM 9085 (SGD)	10.649	1405.998	31.555	1325.315
Support used (cm ³)	12.48	1646.77	31.23	1311.74
Cost of support material (SGD)	10.858	1432.69	27.17	1141.214
Total material cost (SGD)	21.51	2,838.69	58.73	2,466.53
1 Foundation sheet (SGD)	-	55	-	55
Total cost of print (SGD)	203.68	24,408.54	325.30	12,961.36
Total cost/spring (SGD)	203.68	184.91	325.30	308.60

Figure 8.1 shows the normalized cost breakdown from Table 8.2. As can be seen, roughly four fifths of the springs' cost is in machine time, caused by long print times, and printing more springs together results in a lower cost per spring, which are results similar to those obtained by Atzeni et al. [45]. Similar to Ta-

ble 8.1, the ULTEM/support ratio for the maximum amount of springs per print is about 1 so minimizing the supports would decrease the time and cost. Reducing the amount of material inside the spring is another way to lower the printing time, which could be achieved by using a different wire cross-section, as will be discussed in section 8.3.

Figure 8.1: Normalised cost breakdown for springs from Table 8.2.

8.3 Leveraging the design freedom of 3D printing to reduce the cost per spring

Since supports cause the price per spring to increase, both because of material cost but mainly due to increased printing time, some considerations have been made about how to use AM's design freedom in order to reduce the amount

of supports needed per spring. Several methods have been identified and their applicability will now be discussed.

8.3.1 Deactivation of support generation

In some slicing programs, like Simplify3D, support generation can be deactivated but this typically leads to poorer print quality. In that case the print settings have to be adjusted to account for this, such as a slower deposition speed and thinner layers. But this not possible in all slicing programs, for example Stratsys's proprietary slicer for the Fortus 450mc, Insight, does not have an option to disable supports. Therefore the method of deactivating support generation in the slicing program is only feasible in specific cases and so not widely applicable.

8.3.2 Changing the spring's orientation

While leaving support generation active, it is impossible to print springs without supports by changing the orientation, as shown in Figure 8.2. Printing in orientations other than that used in this research will also change the material distribution inside the coils, leading Equation 7.46 to become invalid. Therefore this method for cost reduction is not considered viable.

8.3.3 Increasing the pitch

Another potential method for reducing the amount of supports produced is by increasing the rise angle, θ_{rise} , of the spring coils (the angle between the coils and the base of the spring), which is found from the arctangent of the pitch divided by the spring diameter,

$$\theta_{rise} = \frac{P}{D} \quad (8.1)$$

Three springs with no closed end at the top, which can be printed aside, were sliced in Simplify3D, shown in Figure 8.3, with support generation set to occur beyond 45° . As expected, Figure 8.3a causes supports to be generated. The

Figure 8.2: Springs in Simplify3D showing that no orientation is possible that does not require supports. The printer axes are shown for reference.

spring in Figure 8.3b also has supports in equal amount to the spring with $\theta_{rise} = 45^\circ$. The final spring, with $\theta_{rise} = 76^\circ$ (Figure 8.3c), has less supports than the other two but the pitch is so great that it would make a very stiff spring, therefore increasing the pitch is not a feasible method to reduce the amount of supports.

8.3.4 Hollow wire springs

The last potential method for lowering the printing time is to manufacture hollow wire springs, thus reducing the amount of material needed for printing [66]. A shaft under torsion τ about the central axis z with length ℓ has an angular twist φ given by

$$\varphi = \frac{\ell\tau}{GJ_z} \quad (8.2)$$

where G is the shear modulus and J_z the second moment of area, also known as the area moment of inertia. J_z for a disk is

$$J_z = \frac{\pi r^4}{2} \quad (8.3)$$

Figure 8.3: Support generation as θ_{rise} is increased.

and, since it is additive,

$$J_z = J_{zo} - J_{zi} = \frac{\pi(r_o^4 - r_i^4)}{2} \quad (8.4)$$

where r_o and r_i are the outer and inner radii. As can be seen in Figure 8.4, a hollow tube with $r_o=2$ mm will have almost the same moment of inertia up to $r_i=1$ mm. Thus printing a hollow tube would be advantageous in saving both time and resources.

Vertical round shapes typically require supports therefore printers with soluble supports would be advantageous. Otherwise, a solution is to use a triangular or rhombus cross-section, see Figure 8.5a, the former with a flat edge parallel to the layers, both of which do not need internal supports if the sides are steep enough. The rhombus needs less external supports, as shown in Figure 8.5c, by having a support/material ratio of 0.56 as opposed to 0.95 for the triangular cross-section, which can be seen in Figure 8.5b. The rhomboidal wire cross-section springs could also be printed using powder based technologies such as SLS, assuming a drainage hole is left to let the powder out from

Figure 8.4: Second moment of area for a hollow tube with outer radius 2 mm.

inside the spring.

Figure 8.5: Hollow springs with a wall thickness of 2 mm.

The rhombus can be squashed to a square, like the one at the shown at the bottom of Figure 8.5a, so that Equation 7.42 can be used. Figure 8.6a shows the change in torsional rigidity of a spring with a square wire cross-section of outer diameter 5 mm and with inner diameter d_i . Similar to Figure 8.4, the torsional rigidity does not change significantly up to $d_i = 2$ mm, therefore a significant

amount of material could be removed in order to decrease the cost. Figure 8.6b shows an example of a compression spring with a hollow, square wire.

Figure 8.6

The d5D40P15 spring from Table 8.2 has a machine and material cost of 304.35 SGD for a single spring. Table 8.3 shows a comparison of the costs for the same spring but with a square, hollow wire cross-section and different shell thicknesses t shown in Figure 8.5a. Only the machine and material costs are considered because they have the biggest effect on the cost.

Table 8.3: Comparison of costs for square hollow springs with different shell thicknesses t . The machine cost per hour is 56.90 SGD and the cost of the ULTEM and support is 0.87 SGD/cm³.

t (mm)	ULTEM 9085 (cm ³)	Support (cm ³)	Build time (h)	Machine and material cost (SGD)
Full (2.5)	35.48	33.24	4.05	290.52
2	33.56	32.41	4.15	293.80
1.5	34.32	33.31	4.10	292.41
1	29.19	34.20	3.87	275.43
0.6	22.70	34.86	3.80	266.54

As can be seen, the full spring in Table 8.3 costs less than the one from Table 8.2. As t decreases, at first there is an increase in cost but when t is small

enough the price drops significantly. Comparing this to Figure 8.6a, when a shell of thickness 1 mm is used the torsional rigidity has dropped significantly therefore a future study could be made to optimize the amount of material removed while maintaining stiffness. The final thickness greater than 0.5 mm because the default raster width on the Fortus for ULTEM 9085 is 0.5080 mm.

Summary

In this chapter the costs of manufacturing ULTEM 9085 springs were analysed. About 80% of the cost comes from machine printing time so four methods for reducing this were investigated. Of the four, changing the shape of the wire to a rhombus and printing hollow springs was the only method found to be universally applicable and that had a tangible impact on the cost.

CHAPTER 9

CONCLUSION

9.1 Summary and Conclusions

AM is a revolutionary manufacturing technology that allows unprecedented design freedom. It can print a huge variety of materials at high quality. It is finding a use in an enormous variety of applications, from printing houses to parts for spacecraft to electronics. Yet it has not yet been adopted universally, there are still issues that need to be sorted out before it can be fully embraced. The space industry, amongst others, has recognized the importance of 3D printing and there is a lot of work underway to ameliorate the issues faced by AM.

Springs are an essential part of mechanisms for storing and releasing mechanical energy. They are easy to manufacture and obtain, finding use in many types of applications, from the suspensions of vehicles to satellite deployment systems. By leveraging the design freedom that AM affords, new types of springs could be developed with shapes and dimensions that were previously hard or impossible to make. The results of the literature review showed that the application of 3D printing to springs is a research area that is still very new and only a few studies

had been made.

With regards to AMFS a large body of literature is present. AMFS is one of a few manufacturing areas where a distinction has to be made between the research that has been done on Earth and in space. The second generation of space 3D printer is currently on the ISS and up to the present the research done has been about the 3D printing process and if the parts produced in flight are of the same quality as those manufactured on the ground, which they are. Some printing has also been done of tools that incorporate several functions in one, demonstrating the flexibility of AM.

ISAM is tied to ISM, whose goal is to manufacture and assemble large structures in space. There are many challenges such as recycling of materials, ability to move large structures, and being limited to materials that can survive the space environment. Still there are several proposals for spacecraft that are dedicated to AM of large metal structures and even one for polymer.

When it comes to AMFS research on the ground, there is a lot of activity. Many entities, both governmental and private, are performing research in many different areas. The most prominent one is metal, where the focus is on parts for engines. Polymer research instead focuses on parts for small satellites like structures or thrusters. The ability of 3D printers to use almost any material is being leveraged in ISRU, where research focuses on construction of habitats and objects for astronauts on other planets or the Moon.

The literature review revealed gaps in AMFS research, mainly the lack of research into DFAM and a lack of standards specifically for AMFS. Also, as previously mentioned, there was very little literature on the subject of 3D printed springs for the space industry. Therefore the objective of this research was to investigate 3D printed helical springs. A hypothetical, novel CGT design that used the design freedom of 3D printed springs was proposed as a possible application. Another potential application of 3D printed springs is their use in deployable helical antennae for CubeSats. This required the modelling of the spring constant

of 3D printed springs to avoid the process of printing springs until one was made that achieved the intended effect.

The research began with the characterization of PLA printed with FFF using two in-fills, +45 and ± 45 , according to the orthotropic material model. The DIC program GOM Correlate was used to measure strain rather than strain gauges, which allowed a much greater level of detail limited only by the resolution of the camera used. The measured constants showed that the elastic modulus of both in-fill was only greatly affected when the loading direction was parallel to layer deposition and the Poisson ratios had the biggest errors, most likely due to the fragility of PLA and the difficulty in tracking transversal strain.

After the model was complete an experiment was performed to compare the simulated and experimental elastic modulus and Poisson's ratio of samples with varying numbers of perimeters. The simulations used two different materials for the perimeter and in-fill, the former being aligned so that the material constants followed the direction of the perimeters. The results showed that although there was a difference between the experimental and simulated constants, it was small and not consequential. This experiment showed that in applications where the size of the in-fill is much greater than the perimeters, simulations of tensile loading can be considered accurate even if the number of perimeters is varied.

The next step in the research was printing and testing springs. Two sets of helical springs were printed, compression and tension, and their parameters varied. The in-fill was also varied between the classic ± 45 and the mono-directional. The spring constant of the compression springs was measured with cyclical loading while in the linear region and revealed that the pitch did not significantly affect the stiffness of the springs, just like with conventionally manufactured springs. Comparison between ULTEM 9085 springs and PLA springs, as well as further experiments, revealed that layer height plays a role in determining the stiffness 3D printed springs with smaller layers producing higher spring constants. The tension springs could be stretched to breakage therefore cyclical testing was per-

formed in the post-deformation region, where the slopes of the $F - x$ graphs were comparable to the first linear region, suggesting that the spring shape still had an effect on the stiffness even after plastic deformation. The two different in-fills were compared and the mono in-fill produced springs that broke much later than the ± 45 in-fill.

Then the equation for the spring constant was developed. The derivation method involved equating the energy stored by a spring to the energy stored by a shaft of the same length under torsion. The mono in-fill and a square wire cross-section were used in the derivation because they simplified the problem compared to the ± 45 in-fill and circular wire. Two approaches were attempted and the first one, stress functions, did not produce a viable equation. The second approach instead produced a satisfactory equation that was able to accurately predict the spring constants of 3D printed springs. A slight variation was made to the equation to verify if the misalignment of the layers compared to the hypothetical shaft made a difference but comparison to the experimental data did not reveal any conclusive pattern.

The last part of the research was about leveraging the flexibility of 3D printing to reduce the cost of manufacturing springs in this way. Only ULTEM 9085 was considered because PLA was only used to help develop the model. Four methods were considered and only one was found to be viable in all cases, which was using a rhombus shaped, hollow wire.

9.2 Contributions

9.2.1 PLA material characteristics

Given that mechanical properties are dependent on the printer and print settings, a contribution is the characterization of 3D printed PLA measured using two different in-fills: ± 45 and $+45$. Other researchers may still find the information useful since all mechanical properties have been measured, including the

shear moduli which are not always included in material characterizations. Since the +45 in-fill has better shear properties than the more traditional in-fill, in applications where the main loads are shear it would be good to consider this in-fill type.

9.2.2 Multi-material FEA of 3D printed PLA

The study presented in chapter 5 focuses on comparing the results of FEA and experiments to establish if simulations of samples with varying numbers of perimeters give the same elastic moduli and Poisson ratios as real printed coupons when subjected to tensile loading. The findings were that there is a small discrepancy that for most applications would not make a difference. Therefore, coupled with the results from chapter 4, which represent the extreme case of the in-fill being composed of only perimeters, the main contribution of this investigation is the following. The E and ν from the simulations did not change with N_{out} therefore it is possible to perform simulations of parts with just the regular in-fill and no perimeters without running into too many issues, being aware that the Poisson's ratio from the simulations will be smaller than that of the real part and that the elastic modulus will vary slightly. This means that users of simulations do not have to account for varying numbers of perimeters in their FEA models, greatly simplifying the process especially for complex parts.

9.2.3 3D printing of helical springs

AM enables the fabrication of parts that were previously thought impossible and the research in chapter 6 has further expanded this possibility. Two major contributions are design guidelines for the printing of springs. Firstly the results show that the mono in-fill produces a better spring compared to the ± 45 in-fill because, as shown in chapter 4, it has better shear properties. Secondly, the square cross-section prints better and does not require a keystone profile because there is no winding. A further contribution was made by the comparison between

ULTEM 9085 and PLA springs, which demonstrated that layer height makes a difference to the spring constant: thinner layers result in stiffer springs. Given that under cyclic loading the spring still behaves semi-elastically in after plastic deformation, another contribution is the possibility of leveraging this behaviour as a safety mechanism if the spring should become deformed, it is still possible to use the spring but with caution until repairs can be made. The final contribution by this study is the confirmation that, like for springs made of isotropic materials, 3D printed springs are mainly affected by the wire diameter and coil diameter and not as much by the pitch, so the spring index c can be applied to help guide design.

9.2.4 Equation for calculating the spring constants of springs manufactured via AM

Building on the work in chapter 6, the successful derivation of Equation 7.46 produces several contributions. First is the fact that, since the orthotropic model was used as a base, this equation is valid for springs made of any composite material, not those made via AM. The equation is also quite flexible, it can be used for rectangular wire cross-section springs by setting a and b to whatever values are needed. Another contribution, which was previously mentioned, is that Equation 7.46 greatly cuts down on development times of mechanisms that use 3D printed springs by allowing the prediction of the spring constant. The fact that the shear moduli realignment is not needed is also a contribution since it means that Equation 7.46 can be used as it is without further complications. Another contribution of this chapter is the fact that Equation 7.46 is a step closer to the idea of being able to print springs with completely new designs that would otherwise be impossible manufacture, thus allowing a new generation of mechanisms to be developed that take full advantage of AM's design freedom.

9.2.5 3D printed springs and design freedom

The main contribution of this chapter is the determination of the best method for reducing the cost of 3D printed springs: by using rhombus shaped, hollow wire.

9.3 Future work

Future research could be performed using metal printing, comparing the properties of printed and conventional springs in an effort to create printing guidelines that enable high quality printed springs to be manufactured. Also guidelines could be developed to omit the need for supports or print them so that they are easy to remove.

9.3.1 Multi-material FEA

Two of three main material constants were covered in this study: E and ν . Therefore the logical area of expansion for this research would be to perform the same experiments but for G . This would verify if simulations of shear are also accurate in the same way as it has been done for the elastic modulus and Poisson's ratio, creating a complete set of guidelines for designers and engineers with regards to the differences between simulations and experiments when changing the numbers of perimeters for a printed part.

9.3.2 Investigation of 3D printed springs

An area of further research could be in determining the best method for printing springs with round wire cross-sections. Another area for future investigation is high-volume cyclical loading of springs to verify their integrity and performance when undergoing many cycles of loading and unloading. The final area for future investigation is the comparison of PLA and ULTEM 9085 tension springs stretched to breakage to investigate the post-deformation behaviour of ULTEM.

9.3.3 Modelling the spring constant of springs manufactured via AM

The most obvious area for expansion here is determining if the shear correction is necessary or not. Apart from that, using the same principle of equating energies it should be possible to derive an entirely new equation that calculates the spring constant of spiral and torsion springs, since in this case instead of a shaft under torsion they are beams undergoing bending. The other area for future work is expanding the equation to take into account variations in the diameter and shape of the wire as well as changes in the diameter of the coil, for example in the case of cone springs. For this application the aforementioned method for calculating the torsion of an arbitrarily shaped orthotropic beam would prove invaluable. The last area of expansion would be to derive an equation for a spring with circular cross-section, which has no warping but the anisotropy would still need to be taken into account.

9.3.4 Design freedom

There is the possibility of printing other types of springs other than helical, like conical, spiral, or torsion. Making use of 3D printing's design freedom new spring designs could be explored, for example ones whose cross-section changes, either in diameter or shape. Or it would be possible to print single use springs that lock into place once they reach a predefined length.

Appendices

APPENDIX A

INVESTIGATION OF LOCALISED STRAIN OSCILLATIONS DURING SLOW TENSILE LOADING

The content of this appendix has been included to provide a record of a phenomenon that has been observed during testing in chapter 4 and subsequently investigated. No definite conclusions can be drawn with regards to the phenomenon's origin or mechanisms, only the observable effect, hence why it has been placed as an appendix instead of a main chapter. The investigation of the phenomenon also lies outside the research on 3D printed springs. What is reported here is what has been observed during several experiments and the few definite conclusions that can be drawn from the observation of the phenomenon's effect but, as stated before, no insight was gleamed as to how the

phenomenon comes about and how it generates the observable effects.

A.1 Observation of strain oscillations

The procedure for extracting the strain data from the filmed experiments has been described in subsection 4.3.3 but will be summarised here:

1. During testing, videos are taken of samples
2. The videos are converted from their native frame-rate to 10 frames-per-second so as to match the rate at which stress data was collected, no resolution was lost
3. The videos are individually imported into GOM Correlate
4. The area of the sample is selected where the strain is to be measured (the coloured area in Figure A.1)
5. For the shear coupons, a new coordinate system is created to comply with ASTM standard D5379 [29]
6. The strains in the x and y -directions are computed and exported
7. A linear fitting is performed in MATLAB on the stress-strain data, which gives the wanted material constant

During the experiments in chapter 4, when extracting the strain data there are two main methods: deviation labels and average. When using the average, GOM calculates the strain for every part of the sample's surface and takes the average. This is repeated for every frame and when plotted over time the data results in a line like the one shown in Figure A.2b.

The other method for extracting strain data is via deviation labels. It is possible to mark any number of specific points on the surface of a sample for tracking, called deviation labels, such as the one shown in Figure A.2a. GOM is then able

Figure A.1: Type IV sample in the DIC program. The red area corresponds to the gauge area and is where the strain was measured. The green arrow (y-axis) shows the direction of axial strain while the red one (x-axis) shows the direction of transverse strain.

to generate the strains over time for the deviation labels along any axis. As can be seen in Figure A.2b, when the strain for the point in Figure A.2a is plotted over time, it does not form a straight line, instead oscillating as the sample is stretched. For this reason, the average strain was used in section 4.3 instead of the data from single deviation labels.

The oscillatory behaviour for the single point observed in Figure A.2b is clearly not noise since the pattern is too regular and the amplitude of the signal is much bigger than the noise. The point oscillations were found in tensile samples but not the shear samples, because the data resulted in plots that were too noisy to be useful, therefore all analysis was carried out on the tensile coupons. Figure A.3 shows examples of point oscillations obtained from samples in the E_1 , E_2 , and E_3 orientations. As can be seen, the signal from the E_3 coupon produced a more consistent strain wave pattern, the peaks are much clearer and well spaced out, and the amplitude of the oscillations is relatively consistent. The drawback is that coupons in the E_3 orientation break earlier than the others so less data could be collected per sample. Despite this, more discernible wave properties remained a priority for analysis so this orientation was used regardless. It is likely that the other orientations also produce the oscillations but it was not possible to conclusively identify them in this study. Bartolai et al. also used DIC in their research but seem to not have observed this phenomenon since they don't discuss it [194].

Another example of the oscillations is shown in Figure A.4, where the axial and transverse strains for a point on an E_3 sample are shown. As can be seen, the plot of the strain in the x -direction, the transverse strain, has a greater signal-to-noise ratio so it is difficult to determine if the oscillations are occurring or not. The oscillations are instead much clearer for the axial strain, which is measured parallel to the layer deposition direction. Similar plots were observed in all E_3 tensile samples, even the type IV ones, although the oscillations were more difficult to identify. Therefore, all experimental analysis was performed on samples

(a) Example of a deviation label, identified by the green label, on the surface of sample $\pm 45\text{-E3-07}$.

(b) Average strain in the y direction compared to the strain for the point shown in (a), also in the y -direction, for sample $\pm 45\text{-E3-07}$.

Figure A.2

Figure A.3: Examples of point oscillations from tensile samples in different orientations.

printed in the E_3 orientation and parallel to the layer deposition direction, which is also the axis along which the stress was applied. This is the weakest of the material directions from Figure 4.7b according to the result in Figure 4.20a, which is expected. The phenomenon has been labelled localised strain oscillations, or just strain oscillations, due to the fact that the strain values oscillated over time as stress was applied.

Figure A.4: Strains for a single point on sample ± 45 -E3-07, where the axes are aligned like in Figure 4.13b.

A.2 Methodology

A.2.1 Tensile coupon specimens

Three different types of samples were used in total: type I coupons, type IV coupons, and shorter, thicker coupon based on type I. All samples were printed with the settings shown in Table 4.3. Table A.1 compares the dimensions of the type I and redesigned type I coupons.

Table A.1: Dimensions of redesigned type I coupon compared to the regular type I (the dimensions referenced can be found in Figure 4.8).

Dimensions	Type I (mm)	Redesigned type I (mm)
W	13	13
L	57	30
WO	19	19
LO	165	120
G	50	24
D	115	88
R	76	76
T	4	10

The orientations initially investigated were E_1 , E_2 , and E_3 from Figure 4.11b. As shown in Figure A.3, it was found that the E_3 orientation produced the clearest oscillations therefore that was the main orientation used, the modified type I coupons were printed in this orientation. The procedure hereafter described pertains only to coupons the E_3 orientation.

Some of the samples were marked with black ink in an effort to emphasize the layers during DIC as shown in Figure A.5a. These areas were not used for data gathering as it was feared that the black markings would interfere with GOM Correlate and produce invalid data. Various test speeds below 1 mm/min were used and the results will be discussed later.

(a) Example of black markings on the right of the sample to emphasize the layers.

(b) Testing on the UTM.

Figure A.5: Modified type I coupon details.

A.2.2 Analysis of experimental data

The data gathered during this series of experiments was analysed similarly to chapter 4. The videos taken by the UTM were first converted to match the rate of data gathering then imported into GOM Correlate. Within GOM Correlate, deviation labels were then placed on the area being analysed, these show the strain at a particular location and can be tracked individually, which is how the phenomena of strain oscillations was discovered in the first place. Depending on the type of analysis the labels can be placed anywhere in the analysis area.

One special way that the labels were placed was by referencing the marked area at the edge of the coupons where the distance between each black line will correspond to a single layer height or 0.15 mm. With this reference distance set, a series of points can be created, one per layer in an effort to try to understand how the strain oscillations behave. Figure A.6 is an example of a series of deviation labels and their outputs.

Figure A.6: Example of a series of deviation labels aligned to layers (left) and their strain-time plots (right), where they are all shown together.

One of the limitations faced was that the strain oscillations were not consistent over the whole sample, the clarity of the oscillations varied greatly as can be

seen in Figure A.7, which shows the axial strain against time of 5 deviation labels placed in adjacent layers. Points 1 and 2 have clear oscillations from 45 seconds on while point 3 doesn't seem to have any discernible oscillations. Then points 4 and 5 once again have some oscillations from 50 seconds onwards. Locating points that displayed good oscillations was often a matter of generating tens of points in a grid pattern and then finding ones that had clear, consistent oscillations. Moreover there was significant displacement noise in certain regions of the samples which would hamper analysis. The variation in signal quality of the points is likely due to the printing process resulting in an inhomogeneous material where there are slight differences from layer to layer and track to track. This in turn would affect the ability of different parts of the sample to react to stress which, along with interactions with neighbouring parts, result in the inhomogeneous oscillations seen.

Something to note is the comparison between the displacement and the strain for single points. Figure A.8a shows the plot of displacement against time for 5 points on the surface of sample $\pm 45\text{-E3-01}$. GOM Correlate can output displacements by giving it a gauge distance, which involves entering the distance between two points on the surface of the sample. In this case two vertically aligned points on adjacent layers were used so the distance between them was the layer height, 0.15 mm.

The plots of the displacements are then compared with the plots of the strains for the same points in Figure A.8b. As can be seen, the two sets of plots are very different in behaviour. The displacement plots, i.e. the distance that a point moves from its initial position, create straight lines as is expected, since the head speed is constant. The strain plots, instead, show the oscillatory behaviour that has been discussed, although the oscillations are clear only for points 5, 2, and 1. This discrepancy in the behaviours of the two plots cannot be explained with the information available here and has been described only for completeness.

Once points had been located with some clear oscillations, the strain-time

Figure A.7: Example of a series of 5 deviation labels aligned to layers.

(a) Displacement over time in the axial direction. (b) True strain over time in the axial direction.

Figure A.8: Plots of displacement and strain for 5 deviation labels on the surface of sample $\pm 45\text{-E3-01}$.

data was imported into MATLAB. Here a Savitsky-Golay filter was used to remove excessive noise in the readings which can be seen in Figure A.9. Determining how much noise to remove was done through a trial and error approach by comparing the cleaned signal to the original but every effort was made to not lose important information. Next the linear trend caused by the movement of the jaws during testing was removed as shown by the de-linearized line in Figure A.9. Following this, the wave properties of the oscillations were analysed in MATLAB.

Figure A.9: Example of processing of noisy strain-time data within MATLAB.

MATLAB analysis

This involved measuring the amplitude and approximate period of the oscillations, which was achieved first with the `findpeaks` function and produced plots like the one in Figure A.10. Finding the approximate period was difficult since the `findpeaks` function occasionally detected secondary peaks due to residual signal noise even after applying the filter, which are circled in red in Figure A.10. The false peaks were ignored for all analysis and calculations.

Figure A.10: Example of peaks found on a filtered and de-linearised signal, primary (green) and secondary peaks (highlighted in red) are shown.

MATLAB's CFT was also used in an attempt to fit a sinusoidal curve to the oscillations and obtain the wave properties. The coefficient of determination, also called R^2 , was used to gauge how well the fitted wave matched the original signal. The coefficient of determination is the proportion of the variance in the dependent variable (true strain) that is predictable from the independent variable (time). Fits such as the one in Figure A.11 were typical and R^2 was never higher than 0.8 due to the shifting pattern of the signal. The next section will examine the results obtained in the experiments as well as the subsequent analysis and modelling in MATLAB.

A.3 Results

A.3.1 Analysis of type I coupons

Visual comparison of oscillations produced by type I samples tested at 1 mm/min and 0.5 mm/min showed that slower speeds produce better oscillations for anal-

Figure A.11: Fitting a sinusoidal function using the CFT.

ysis. Ten consecutive deviation labels were placed on samples lined up with the layers to examine the relationship between the extruded layers and the oscillations. Several series of points were identified and analysed on various samples but only a typical one is shown here due to space limitations. An example of the strain oscillations observed in subsequent layers, after using the `findpeaks` function, is shown in Figure A.12. MATLAB analysis was performed on this series of points using the techniques described in section A.2.2 and the results are presented in the next section.

Wave properties using MATLAB

After removal of the linear trend the peaks of the waves were identified, as shown in Figure A.12, and used to calculate the mean amplitude $\bar{A}$ and period $\bar{T}$ per layer, which are tabulated in Table A.2. The mean period was computed by measuring the distance between consecutive peaks while the mean amplitude was computed by taking the average of the modulus of the y -coordinates of each peak and trough.

As can be seen, the average of the amplitudes for each point have very large

Figure A.12: Strain-time plots for strain oscillations observed in 10 adjacent layers.

Table A.2: Mean amplitudes and periods of strain oscillations in each layer of a Type I coupon.

Layer	$\bar{A}$	$s_{\bar{A}}$	$\bar{T}$ (sec)	$s_{\bar{T}}$ (sec)
1	0.0011	0.0004	13.54	2.35
2	0.0011	0.0005	13.48	2.00
3	0.0012	0.0007	13.33	2.68
4	0.0008	0.0006	13.21	3.04
5	0.0009	0.0005	13.48	2.80
6	0.0012	0.0006	13.46	2.52
7	0.0013	0.0006	13.45	2.16
8	0.0011	0.0005	13.46	2.23
9	0.0010	0.0006	13.39	2.28
10	0.0010	0.0007	13.38	2.33

standard deviations, $s_{\bar{A}}$ varies from about 36% for layer 1 to about 75% for layer 4, which, referring to Figure A.12, is to be expected given the quality of the signals. The mean periods have less variation, $s_{\bar{T}}$ being in the range of 15-20% of $\bar{T}$. What can be observed from these results is that the oscillations occur relatively regularly but their effects are quite random, likely due to the previously discussed material inhomogeneities.

An apparent phase shift was noticed to occur in consecutive layers of some samples where a few of the peaks appear to move to the left when tracking them from point 1 to 10 in Figure A.12. Therefore, MATLAB's CFT was then used to attempt to extract more useful information from the data. Furthermore, a Fourier decomposition of the signal could be performed in the hope of identifying how different wave components contribute to the overall oscillations. Table A.3 shows the values obtained from fitting the following equation to the signal data produced by the layers,

$$\varepsilon(t) = A_1 \sin(B_1 t + C_1) \quad (\text{A.1})$$

The R^2 value is included to show the goodness of the fit while Figure A.13 shows an example of what the fitted line looked like superimposed to the original signal.

Table A.3: Curve fitting for 10 layers using a single sine term.

Layer	A_1	B_1	C_1	R^2 value
1	0.0007679	0.4633	2.4420	0.5001
2	0.0007084	0.4635	2.3510	0.4003
3	0.0006499	0.4638	2.2350	0.2446
4	0.0003636	0.5632	1.4080	0.1493
5	0.0003391	0.5647	1.0380	0.1382
6	0.0007122	0.4623	-0.2018	0.3397
7	0.0008538	0.4628	-0.2736	0.4148
8	0.0007621	0.4630	-0.2838	0.4160
9	0.0006579	0.4634	-0.3255	0.3439
10	0.0005352	0.4643	-0.3853	0.2198
Average	0.00063501	0.48343		0.31667
s	0.0001716	0.0424		0.122859667

Figure A.13: Example of fitting Equation A.1 to the strain-time data of a layer.

The R^2 values show that a single sine term is not enough to generate a good fit since the layers produce values that are at or below 0.5. The amplitude of the oscillations A_1 is the one with the highest variation, a standard deviation of 0.0001716 so no analysis of this value was performed. B_1 , the frequency of the oscillations, is slightly better with a standard deviation of only 0.0424. This indicates that the oscillations between layers are comparable and lending credence to the samples displaying a relatively periodic oscillatory behaviour. C_1 is the phase constant and the fact that it changes from layer to layer indicates that the peaks of the oscillations are moving so there is a propagation of strain waves throughout the samples. Perhaps due to the dampening effect of viscosity and the interface between the layers, the oscillations are slightly slowed from one layer to another, thus causing the phase shift.

Next the number of sine terms in the series was increased to two producing the following equation

$$\varepsilon(t) = A_1 \sin(B_1 t + C_1) + A_2 \sin(B_2 t + C_2) \quad (\text{A.2})$$

With this equation the average R^2 in Table A.4 is slightly higher than in Table A.3 with a smaller standard deviation, which is to be expected. Overall the fit is still very bad and although adding more terms would make it better, no additional information can be gleamed from this so no further analysis was performed in this direction. Due to the fact that signal fitting is very inaccurate, most of the analysis done in the rest of this section is more qualitative than quantitative.

Resonance

During the initial analysis of the layers some showed signs of resonance. What is meant by that is the fact that the local strain in some parts of the samples were larger or smaller than in adjacent layers. For example in Figure A.14 it is possible to see that the oscillations in the highlighted layer are smaller than in the adjacent

Table A.4: Curve fitting for 10 layers using two sine terms.

Layer	R^2 value
1	0.5459
2	0.4565
3	0.3161
4	0.2297
5	0.283
6	0.4383
7	0.5252
8	0.5351
9	0.4471
10	0.3138
Average	0.40907
s	0.114711959

layer.

It is also possible to observe how the waveform changes shape from one layer to the other in Figure A.12. The oscillations in layer 1 start large then become progressively smaller in the interval $t \approx 0, 80$ then the reverse happens in the interval $t \approx 80, 180$, creating a bottleneck region in the interval $t \approx 80, 110$. This pattern is similar to that produced by an amplitude modulated signal and is roughly present in subsequent layers but in layers 6 and 7 there is no distinct bottleneck region, the oscillations having become relatively uniform. Amplitude modulation is where a signal $m(t)$, such as $\sin(A_m t)$, is multiplied by a another signal, for example $\varepsilon(t)$ from Equations A.1 and A.2, with a frequency much larger than A_m . Therefore the final signal is $\varepsilon(t) \sin(\omega_0 t)$ [218], see Figure A.15.

By layer 10 of Figure A.12 a new pattern seems to be forming where there is a distinct downward trend in the interval $t \approx 0, 110$ followed by an upward trend from $t \approx 110$ onwards. This coupled with the example in Figure A.14 suggests that tensile loading induces a standing wave behaviour across the sample with each layer representing a different point of the wave. Although difficult to tell, layers 6 and 7 in Figure A.12 are where there might be a node, since before and after these layers the uniformity of the signal breaks down.

Figure A.14: Example of two adjacent layers that have different oscillation amplitudes. The plot highlighted in red corresponds to the strain produced by the deviation label also highlighted in red, while the plot below the highlighted one corresponds to the deviation label just below the highlighted one.

Striations

An observation made during the course of testing was the relationship between the oscillatory behaviour and the striated regions generated by GOM Correlate shown in Figure A.17. The striations were found to occur in all tensile coupons, the strain values varying from one frame to the next but the general distribution of the striations does not change over the course of testing, indicating that they are a consequence of the sample's geometry. Setting deviation points in striated regions allows the observation of the oscillatory behaviour of these regions, as shown in Figure A.16. In Figure A.16b the red time line, which marks the current frame of the video being shown in GOM Correlate, is at a trough while the next point in Figure A.16c is at a peak and the final point is close to a trough. The fact that the red line in Figure A.16d is not exactly on a trough is likely due to an imperfection in the sample which is also why the striations are not perfectly horizontal and instead are skewed. The fact that the points generate alternating

Figure A.15: Analogue amplitude modulation.

oscillations suggests that the striations might be the “unit” of the oscillations, so placing deviation labels in adjacent regions will result in the oscillations being out of phase by π . The alternation of peak and trough in adjacent layers was found to be generally true for all samples. No explanation for this behaviour can be given, though, since the striations seem to be independent of orientation.

Sample (c) in Figure A.17c, from Bartolai et al., is the same as the $\pm 45^\circ$ -E1 samples in this research and, as can be seen, there are no striations in the full-field strain images that they produced. Bartolai et al. described these as strain localizations in the loading direction and explained that they are to be expected since they are caused by poor welding of neighbouring roads. Yet, there are clear differences in the strain fields produced by the two experiments and there are a number of possible reasons for this discrepancy, including different:

- material - ABS vs PLA

(a) Deviation points in adjacent striation regions.

(b) Point 1.

(c) Point 2.

(d) Point 3.

Figure A.16: Strain oscillations seen in GOM from deviation labels placed in regions of alternating striations.

- printers - Mendel Max 3 vs Prusa i3 MK3 and Cubicon Single 3DP-110F
- data gathering rate and testing speed - 1 Hz at 5 mm/min vs 10 Hz at 0.5 mm/min
- sample orientation - only the printer's XY plane (see Figure 4.1) vs E1, E2, and E3
- cameras and their setup

With the results obtained in this research it is not possible to narrow down which factor(s) result in the difference seen in Figure A.17. The likeliest reason why the striations are present is the material/printer combination, but it could also be any of the other differences discussed. As has been observed in this research, faster testing speeds result in less visible oscillations and, when coupled with lower data gathering rates, would therefore result in less striations. Since the experiments done by Bartolai et al. were at ten times the rate of those in this research, with ten times less data gathered, this might have resulted in no visible striations. The sample orientation likely was not a big factor since the striations are similar in both flat and vertical orientations (Figures Figure A.17a and Figure A.17b) but it is possible that if ABS samples were printed in the E3 orientation and tested at a slow speed, some striations might be observed. Finally, differences in resolution and distance from the samples might have resulted in no striations in the images captured by Bartolai et al., as can be seen when comparing the images captured in this research vis-a-vis those from their research. As previously mentioned, though, it is not possible to infer if one, all, or a combination of these differences can explain the lack of striations in Bartolai et al.'s work.

Similar to Bartolai et al., Schnittker et al. also used DIC to measure the tensile properties of plastic samples, specifically large scale tensile samples made of ABS reinforced with 20% (by weight) glass fibres [38]. For the dimensions of the samples see Figure A.18a. Figure A.18b shows the strain fields captured before the rupture of one of the samples and, as can be seen at the centre of the sample, the

(a) ± 45 -E3-01.

(b) ± 45 -E1-01.

(c) Full field strain images of strain in the loading direction for 100% infill density with ± 45 infill with ± 45 deg (left), $+30$ deg / -60 deg (middle), and 0 deg / 90 deg (right) tool-path orientations [37].

Figure A.17: Example of striations observed in this research compared to Bartolai et al. The strain fields in (a) and (b) are not superimposed on the video of the samples.

patterns are similar to those seen in Figures A.17a and A.17b. Unlike in the strain fields produced by Bartolai et al. (see Figure A.17c), which are very smooth, in Schnittker et al.'s images the strain fields are broken up by a spotted, striation pattern that is reminiscent of the images captured in this research, especially in the E2 and ϵ_{xx} images. Schnittker et al. don't comment on the patterns, though, since they are not unexpected in samples that are about to rupture.

(a) Dimensions of large tensile specimen with a thickness of 19 mm [38].

(b) DIC strain fields taken the instant before sample rupture [38].

Figure A.18

The images capture by Schnittker et al., though, are subject to the same comments made on those produced by Bartolai et al. The material, printer, sample, and testing conditions differ from those in this research therefore a direct comparison cannot be made. Ituarte et al. used multimaterial jetting to produce samples and tested them using DIC to measure their mechanical properties but produced smooth fields like Bartolai et al. [219]. There are other instances in the literature where DIC is used but either the material is much tougher than PLA [220, 221, 222, 223, 224], or the samples are made of lattice structures [225]. In both cases the direct comparison to the images captured in this research is not

possible.

A.3.2 Analysis of modified type I coupons in the E_3 orientation

The following testing was still based on layers because the striations are irregular and can change shape and size during testing, whereas the layers remain evenly spaced out and regular in their features. As previously explained, these coupons were shorter and thicker than the regular type I samples, the objective here being to see the effects of using a stiffer sample. Initial testing showed that the oscillations were still present in the modified coupons, confirming the observations that had been made before.

The samples were tested at 0.5 mm/min until rupture. The plots in Figure A.19 are strain-time graphs produced by the type I samples and highlighted are the regions of clear oscillations that they produced. These signals are from a set of 10 deviation labels on adjacent layers similar to those shown in Figure A.6. As can be seen, the oscillations are close together and appear to be more regular in amplitude, which is a consequence of the samples being stiffer.

Larger oscillations were also observed, which are present especially in Figure A.19c. The same signal analysis as in section A.3.1 was performed so Equation A.2, the two term sine equation, was fitted in MATLAB to the de-linearised signals, an example of which is shown in Figure A.20. Table A.5 shows the R^2 values obtained from the fit and, as with previous attempts, MATLAB was unable to fit a two term equation to the signal, opting instead to fit the larger oscillations rather than the small ones, which is what the R^2 value in Table A.5 refers to. Compared to Table A.4 the fit is much better and with a smaller deviation, although still not low enough to be considered satisfactory data. This indicates that the original theory was correct and oscillations are affected by the stiffness of the samples. The fact that the small oscillations are themselves oscillating lends credence to the idea of a modulated signal, where the carrier wave is the one that MATLAB found a fit for.

(a)

(b)

(c)

Figure A.19: Strain oscillations produced by modified type I coupons.

Figure A.20: Fitting Equation A.2 on the signal produced by modified type I coupons in MATLAB's CFT.

Table A.5: Quality of curve fitting for modified type I coupons.

Layer	R^2 value
1	0.6604
2	0.6907
3	0.6717
4	0.6074
5	0.7199
6	0.7541
7	0.6048
8	0.6332
9	0.7011
10	0.7670
Average	0.68103
s	0.056539073

APPENDIX B

DERIVATION OF THE SHEAR MODULUS FROM THE TORSION CONSTANT

The derivation starts with what is shown on the left of Figure B.1, a thin walled, cylindrical element of length L , radius r and thickness dr which will be considered to be part of a solid rod or wire. The end area of the cylinder is

$$dA = 2\pi r dr \quad (\text{B.1})$$

A horizontal force dF is applied to the top of the cylinder causing a torque

$$dT = r dF \quad (\text{B.2})$$

which causes a rotation of angle θ . The top surface of the cylinder moves a dis-

Figure B.1: Cylinder before torsion (left) and after torsion (right).

tance δx . The shear stress τ and strain γ are

$$\tau = \frac{1}{2\pi r} \frac{dF}{dr} \quad (\text{B.3a})$$

$$\gamma = \frac{\delta x}{L} = \frac{r\theta}{L} \quad (\text{B.3b})$$

which give the shear modulus G

$$G = \frac{\tau}{\gamma} = \frac{L}{2\pi r^2 \theta} \frac{dF}{dr} \quad (\text{B.4})$$

The top and bottom of Equation B.4 are multiplied by $\frac{r}{r}$ and using Equation B.2 gives

$$G = \frac{L}{2\pi r^3 \theta} \frac{rdF}{dr} = \frac{L}{2\pi r^3 \theta} \frac{dT}{dr} \quad (\text{B.5})$$

After rearranging for dT we have

$$dT = \frac{2\pi r^3 \theta G}{L} dr \quad (\text{B.6})$$

then integrating over the whole cylinder gives

$$\int_0^T dT = \frac{2\pi G\theta}{L} \int_0^r r^3 dr \quad (\text{B.7a})$$

$$T = \frac{2\pi G\theta r^4}{2L} \quad (\text{B.7b})$$

The torque can be written as $T = \kappa\theta$ where κ is the torsion constant. Plugging this into Equation B.7b results in an expression that gives the shear modulus in terms of the torsion constant,

$$\kappa = G \frac{\pi r^4}{2L} \quad (\text{B.8a})$$

$$G = \kappa \frac{2L}{\pi r^4} \quad (\text{B.8b})$$

APPENDIX C

COMPARISON OF CALCULATED AND EXPERIMENTAL SPRING CONSTANTS

Table C.1: Calculated and measured spring constants with the shear modulus realignment.

Spring	d (mm)	D (mm)	P (mm)	k_{exp} (N/m)	k_{calc} (N/m)	$\frac{(k_{calc}-k_{exp})}{k_{exp}} \times 100$
d3D20P10	3	20	10	362.728	397.841	8.8
d3D20P12_5	3	20	12.5	346.063	402.825	14.1
d3D20P15	3	20	15	319.742	406.006	21.2
d3D30P10	3	30	10	108.013	115.005	6.1
d3D30P12_5	3	30	12.5	109.365	116.576	6.2
d3D30P15	3	30	15	107.934	117.879	8.4
d3D40P10	3	40	10	40.855	47.738	14.4
d3D40P12_5	3	40	12.5	46.256	48.334	4.3
d3D40P15	3	40	15	42.036	48.863	14.0
d4D20P10	4	20	10	1122.010	1257.370	10.8
d4D20P12_5	4	20	12.5	1111.570	1273.130	12.7
d4D20P15	4	20	15	1141.920	1283.180	11.0
d4D30P10	4	30	10	350.335	363.472	3.6
d4D30P12_5	4	30	12.5	344.054	368.437	6.6
d4D30P15	4	30	15	353.480	372.555	5.1
d4D40P10	4	40	10	142.863	150.876	5.3
d4D40P12_5	4	40	12.5	154.380	152.759	-1.1
d4D40P15	4	40	15	148.643	154.432	3.7
d5D20P10	5	20	10	2778.804	3069.760	9.5
d5D20P12_5	5	20	12.5	2985.170	3108.220	4.0
d5D20P15	5	20	15	2778.804	3132.760	11.3
d5D30P10	5	30	10	892.075	887.383	-0.5
d5D30P12_5	5	30	12.5	873.143	899.504	2.9
d5D30P15	5	30	15	870.282	909.558	4.3
d5D40P10	5	40	10	343.148	368.350	6.8
d5D40P12_5	5	40	12.5	371.106	372.947	0.5
d5D40P15	5	40	15	337.879	377.032	10.4
					Average	7.6
					s	5.1

Table C.2: Calculated and measured spring constants without the shear modulus realignment.

Spring	d (mm)	D (mm)	P (mm)	k_{exp} (N/m)	k_{calc} (N/m)	$\frac{(k_{calc}-k_{exp})}{k_{exp}} \times 100$
d3D20P10	3	20	10	362.728	379.066	4.3
d3D20P12_5	3	20	12.5	346.063	376.459	8.1
d3D20P15	3	20	15	319.742	373.345	14.4
d3D30P10	3	30	10	108.013	113.094	4.5
d3D30P12_5	3	30	12.5	109.365	112.742	3.0
d3D30P15	3	30	15	107.934	112.316	3.9
d3D40P10	3	40	10	40.8554	47.8284	14.6
d3D40P12_5	3	40	12.5	46.25605	47.7439	3.1
d3D40P15	3	40	15	42.0355	47.6414	11.8
d4D20P10	4	20	10	1122.01	1198.03	6.3
d4D20P12_5	4	20	12.5	1111.57	1189.8	6.6
d4D20P15	4	20	15	1141.92	1179.95	3.2
d4D30P10	4	30	10	350.335	357.434	2.0
d4D30P12_5	4	30	12.5	344.054	356.321	3.4
d4D30P15	4	30	15	353.48	354.973	0.4
d4D40P10	4	40	10	142.863	151.161	5.5
d4D40P12_5	4	40	12.5	154.38	150.894	-2.3
d4D40P15	4	40	15	148.643	150.57	1.3
d5D20P10	5	20	10	2778.804	2924.89	5.0
d5D20P12_5	5	20	12.5	2985.17	2904.78	-2.8
d5D20P15	5	20	15	2778.804	2880.75	3.5
d5D30P10	5	30	10	892.075	872.643	-2.2
d5D30P12_5	5	30	12.5	873.143	869.923	-0.4
d5D30P15	5	30	15	870.282	866.634	-0.4
d5D40P10	5	40	10	343.148	369.046	7.0
d5D40P12_5	5	40	12.5	371.106	368.395	-0.7
d5D40P15	5	40	15	337.879	367.603	8.1
d7D20P15	7	20	15	25,009.50	24,361	2.6
Average						4.1
s						4.6

PUBLICATIONS

- E. Sacco and S. K. Moon, “Additive manufacturing for space: status and promises,” *The International Journal of Advanced Manufacturing Technology*, pp. 1–24, 2019
- E. Sacco, Z. Y. Chua, and S. K. Moon, “Comparison of elastic properties for different sample types fabricated with additive manufacturing,” in *Proceedings of the 3rd International Conference on Progress in Additive Manufacturing*, Singapore Centre for 3D Printing, 2018. (Pro-AM 2018)

BIBLIOGRAPHY

- [1] M. A. Saleh and A. E. Ragab, "Ti-6Al-4V helical spring manufacturing via SLM: effect of geometry on shear modulus," in *Proceedings of the International MultiConference of Engineers and Computer Scientists*, vol. 2, 2013.
- [2] L. He, H. Peng, M. Lin, R. Konjeti, F. Guimbretière, and J. E. Froehlich, "Ondulé: Designing and Controlling 3D Printable Springs," in *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, pp. 739–750, 2019.
- [3] S. V. Hoa, "Development of composite springs using 4D printing method," *Composite Structures*, vol. 210, pp. 869 – 876, 2019.
- [4] N. Werkheiser, "In-space manufacturing: Pioneering a sustainable path to mars," 2015. Presented at NASA Marshall Space Flight Center; Huntsville, AL, United States. NASA Report/Patent Number: M15-4866.
- [5] K. Rainey, "Building the future: Space station crew 3-d prints first student-designed tool in space," 2016. Accessed: 2016-08-01.

- [6] N. Werkheiser and J. Edmunson, "3D Printing in Zero-G ISS Technology Demonstration," 2014. Presented at 3rd Annual International Space Station Research and Development Conference, Chicago, IL, USA. NASA document ID: 20140011720.
- [7] R. P. Hoyt, J. I. Cushing, J. T. Slostad, G. Jimmerson, T. Moser, G. Kirkos, M. L. Jaster, and N. R. Voronka, "Spiderfab: An architecture for self-fabricating space systems," in *AIAA Space 2013 Conference and Exposition*, p. 5509, 2013.
- [8] T. McGuire, M. Hirsch, M. Parsons, S. Leake, and J. Straub, "Design for an in-space 3d printer," in *Sensors and Systems for Space Applications IX*, vol. 9838, p. 98380V, International Society for Optics and Photonics, 2016.
- [9] W. M. Marshall, M. Zemba, C. Shemelya, R. Wicker, D. Espalin, E. MacDonald, C. Keif, and A. Kwas, "Using additive manufacturing to print a cubesat propulsion system," in *AIAA/SAE/ASEE Joint Propulsion Conference*, NASA, 2015.
- [10] P. Gradl, W. Brandsmeier, M. Calvert, S. Greene, D. O'Neal, C. Protz, J. Richard, and K. Morgan, "Additive manufacturing overview: Propulsion applications, design for and lessons learned," 2017. NASA Report/Patent Number: M17-6434.
- [11] S. Masugana, "Entrepreneur seeks to boldly go where no one has gone before: 3-d printing nearly an entire rocket," 2018. Accessed: 2018-11-25.
- [12] J. L. Finseth, "Rover nuclear rocket engine program: Overview of rover engine tests. Final Report," tech. rep., Sverdrup Technology, Inc., Huntsville, AL (United States), 1991.
- [13] EOS, "Airbus Defence and Space - Additive Manufacturing process by EOS optimizes Satellite Technology." www.eos.info, 2015.

- [14] ESA, "3D-printed deployment mechanism." https://www.esa.int/spaceinimages/Images/2014/10/3D-printed_deployment_mechanism, 2014. Accessed on 2018-04-07.
- [15] K. R. Gagne, D. L. Hitt, and M. R. McDevitt, "Development of an additively manufactured microthruster for nanosatellite applications," in *54th AIAA aerospace sciences meeting*, p. 0963, 2016.
- [16] Utah State University, *Design and Characterization of a 3D-Printed Attitude Control Thruster for an Interplanetary 6U CubeSat*, 2016.
- [17] M. Fiske and J. Edmunson, "Additive Construction with Mobile Emplacement (ACME) 3D Printing Structures with In-Situ Resources," 2017. Presented at the University of Alabama, Huntsville, AL, USA. NASA Report/Patent Number: MSFC-E-DAA-TN48929.
- [18] A. Meurisse, M. Sperl, and A. Makaya, "3D printing of a model building block for a lunar base outer shell," *Materials Science and Engineering: A*, vol. 413-414, pp. 533–537, dec 2005.
- [19] G. Cesaretti, E. Dini, X. D. Kestelier, V. Colla, and L. Pambaguian, "Building components for an outpost on the lunar soil by means of a novel 3d printing technology," *Acta Astronautica*, vol. 93, pp. 430 – 450, 2014.
- [20] Mechanical Engineering Community, "Types of springs." <https://mechanical-engg.com/gallery/image/2751-types-of-springs/>. Accessed on 2019-01-20.
- [21] S. Arestie, E. G. Lightsey, and B. Hudson, "Development of a modular, cold gas propulsion system for small satellite applications," *Journal of Small Satellites*, vol. 1, no. 2, pp. 63–74, 2012.

- [22] Access Spring, "Non-Linear Springs."
<https://www.accessspring.com/non-linear-springs.html>. Accessed on 2019-05-15.
- [23] M. Sakovsky, S. Pellegrino, and J. Costantine, "Rapid Design of Deployable Antennas for CubeSats: A tool to help designers compare and select antenna topologies.," *IEEE Antennas and Propagation Magazine*, vol. 59, no. 2, pp. 50–58, 2017.
- [24] G. Olson, S. Pellegrino, J. Banik, and J. Costantine, "Deployable helical antennas for CubeSats," in *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, p. 1671, 2013.
- [25] ASTM International, "ASTM52921-13, Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies," 2013.
- [26] O. A. Mohamed, S. H. Masood, and J. L. Bhowmik, "Optimization of fused deposition modeling process parameters: a review of current research and future prospects," *Advances in Manufacturing*, vol. 3, no. 1, pp. 42–53, 2015.
- [27] O. S. Es-Said, J. Foyos, R. Noorani, M. Mendelson, R. Marloth, and B. A. Pregger, "Effect of layer orientation on mechanical properties of rapid prototyped samples," *Materials and Manufacturing Processes*, vol. 15, no. 1, pp. 107–122, 2000.
- [28] B. Rankouhi, S. Javadpour, F. Delfanian, and T. Letcher, "Failure analysis and mechanical characterization of 3d printed abs with respect to layer thickness and orientation," *Journal of Failure Analysis and Prevention*, vol. 16, no. 3, pp. 467–481, 2016.
- [29] ASTM International, "ASTM D5379/D5379M - 12 Standard Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method," 2012.

- [30] ASTM International, "ASTM D638 - 14 standard test methods for tensile properties of plastics," 2014.
- [31] T. Letcher and M. Waytashek, "Material property testing of 3D-printed specimen in PLA on an entry-level 3D printer," in *ASME 2014 international mechanical engineering congress and exposition*, American Society of Mechanical Engineers Digital Collection, 2014.
- [32] J. Prusa. <https://www.prusa3d.com/>.
- [33] R. W. Landgraf and R. C. Francis, "Material and processing effects on fatigue performance of leaf springs," *SAE Transactions*, pp. 1485–1494, 1979.
- [34] M. Berzal, C. Barajas, D. del Mazo, J. Caja, and P. Maresca, "Simple filling patterns to model mechanical behaviour of FDM's test pieces under torsion," *Procedia Manufacturing*, vol. 13, pp. 786 – 793, 2017. Manufacturing Engineering Society International Conference 2017, MESIC 2017, 28-30 June 2017, Vigo (Pontevedra), Spain.
- [35] Newcomb Spring Corp., "Rectangular wire compression springs." <https://www.newcombspring.com/resources/compression-springs-rectangular-wire>. Date accessed: 2018-12-10.
- [36] S. A. Nama, "Modeling and analysis of a helical machined springs," *Iraqi journal of mechanical and material engineering*, vol. 15, no. 2, pp. 152–163, 2015.
- [37] J. Bartolai, T. W. Simpson, and R. Xie, "Predicting strength of additively manufactured thermoplastic polymer parts produced using material extrusion," *Rapid Prototyping Journal*, vol. 24, no. 2, pp. 321–332, 2018.
- [38] K. Schnittker, E. Arrieta, X. Jimenez, D. Espalin, R. B. Wicker, and D. A. Roberson, "Integrating digital image correlation in mechanical testing for

the materials characterization of big area additive manufacturing feedstock," *Additive Manufacturing*, vol. 26, pp. 129–137, 2019.

- [39] D. L. Skran, "Battle of the collossi: Sls vs falcon heavy," 2015. Accessed: 2016-03-16.
- [40] Made In Space, "Additive manufacturing facility," 2018. Accessed: 2018-05-31.
- [41] T. J. Prater, Q. A. Bean, R. D. Beshears, T. D. Rolin, N. J. Werkheiser, E. A. Ordonez, R. M. Ryan, and F. E. Ledbetter III, "Summary report on phase I results from the 3D printing in zero g technology demonstration mission, volume I," tech. rep., NASA Marshall Space Flight Center, 2016.
- [42] D. Thomas, M. P. Snyder, M. Napoli, E. R. Joyce, P. Shestopole, and T. Letcher, "Effect of Acrylonitrile Butadiene Styrene Melt Extrusion Additive Manufacturing on Mechanical Performance in Reduced Gravity," in *AIAA SPACE and Astronautics Forum and Exposition*, p. 5278, 2017.
- [43] N. Werkheiser, "Nasa additive manufacturing overview," 2017. Presented at Military Additive Manufacturing Summit 2017, Tampa, FL, USA. NASA Report/Patent Number: MSFC-E-DAA-TN38811.
- [44] E. Ordonez, J. Edmunson, M. Fiske, E. Christiansen, J. Miller, B. A. Davis, J. Read, M. Johnston, and J. Fikes, "Hypervelocity impact testing of materials for additive construction: Applications on earth, the moon, and mars," *Procedia Engineering*, vol. 204, pp. 390–396, 2017.
- [45] E. Atzeni, L. Iuliano, P. Minetola, and A. Salmi, "Redesign and cost estimation of rapid manufactured plastic parts," *Rapid Prototyping Journal*, 2010.

- [46] H. Bikas, P. Stavropoulos, and G. Chryssolouris, "Additive manufacturing methods and modelling approaches: a critical review," *International Journal of Advanced Manufacturing Technology*, vol. 83, 2016.
- [47] H. Kodama, "Automatic method for fabricating a three-dimensional plastic model with photo-hardening polymer," *Review of scientific instruments*, vol. 52, no. 11, pp. 1770–1773, 1981.
- [48] A. Khorasani, I. Gibson, M. Goldberg, and G. Littlefair, "On the role of different annealing heat treatments on mechanical properties and microstructure of selective laser melted and conventional wrought ti-6al-4v," *Rapid Prototyping Journal*, vol. 23, no. 2, pp. 295–304, 2017.
- [49] S. L. Sing, W. Y. Yeong, F. E. Wiria, B. Y. Tay, Z. Zhao, L. Zhao, Z. Tian, and S. Yang, "Direct selective laser sintering and melting of ceramics: a review," *Rapid Prototyping Journal*, vol. 23, no. 3, pp. 611–623, 2017.
- [50] X. Wang, M. Jiang, Z. Zhou, J. Gou, and D. Hui, "3D printing of polymer matrix composites: A review and prospective," *Composites Part B: Engineering*, vol. 110, pp. 442 – 458, 2017.
- [51] C. Bang Pham, K. Fai Leong, T. Chiun Lim, and K. Sin Chian, "Rapid freeze prototyping technique in bio-plotters for tissue scaffold fabrication," *Rapid Prototyping Journal*, vol. 14, no. 4, pp. 246–253, 2008.
- [52] D. M. Atyam and N. H. Nguyen, "Designing and testing liquid engines for additive manufacturing," in *51st AIAA/SAE/ASEE Joint Propulsion Conference*, p. 4051, 2015.
- [53] M. B. Koelbl, "Technology development and trends: Liquid rocket propulsion," 27-29 July 2015. Presented at 51st AIAA/SAE/ASEE Joint Propulsion Conference (AIAA Propulsion and Energy), Orlando, FL, USA. NASA Report/Patent Number: M15-4789.

- [54] T. Ghidini, "An overview of current am activities at the european space agency," 2013. Presented at the 3D Printing & Additive Manufacturing - Industrial Applications Global Summit 2013, London, UK.
- [55] A. K. Misra, J. E. Grady, and R. Carter, "Additive manufacturing of aerospace propulsion components," 01 October 2015. Presented at Additive Manufacturing for Small Manufacturers, Pittsburgh, PA, USA. NASA Report/Patent Number: GRC-E-DAA-TN27123.
- [56] M. C. Halbig and M. Singh, "Additive manufacturing of sic-based ceramics and ceramic matrix composites," 14 June 2015. Presented at 11th International Conference on Ceramic Materials and Components for Energy and Environmental Applications in Vancouver, BC, Canada. NASA Report/Patent Number: GRC-E-DAA-TN24157.
- [57] W. E. Frazier, "Metal additive manufacturing: A review," *Journal of Materials Engineering and Performance*, vol. 23, pp. 1917–1928, Jun 2014.
- [58] V. K. Ball, L. B. Roberson, G. W. O'Connor, S. Trigwell, S. Bose, and A. Bandyopadhyay, "First demonstration on direct laser fabrication of lunar regolith parts," *Rapid Prototyping Journal*, vol. 18, no. 6, pp. 451–457, 2012.
- [59] N. R. Council, *3D Printing in Space*. Washington, DC: The National Academies Press, 2014.
- [60] G. P. Merrill, *A treatise on rocks, rock-weathering and soils*. Macmillan, 1897.
- [61] M. Mobrem and D. S. Adams, "Deployment analysis of the lenticular jointed antennas onboard the mars express spacecraft," *Journal of Spacecraft and Rockets*, vol. 46, no. 2, pp. 394–402, 2009.
- [62] Ultimaker, "Ultimaker Tough PLA." Accessed: 2020-01-06.

- [63] E. R. Ponslet and W. O. Miller, "Coil springs with constrained-layer viscoelastic damping for passive isolation," in *Smart Structures and Materials 1998: Passive Damping and Isolation* (L. P. Davis, ed.), vol. 3327, pp. 432 – 443, International Society for Optics and Photonics, SPIE, 1998.
- [64] T. Yokota, T. Taguchi, and M. Gen, "A solution method for optimal weight design problem of helical spring using genetic algorithms," *Computers & Industrial Engineering*, vol. 33, no. 1, pp. 71 – 76, 1997. Proceedings of the 21st International Conference on Computers and Industrial Engineering.
- [65] J. C. Hendry and C. Probert, "Carbon fibre coil springs," *Materials & Design*, vol. 7, no. 6, pp. 330 – 337, 1986.
- [66] G. Mastinu, M. Gobbi, and C. Miano, *Optimal design of complex mechanical systems: with applications to vehicle engineering*. Springer Science & Business Media, 2007.
- [67] E. G. Merriam, J. E. Jones, and L. L. Howell, "Design of 3D-printed titanium compliant mechanisms," 2014.
- [68] Y. Zhou, W. M. Huang, S. F. Kang, X. L. Wu, H. B. Lu, J. Fu, and H. Cui, "From 3D to 4D printing: approaches and typical applications," *Journal of Mechanical Science and Technology*, vol. 29, no. 10, pp. 4281–4288, 2015.
- [69] A. Garaigordobil, R. Ansola, E. Veguería, and I. Fernandez, "Overhang constraint for topology optimization of self-supported compliant mechanisms considering additive manufacturing," *Computer-Aided Design*, vol. 109, pp. 33 – 48, 2019.
- [70] C. R. de Lima and G. H. Paulino, "Auxetic structure design using compliant mechanisms: a topology optimization approach with polygonal finite elements," *Advances in Engineering Software*, vol. 129, pp. 69 – 80, 2019.

- [71] R. Mutlu, G. Alici, M. in het Panhuis, and G. Spinks, "Effect of flexure hinge type on a 3D printed fully compliant prosthetic finger," in *2015 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, pp. 790–795, IEEE, 2015.
- [72] N. Meisel, A. Gaynor, C. Williams, and J. Guest, "Multiple-material topology optimization of compliant mechanisms created via polyjet 3d printing," in *24th Annual international solid freeform fabrication symposium an additive manufacturing conference*, p. 28, 2013.
- [73] Z. Pan, D. Ding, B. Wu, D. Cuiuri, H. Li, and J. Norrish, "Arc welding processes for additive manufacturing: A review," in *Transactions on Intelligent Welding Manufacturing* (S. Chen, Y. Zhang, and Z. Feng, eds.), (Singapore), pp. 3–24, Springer Singapore, 2018.
- [74] Y. Kok, X. P. Tan, P. Wang, M. L. S. Nai, N. H. Loh, E. Liu, and S. B. Tor, "Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: A critical review," *Materials & Design*, vol. 139, pp. 565 – 586, feb 2018.
- [75] P. Parandoush and D. Lin, "A review on additive manufacturing of polymer-fiber composites," *Composite Structures*, vol. 182, pp. 36 – 53, dec 2017.
- [76] B. Schoinochoritis, D. Chantzis, and K. Salonitis, "Simulation of metallic powder bed additive manufacturing processes with the finite element method: A critical review," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 231, pp. 96–117, aug 2017.
- [77] G. Costabile, M. Fera, F. Fruggiero, A. Lambiase, and D. Pham, "Cost models of additive manufacturing: A literature review," *International*

Journal of Industrial Engineering Computations, vol. 8, no. 2, pp. 263–283, 2017.

- [78] A. Busachi, J. Erkoyuncu, P. Colegrove, F. Martina, C. Watts, and R. Drake, “A review of additive manufacturing technology and cost estimation techniques for the defence sector,” *CIRP Journal of Manufacturing Science and Technology*, vol. 19, pp. 117 – 128, nov 2017.
- [79] J. R. Dennison, “An overview of the dynamic interplay between the space environment and spacecraft materials,” 2015. Laboratory of Spacecraft Environment Interaction Engineering.
- [80] N. Werkheiser, “Overview of nasa initiatives in 3d printing and additive manufacturing,” 2014. Presented at 2014 DoD Maintenance Symposium, Birmingham, AL, USA. NASA Report/Patent Number: M15-4252.
- [81] D. C. Brown, “Nasa to launch new science mission to asteroid in 2016,” 2011. Accessed: 2015-11-23.
- [82] GlobalCom Satellite Phones, “The cost of building and launching a satellite,” 2015. Accessed: 2016-06-15.
- [83] T. K. Imken, T. H. Stevenson, and E. G. Lightsey, “Design and testing of a cold gas thruster for an interplanetary cubesat mission,” *Journal of Small Satellites*, vol. 4, no. 2, pp. 371–386, 2015.
- [84] M. Molitch-Hou, “3d printing has its place in martian settlements, according to nasa,” 2016. Accessed: 2017-09-01.
- [85] J. Y. Wong and A. C. Pfahnl, “3D Printing of Surgical Instruments for Long-Duration Space Missions,” *Aviation, Space, and Environmental Medicine*, vol. 85, pp. 758–763, jul 2014.
- [86] Made In Space, “3d printing in zero gravity experiment,” 2018. Accessed: 2016-05-10.

- [87] ASTM International, "ASTM D638-14 Standard Test Method for Tensile Properties of Plastics," 2014.
- [88] ASTM International, "ASTM D790 - 15e2 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials," 2015.
- [89] ASTM International, "ASTM D695 - 15 Standard Test Method for Compressive Properties of Rigid Plastics," 2015.
- [90] Q. A. Bean, K. G. Cooper, J. E. Edmunson, M. M. Johnston, and M. J. Werkheiser, "International space station (iss) 3d printer performance and material characterization methodology," 2015. Presented at 62nd JANNAP Propulsion Meeting, Nashville, TN, USA. NASA Report/Patent Number: M15-4563.
- [91] R. G. Clinton and K. Morgan, "Additive manufacturing at nasa marshall space flight center: In-space and for-space initiatives," 2015. Presented at the Additive Manufacturing for Defense and Government Symposium in Huntsville, AL, USA. NASA Report/Patent Number: M16-5001.
- [92] A. Boyle, "Tethers unlimited delivers 3-d printer and recycler combo to nasa for space station," 2018. Accessed: 2018-10-21.
- [93] SBIR and NASA, "Positrusion filament recycling system for iss," 2014. Accessed: 2017-08-17.
- [94] T. U. Inc., "Positrusion Filament Recycler, Superior Quality Filament For 3D Printers." Brochure, 2015.
- [95] A. Boyle, "Tethers Unlimited wins NASA grant to work on future FabLab for 3-D printing in space." www.geekwire.com, 2017.
- [96] Tethers Unlimited, "Spiderfab," 2014. Accessed: 2018-03-06.

- [97] S. Patane, E. R. Joyce, M. P. Snyder, and P. Shestople, "Archinaut: In-space manufacturing and assembly for next-generation space habitats," in *AIAA SPACE and Astronautics Forum and Exposition*, p. 5227, 2017.
- [98] R. G. Clinton, "Additive manufacturing for human space exploration," 2018. Presented at the Additive Manufacturing for Aerospace and Space conference, Munich, Germany. NASA Report/Patent Number: MSFC-E-DAA-TN52182.
- [99] J. P. Kruth, M. C. Leu, and T. Nakagawa, "Progress in Additive Manufacturing and Rapid Prototyping," *{CIRP} Annals - Manufacturing Technology*, vol. 47, no. 2, pp. 525 – 540, 1998.
- [100] G. Konecny, "Small satellites - A tool for Earth observation?," in *XXth ISPRS Congress, Commission*, vol. 4, pp. 12–23, 2004.
- [101] SaRC, "Satellite Research Centre (SaRC) factsheet," 2016.
- [102] E. Mahoney, "First cubesat built by an elementary school deployed into space," May 2016. Accessed: 2016-12-03.
- [103] amsat-uk, "Ossi-1 amateur radio cubesat launched," April 2013. Accessed: 2018-02-26.
- [104] J. Tylka, "Evaluation of additively manufactured metals for use on oxygen systems," 2016. Presented at Additive Manufacturing for Propulsion Applications, Huntsville, AL, USA. NASA Report/Patent Number: JSC-CN-37294.
- [105] R. G. Clinton, "Overview of additive manufacturing initiatives at nasa marshall space flight center - in space and rocket engines," Feb. 22 2017. Presented at the Additive Manufacturing for Aerospace, Defence & Space Conference, London, UK. NASA Report/Patent Number: MSFC-E-DAA-TN38745.

- [106] R. Carter, S. Draper, I. Locci, B. Lerch, D. Ellis, P. Senick, M. Meyer, J. Free, K. Cooper, and Z. Jones, "Materials characterization of additively manufactured components for rocket propulsion," in *66th International Astronautical Congress*, 2015.
- [107] A. Hinojos, J. Mireles, A. Reichardt, P. Frigola, P. Hosemann, L. E. Murr, and R. B. Wicker, "Joining of inconel 718 and 316 stainless steel using electron beam melting additive manufacturing technology," *Materials & Design*, vol. 94, pp. 17 – 27, 2016.
- [108] R. W. Carter, "Grc metal additive manufacturing," July 2015. Presented in Cleveland, OH, USA. NASA Report/Patent Number: GRC-E-DAA-TN25102.
- [109] D. Susan, L. Brad, R. Richard, M. Richard, L. Ivan, and G. Anita, *Materials Characterization of Electron Beam Melted Ti-6Al-4V*, ch. 242, pp. 1433–1440. Wiley-Blackwell, 2016.
- [110] D. L. Ellis, "Grcop-84: A high-temperature copper alloy for high-heat-flux applications," tech. rep., NASA Glenn Research Center, 2005. NASA Report/Patent Number: NASA/TM-2005-213566, E-15011.
- [111] D. Greitemeier, F. Palm, F. Syassen, and T. Melz, "Fatigue performance of additive manufactured tial6v4 using electron and laser beam melting," *International Journal of Fatigue*, vol. 94, pp. 211 – 217, 2017. Fatigue and Fracture Behavior of Additive Manufactured Parts.
- [112] R. Minneci, C. Rawn, J. Bunn, J. Floyd, and Z. Jones, "Preliminary residual stress mapping of grcop-84 fabricated by slm," 2017. Presented at 2017 Joint Nanoscience and Neutron Scattering User Meeting, Oak Ridge, TN, USA. NASA Report/Patent Number: M17-6172.
- [113] J. Vickers, "Low cost upper stage-class propulsion (lcusp)," techreport, NASA, 2015.

- [114] D. Ding, Z. Pan, D. Cuiuri, and H. Li, "Wire-feed additive manufacturing of metal components: technologies, developments and future interests," *The International Journal of Advanced Manufacturing Technology*, vol. 81, pp. 465–481, Oct 2015.
- [115] C. K. Sudbrack, M. M. Kirka, R. R. Dehoff, R. W. Carter, S. L. Semiatin, and T. P. Gabb, "Nasa/ornl/afri project work on ebm lshr: Additive manufacturing of high-temperature gamma-prime strengthened ni-based superalloys," tech. rep., NASA Glenn Research Center, jun 2016.
- [116] D. Mosher, "Defectors from SpaceX, Blue Origin, and Tesla are developing a remarkable technology called 'Stargate' to help colonize other planets," 2018. Accessed: 2018-11-25.
- [117] Relativity Space, "Terran 1," 2018. Accessed: 2018-11-25.
- [118] S. M. George, "Atomic layer deposition: an overview," *Chemical reviews*, vol. 110, no. 1, pp. 111–131, 2009.
- [119] O. Mireles, C. Garcia, and Z. Jones, "Potential for additive manufacture in nuclear thermal propulsion (ntp)," 24 February 2016. Presented at Nuclear and Emerging Technologies for Space, Huntsville, AL, USA. NASA Report/Patent Number: M16-5074.
- [120] Community Research and Development Information Service (CORDIS), "Amaze report summary," 2018.
- [121] N. Adkins, N. Lavery, K. Cabannes, F. Montredon, and K. Schmidtke, "Apod 15 – invar space parts," 2017. Presented at the AMAZE Project Technology Forum, Coventry, UK.
- [122] F. Montredon, "Sun sensor and antenna support," 2017. Presented at the AMAZE Project Technology Forum, Coventry, UK.

- [123] SpaceX, "Spacex launches 3d-printed part to space, creates printed engine chamber," 2014. Accessed: 2016-02-02.
- [124] Airbus Defence and Space, "Airbus Defence and Space optimising components using 3D printing for new Eurostar E3000 satellite platforms." www.airbusdefenceandspace.com, 2015.
- [125] M. E. Orme, M. Gschweidl, M. Ferrari, R. Vernon, I. J. Madera, R. Yancey, and F. Mouriaux, "Additive manufacturing of lightweight, optimized, metallic components suitable for space flight," *Journal of Spacecraft and Rockets*, vol. 54, no. 5, pp. 1050–1059, 2017.
- [126] M. Orme, I. Madera, M. Gschweidl, and M. Ferrari, "Topology optimization for additive manufacturing as an enabler for light weight flight hardware," *Designs*, vol. 2, no. 4, p. 51, 2018.
- [127] M. E. Orme, M. Gschweidl, R. Vernon, M. Ferrari, I. J. Madera, R. Yancey, and F. Mouriaux, "A demonstration of additive manufacturing as an enabling technology for rapid satellite design and fabrication," in *International SAMPE Technical Conference, Long Beach, CA, May*, pp. 23–26, 2016.
- [128] M. E. Orme, M. Gschweidl, M. Ferrari, R. Vernon, I. J. Madera, R. Yancey, and F. Mouriaux, "Additive manufacturing of lightweight, optimized, metallic components suitable for space flight," *Journal of Spacecraft and Rockets*, vol. 54, no. 5, pp. 1050–1059, 2017.
- [129] A. Lin, "Engines - seds ucs." <https://www.sedsucsd.org/projects/engines/>, 2018. Accessed: 2017-09-23.
- [130] J. J. Catina and K. Castonguay, *Use of Additive Manufacturing to Model and Develop Advanced Liquid Propulsion Designs*. Propulsion and Energy Forum, American Institute of Aeronautics and Astronautics, 2015.

- [131] L. Kuentz, A. Salem, M. Singh, M. C. Halbig, and J. A. Salem, "Additive manufacturing and characterization of polylactic acid (pla) composites containing metal reinforcements," 2016. Presented at the 40th International Conference and Expo on Advanced Ceramics and Composites, Daytona Beach, FL. USA. NASA Report/Patent Number: GRC-E-DAA-TN29146.
- [132] A. Mehrparvar, D. Pignatelli, J. Carnahan, R. Munakat, W. Lan, A. Toorian, A. Hutputanasin, and S. Lee, "Cubesat design specification rev 13," *The CubeSat Program, Cal Poly San Luis Obispo, US*, 2014.
- [133] E. A. Slejko, E. Longato, S. Seriani, P. Gallina, V. Lughi, F. Bozzolan, A. Cuttin, M. Fragiaco, and A. Gregorio, "Bricsat: A new satellite structure concept," in *The 4S Symposium*, 2018.
- [134] C. Wyman, "Stratasys 3d printing keeps nasa satellite on time and on budget – fdm strong enough for space," 2015. Accessed: 2015-12-12.
- [135] R. P. Mueller, I. I. Townsend, G. J. Tamasy, C. J. Evers, L. J. Sibille, J. E. Edmunson, M. R. Fiske, J. C. Fikes, and M. Case, "Additive construction with mobile emplacement (acme)/automated construction of expeditionary structures (aces) materials delivery system (mds)," 2018. Presented at the ASCE Earth and Space Conference 2018, Cleveland, OH, USA. NASA Report/Patent Number: KSC-E-DAA-TN48594.
- [136] B. Khoshnevis, D. Hwang, K.-T. Yao, and Z. Yeh, "Mega-scale fabrication by contour crafting," *International Journal of Industrial and Systems Engineering*, vol. 1, no. 3, pp. 301–320, 2006.
- [137] J. Edmunson, M. Fiske, R. Mueller, H. Alkhateb, A. Alhnoukh, H. Morris, V. Townsend, J. Fikes, and M. Johnston, "Additive construction with mobile emplacement: Multifaceted planetary construction materials development," 2018. Presented at the American Society of Civil Engineers

- (ASCE) Earth and Space 2018 Conference, Cleveland, OH, USA. NASA Report/Patent Number: MSFC-E-DAA-TN54927.
- [138] M. J. Werkheiser, M. Fiske, J. Edmunson, and B. Khoshnevis, "On the development of additive construction technologies for application to development of lunar/martian surface structures using in-situ materials," in *AIAA SPACE 2015 Conference and Exposition*, p. 4451, 2015.
 - [139] V. Colla and E. Dini, "Large scale 3D printing: From deep sea to the moon," *Low-Cost 3D Printing, for Science, Education & Sustainable Development*, pp. 127–132, 2013.
 - [140] A. Goulas, J. G. Binner, D. S. Engstrøm, R. A. Harris, and R. J. Friel, "Mechanical behaviour of additively manufactured lunar regolith simulant components," *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, vol. 0, no. 0, p. 1464420718777932, 0.
 - [141] A. E. Jakus, K. D. Koube, N. R. Geisendorfer, and R. N. Shah, "Robust and elastic lunar and martian structures from 3d-printed regolith inks," *Scientific reports*, vol. 7, p. 44931, 2017.
 - [142] A. Boley and L. Fladeland, "The Sustainable Development of Space: on the possibility of debris stream formation during asteroid mining operations," in *AAS/Division for Planetary Sciences Meeting Abstracts #50*, vol. 50 of *AAS/Division for Planetary Sciences Meeting Abstracts*, p. 119.03, Oct. 2018.
 - [143] K. Lietaert, L. Thijs, B. Neirinck, T. Lapauw, B. Morrison, C. Lewicki, and J. V. Vaerenbergh, "Meteorite as raw material for direct metal printing: A proof of concept study," *Acta Astronautica*, vol. 143, pp. 76 – 81, 2018.
 - [144] C. Kief, "3d printing the complete cubesat," 2015. NASA Report/Patent Number: NASA FS-2015-03-32-ARC.

- [145] D. Ahn, J.-H. Kweon, J. Choi, and S. Lee, "Quantification of surface roughness of parts processed by laminated object manufacturing," *Journal of Materials Processing Technology*, vol. 212, no. 2, pp. 339–346, 2012.
- [146] A. Mostafaei, E. L. Stevens, E. T. Hughes, S. D. Biery, C. Hilla, and M. Chmielus, "Powder bed binder jet printed alloy 625: Densification, microstructure and mechanical properties," *Materials & Design*, vol. 108, pp. 126–135, 2016.
- [147] *A Fully Non-Metallic Gas Turbine Engine Enabled by Additive Manufacturing*, 10 2015. Presented at 22nd International Symposium on Air Breathing Engines (ISABE 2015), Phoenix, AZ, USA. NASA Report/Patent Number: ISABE-2015-20168, GRC-E-DAA-TN24606.
- [148] C. Dordlofva, O. Borgue, M. Panarotto, and O. Isaksson, "Drivers and Guidelines in Design for Qualification Using Additive Manufacturing in Space Applications," *Proceedings of the Design Society: International Conference on Engineering Design*, vol. 1, no. 1, p. 729–738, 2019.
- [149] O. Borgue, M. Panarotto, and O. Isaksson, "Impact on design when introducing additive manufacturing in space applications," in *DS 92: Proceedings of the DESIGN 2018 15th International Design Conference*, pp. 997–1008, 2018.
- [150] *Function modelling and constraints replacement to support design for additive manufacturing of satellite components*, Aug 2018.
- [151] O. Borgue, J. Müller, A. Leicht, M. Panarotto, and O. Isaksson, "Constraint Replacement-Based Design for Additive Manufacturing of Satellite Components: Ensuring Design Manufacturability through Tailored Test Artefacts," *Aerospace*, vol. 6, no. 11, p. 124, 2019.

- [152] F. G. Bachmann, W. Hoving, Y. Lu, and K. Washio, eds., *Rapid manufacturing of lattice structures with selective laser melting*, vol. 6107, SPIE, Feb. 2006.
- [153] N. Gupta, C. Weber, and S. Newsome, "Additive manufacturing: status and opportunities," *Science and Technology Policy Institute, Washington*, 2012.
- [154] ASTM International, "ASTM F3122-14, Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes," 2014.
- [155] ASTM International, "ASTM A370-16, Standard Test Methods and Definitions for Mechanical Testing of Steel Products," 2016.
- [156] ASTM International, "ASTM B565-04(2015), Standard Test Method for Shear Testing of Aluminum and Aluminum-Alloy Rivets and Cold-Heading Wire and Rods," 2015.
- [157] ASTM International, "ASTM E132-04(2010), Standard Test Method for Poisson's Ratio at Room Temperature," 2010.
- [158] ASTM International, "ASTM E290-14, Standard Test Methods for Bend Testing of Material for Ductility," 2014.
- [159] America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC), "Standardization Roadmap for Additive Manufacturing 2.0," tech. rep., ANSI, June 2018. Accessed: 2020-02-02.
- [160] ANSI, "America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC)." Accessed: 2020-02-02.
- [161] Marshall Space Flight Center, "MSFC-STD-3716 - standard for additively manufactured spaceflight hardware by laser powder bed fusion in metals," standard, NASA, October 2017.

- [162] Marshall Space Flight Center, "MSFC-SPEC-3717 - specification for control and qualification of laser powder bed fusion metallurgical processes," standard, NASA, October 2017.
- [163] K. Morgan, "Additive manufacturing overview: Propulsion applications, design for and lessons learned," 2017. Presented at AIAA Propulsion and Energy Forum 2017, Atlanta, GA, USA. NASA Report/Patent Number: MSFC-E-DAA-TN44554.
- [164] R. Ranjan, S. K. Chou, F. Riaz, and K. Karthikeyan, "Cold gas micro propulsion development for satellite application," *Energy Procedia*, vol. 143, pp. 754 – 761, 2017. Leveraging Energy Technologies and Policy Options for Low Carbon Cities.
- [165] P. Muri, O. Challa, and J. McNair, "Enhancing small satellite communication through effective antenna system design," in *2010-MILCOM 2010 MILITARY COMMUNICATIONS CONFERENCE*, pp. 347–352, IEEE, 2010.
- [166] S.-H. Ahn, M. Montero, D. Odell, S. Roundy, and P. K. Wright, "Anisotropic material properties of fused deposition modeling ABS," *Rapid prototyping journal*, vol. 8, no. 4, pp. 248–257, 2002.
- [167] C. Ziemian, M. Sharma, and S. Ziemian, "Anisotropic mechanical properties of ABS parts fabricated by fused deposition modelling," *Mechanical engineering*, vol. 23, 2012.
- [168] S. Hassanifard and S. M. Hashemi, "On the strain-life fatigue parameters of additive manufactured plastic materials through fused filament fabrication process," *Additive Manufacturing*, vol. 32, p. 100973, 2020.
- [169] Stratasys, "Stratasys Direct Manufacturing Builds the First 3D Printed Parts to Function on the Exterior of a Satellite." www.stratasysdirect.com, 2017.

- [170] D. Popescu, A. Zapciu, C. Amza, F. Baci, and R. Marinescu, "FDM process parameters influence over the mechanical properties of polymer specimens: A review," *Polymer Testing*, vol. 69, pp. 157–166, 2018.
- [171] O. H. Ezech and L. Susmel, "Fatigue behaviour of additively manufactured polylactide (PLA)," *Procedia Structural Integrity*, vol. 13, pp. 728–734, 2018.
- [172] A. Rodríguez-Panes, J. Claver, and A. Camacho, "The influence of manufacturing parameters on the mechanical behaviour of pla and abs pieces manufactured by fdm: a comparative analysis," *Materials*, vol. 11, no. 8, p. 1333, 2018.
- [173] S. Cheves, "A pilot study to evaluate VOCs outgassed in polymer filaments used in 3D printing," *A proposed study for a National Student Design Competition*, 2014.
- [174] F. Theodore, "Method of making plastic springs," May 1945. US Patent 2,375,357.
- [175] F. W. Reinhart, M. C. Slone, H. Leon, and D. A. George, "Reinforced plastic springs," Sept. 1958. US Patent 2,852,424.
- [176] P. D. Cochrane, "Life extension in hard disk drives through vibration dampening using pre-stressed polymer springs," Nov. 2006. US Patent 7,142,419.
- [177] M. Almasri, W. Zhang, A. Kine, Y. Chan, J. C. LaRue, and R. Nelson, "Tunable infrared filter based on elastic polymer springs," in *Advanced Sensor Technologies for Nondestructive Evaluation and Structural Health Monitoring* (N. Meyendorf, G. Y. Baaklini, and B. Michel, eds.), vol. 5770, pp. 190 – 198, International Society for Optics and Photonics, SPIE, 2005.
- [178] G. B. Jadhav, V. Gawande, and T. Ambi, "Review on development and analysis of helical spring with combination of conventional and

- composite materials," *International Journal of Engineering Research and General Science*, vol. 3, no. 2, pp. 1180–1184, 2015.
- [179] B. H. Lee, J. Abdullah, and Z. A. Khan, "Optimization of rapid prototyping parameters for production of flexible ABS object," *Journal of materials processing technology*, vol. 169, no. 1, pp. 54–61, 2005.
- [180] A. K. Sood, R. K. Ohdar, and S. S. Mahapatra, "Improving dimensional accuracy of fused deposition modelling processed part using grey Taguchi method," *Materials & Design*, vol. 30, no. 10, pp. 4243–4252, 2009.
- [181] A. Bagsik, V. Schöppner, and E. Klemp, "FDM part quality manufactured with Ultem* 9085," in *14th international scientific conference on polymeric materials*, vol. 15, pp. 307–315, 2010.
- [182] F. Rayegani and G. C. Onwubolu, "Fused deposition modelling (FDM) process parameter prediction and optimization using group method for data handling (GMDH) and differential evolution (DE)," *The International Journal of Advanced Manufacturing Technology*, vol. 73, no. 1-4, pp. 509–519, 2014.
- [183] ASTM International, "ASTM52921-13, Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies," 2013.
- [184] R. Sayre III, "A comparative finite element stress analysis of isotropic and fusion deposited 3D printed polymer," in *Submitt. to Grad. Fac. Rensselaer Polytech. Inst. Partial Fulfillment Requir. degree MASTERS Eng*, 2014.
- [185] M. Domingo-Espin, J. M. Puigoriol-Forcada, A.-A. Garcia-Granada, J. Lluma, S. Borros, and G. Reyes, "Mechanical property characterization and simulation of fused deposition modeling polycarbonate parts," *Materials & Design*, vol. 83, pp. 670–677, 2015.

- [186] P. Feng, X. Meng, J.-F. Chen, and L. Ye, "Mechanical properties of structures 3D printed with cementitious powders," *Construction and Building Materials*, vol. 93, pp. 486 – 497, 2015.
- [187] J. Cantrell, S. Rohde, D. Damiani, R. Gurnani, L. DiSandro, J. Anton, A. Young, A. Jerez, D. Steinbach, C. Kroese, and P. Ifju, "Experimental Characterization of the Mechanical Properties of 3D Printed ABS and Polycarbonate Parts," in *Advancement of Optical Methods in Experimental Mechanics, Volume 3: Proceedings of the 2016 Annual Conference on Experimental and Applied Mechanics*, pp. 89–105, Springer International Publishing, 2017.
- [188] C. Casavola, A. Cazzato, V. Moramarco, and C. Pappalettere, "Orthotropic mechanical properties of fused deposition modelling parts described by classical laminate theory," *Materials & Design*, vol. 90, pp. 453 – 458, 2016.
- [189] L. Li, Q. Sun, C. Bellehumeur, and P. Gu, "Composite modeling and analysis of fdm prototypes for design and fabrication of functionally graded parts," in *Solid Freeform Fabrication Symposium (SFF), Austin, TX, Aug*, pp. 6–8, 2001.
- [190] M. Somireddy, A. Czekanski, and C. V. Singh, "Development of constitutive material model of 3D printed structure via FDM," *Materials Today Communications*, vol. 15, pp. 143–152, 2018.
- [191] J. F. Rodríguez, J. P. Thomas, and J. E. Renaud, "Mechanical behavior of acrylonitrile butadiene styrene fused deposition materials modeling," *Rapid Prototyping Journal*, vol. 9, no. 4, pp. 219–230, 2003.
- [192] ASTM International, "ASTM D4255/D4255M - 01 Standard Test Method for In-Plane Shear Properties of Polymer Matrix Composite Materials by the Rail Shear Method," 2001.

- [193] Shimadzu, "AGS-X Series Universal Electromechanical Test Frames." <https://www.ssi.shimadzu.com/products/universal-tensile-testing/ags-x-specifications.html>, 2018. Accessed: 2017-08-21.
- [194] J. Bartolai, A. E. Wilson-Heid, J. R. Kruse, A. M. Beese, and T. W. Simpson, "Full Field Strain Measurement of Material Extrusion Additive Manufacturing Parts with Solid and Sparse Infill Geometries," *JOM*, vol. 71, no. 3, pp. 871–879, 2019.
- [195] GOM, "Gom correlate." <https://www.gom-correlate.com/>, 2018. Date accessed: 2016-05-31.
- [196] N. McCormick and J. Lord, "Digital Image Correlation," *Materials Today*, vol. 13, no. 12, pp. 52 – 54, 2010.
- [197] P. Bai, Y. Xu, F. Zhu, and D. Lei, "A novel method to compensate systematic errors due to undermatched shape functions in digital image correlation," *Optics and Lasers in Engineering*, vol. 126, p. 105907, 2020.
- [198] S. A. Tronvoll, T. Welo, and C. W. Elverum, "The effects of voids on structural properties of fused deposition modelled parts: a probabilistic approach," *The International Journal of Advanced Manufacturing Technology*, vol. 97, pp. 3607–3618, Aug 2018.
- [199] J. Torres, J. Coteló, J. Karl, and A. P. Gordon, "Mechanical Property Optimization of FDM PLA in Shear with Multiple Objectives," *JOM*, vol. 67, pp. 1183–1193, May 2015.
- [200] Society of Automotive Engineers, *Manual on design and application of helical and spiral springs*. New York, 1958. Retrieved from <http://hdl.handle.net/2027/coo.31924004648592>.
- [201] K. L. Richards, *Design engineer's handbook*. CRC Press, 2012.

- [202] Z. Marciniak, J. L. Duncan, and S. J. Hu, "6 - Bending of sheet," in *Mechanics of Sheet Metal Forming (Second Edition)* (Z. Marciniak, J. Duncan, and S. Hu, eds.), pp. 82 – 107, Oxford: Butterworth-Heinemann, second edition ed., 2002.
- [203] E. J. Hearn, "Chapter 26 - FATIGUE, CREEP AND FRACTURE," in *Mechanics of Materials (Second Edition)* (E. HEARN, ed.), pp. 839 – 905, Butterworth-Heinemann, second edition ed., 1985.
- [204] A. M. Wahl, *Mechanical springs*. Penton Publishing Company, 1944.
- [205] T. C. T. Ting, T. Chen, and K. S. Li, "Torsion of an isotropic shaft of arbitrary cross-section embedded with multicoated or graded circular cylinders of cylindrically orthotropic materials," *Quarterly Journal of Mechanics and Applied Mathematics*, vol. 57, no. 3, pp. 347–362, 2004.
- [206] R. Lipton, "An isoperimetric inequality for the torsional rigidity of imperfectly bonded fiber reinforced cylinders," *Journal of elasticity*, vol. 55, no. 1, pp. 1–10, 1999.
- [207] T. Chen and C.-J. Wei, "Saint-Venant torsion of anisotropic shafts: theoretical frameworks, extremal bounds and affine transformations," *Quarterly Journal of Mechanics and Applied Mathematics*, vol. 58, no. 2, pp. 269–287, 2005.
- [208] J. P. Smith, "Highly accurate beam torsion solutions using the p-version finite element method," NASA, 1996. NASA Technical Paper 3608.
- [209] L. A. M. Danao and R. M. Cabrera, "Torsion of a rectangular prismatic bar: solution using a power fit model," *Philippine Engineering Journal*, vol. 28, no. 1, pp. 77–98, 2007.
- [210] O. C. Zienkiewicz, R. L. Taylor, and J. Z. Zhu, "Chapter 5 - Field Problems: A Multidimensional Finite Element Method," in *The Finite Element*

Method: its Basis and Fundamentals (Seventh Edition) (O. Zienkiewicz, R. Taylor, and J. Zhu, eds.), pp. 115 – 149, Oxford: Butterworth-Heinemann, seventh edition ed., 2013.

- [211] K. Darilmaz, E. Orakdöğen, and K. Girgin, “Saint-Venant torsion of arbitrarily shaped orthotropic composite or FGM sections by a hybrid finite element approach,” *Acta Mechanica*, vol. 229, p. 1387, Mar. 2018.
- [212] S. Timoshenko and J. N. Goodier, *Theory of elasticity*. Engineering societies monographs, New York : McGraw-Hill, [1969, c1970], 1969.
- [213] L. S. Srinath, *Advanced mechanics of solids*. New Delhi : Tata McGraw-Hill, c1980., 1980.
- [214] W. S. Slaughter, *The Linearized Theory of Elasticity*. Boston, MA : Birkhäuser Boston : Imprint: Birkhäuser, 2002., 2002.
- [215] X. Rongqiao, H. Jiansheng, and C. Weiqiu, “Saint-Venant torsion of orthotropic bars with inhomogeneous rectangular cross section,” *Composite Structures*, vol. 92, no. 6, pp. 1449 – 1457, 2010.
- [216] K. Hsieh, *Numerical modeling and analysis of composite beam structures subjected to torsional loading*. PhD thesis, Virginia Tech, 2007.
- [217] J. White, R. C. and N. K. Cooperrider, “Guideway-Suspension Tradeoffs in Rail Vehicle Systems,” *Journal of Dynamic Systems, Measurement, and Control*, vol. 103, pp. 237–244, 09 1981.
- [218] L. F. Chaparro and A. Akan, “Chapter 2 - Continuous-Time Systems,” in *Signals and Systems Using MATLAB (Third Edition)* (L. F. Chaparro and A. Akan, eds.), pp. 115 – 165, Academic Press, third edition ed., 2019.
- [219] I. F. Ituarte, N. Boddeti, V. Hassani, M. L. Dunn, and D. W. Rosen, “Design and additive manufacture of functionally graded structures based on digital materials,” *Additive Manufacturing*, vol. 30, p. 100839, 2019.

- [220] J. L. Bartlett, B. P. Croom, J. Burdick, D. Henkel, and X. Li, "Revealing mechanisms of residual stress development in additive manufacturing via digital image correlation," *Additive Manufacturing*, vol. 22, pp. 1 – 12, 2018.
- [221] D. Foehring, H. B. Chew, and J. Lambros, "Characterizing the tensile behavior of additively manufactured Ti-6Al-4V using multiscale digital image correlation," *Materials Science and Engineering: A*, vol. 724, pp. 536 – 546, 2018.
- [222] Y. Balit, E. Charkaluk, and A. Constantinescu, "Digital image correlation for microstructural analysis of deformation pattern in additively manufactured 316L thin walls," *Additive Manufacturing*, vol. 31, p. 100862, 2020.
- [223] A. S. Wu, D. W. Brown, M. Kumar, G. F. Gallegos, and W. E. King, "An experimental investigation into additive manufacturing-induced residual stresses in 316L stainless steel," *Metallurgical and Materials Transactions A*, vol. 45, no. 13, pp. 6260–6270, 2014.
- [224] D. Garcia, Z. Wu, J. Y. Kim, H. Z. Yu, and Y. Zhu, "Heterogeneous materials design in additive manufacturing: Model calibration and uncertainty-guided model selection," *Additive Manufacturing*, vol. 27, pp. 61 – 71, 2019.
- [225] N. Vanderesse, A. Richter, N. Nuño, and P. Bocher, "Measurement of deformation heterogeneities in additive manufactured lattice materials by Digital Image Correlation: Strain maps analysis and reliability assessment," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 86, pp. 397 – 408, 2018.
- [226] E. Sacco and S. K. Moon, "Additive manufacturing for space: status and promises," *The International Journal of Advanced Manufacturing Technology*, pp. 1–24, 2019.

- [227] E. Sacco, Z. Y. Chua, and S. K. Moon, "Comparison of elastic properties for different sample types fabricated with additive manufacturing," in *Proceedings of the 3rd International Conference on Progress in Additive Manufacturing*, Singapore Centre for 3D Printing, 2018. (Pro-AM 2018).