

A LINE-BASED INFILL OPTIMIZATION METHOD FOR MATERIAL
EXTRUSION ADDITIVE MANUFACTURING

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

RAHMAN UNCU

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

SEPTEMBER 2023

Approval of the thesis:

**A LINE-BASED INFILL OPTIMIZATION METHOD FOR MATERIAL
EXTRUSION ADDITIVE MANUFACTURING**

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ABSTRACT

A LINE-BASED INFILL OPTIMIZATION METHOD FOR MATERIAL EXTRUSION ADDITIVE MANUFACTURING

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September 2023, 95 pages

Additive Manufacturing (AM) constitutes diverse manufacturing processes capable of producing intricately shaped components, a departure from conventional fabrication methods. As in the early days of AM, the primary motivation was manufacturing parts for prototyping; however, the mechanical properties of these parts have now assumed paramount importance due to the intention of applying these components as end products. Additionally, AM's advantage of fabricating intricate geometries that were previously challenging using traditional manufacturing methods has led to a surge in the adoption of topology optimization methods. This has sparked a growing interest in strategies to design AM parts with improved mechanical behavior, making it a current focal point of research.

This thesis proposes a novel infill optimization approach to improve AM parts' mechanical behavior. Specifically tailored for material extrusion AM processes, this strategy utilizes a line-based infill optimization approach. This optimization strategy had been meticulously tested across two loading scenarios to ascertain its effectiveness. The mechanical behaviors of the optimized infill geometries were benchmarked against commonly used linear infill patterns prevalent in 3D printing through com-

prehensive structural testing. The tests yielded notable improvements in the strength-to-weight ratios for the test samples when optimized infill patterns were employed, in contrast to the other linear infill options. Specifically, these enhancements were substantial, with an increase of nearly 40% observed in the ABS samples, ranging from 55% to 75% in the case of 17-4PH Stainless Steel samples, and an approximate boost of 30% in the 316L Stainless Steel samples.

This comprehensive study's outcomes unequivocally indicate the potency of the proposed methodology, which empowers designers to attain AM components with vastly improved mechanical behavior. This research demonstrates significant promise within AM, where mechanical performance enhancement is a pivotal consideration in design and production.

Keywords: infill optimization, mechanical behavior, fused filament fabrication, metal additive manufacturing

ÖZ

MALZEME EKSTRÜZYONU EKLEMELİ İMALAT YÖNTEMİ İLE ÜRETİLEN PARÇALAR İÇİN ÇİZGİ TABANLI İÇ YAPI OPTİMİZASYON YÖNTEMİ

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Tez Yöneticisi: Doç. Dr. Ulaş Yaman

Eylül 2023 , 95 sayfa

Eklemeli imalat, geleneksel üretim yöntemlerinden farklı olarak karmaşık şekillere sahip parçalar üretebilen çeşitli imalat süreçlerini oluşturur. Eklemeli imalatın ilk zamanlarında ana motivasyon prototipleme için parça üretmektir; ancak bu parçaların son ürün olarak kullanılma isteği bu parçaların mekanik performanslarının önem kazanmasına yol açmıştır. Ayrıca, eklemeli imalatın konvansiyonel üretim yöntemleri ile üretilmesi zorlayıcı olan karmaşık geometriler üretebilme avantajı, topoloji optimizasyon yöntemlerinin benimsenmesinde yardımcı olmuştur. Bu durum, iyileştirilmiş mekanik davranışa sahip eklemeli imalat parçaları tasarlama stratejilerine olan ilginin artmasına neden olmakta ve mevcut araştırmaların odak noktası haline getirmektedir.

Bu tez çalışması, eklemeli imalat ile üretilen parçaların mekanik davranışını iyileştirmek için yeni bir iç yapı optimizasyonu yaklaşımı önermektedir. Malzeme ekstrüzyonu eklemeli imalat yöntemleri için özel olarak geliştirilen bu strateji, çizgi tabanlı bir iç yapı optimizasyon yaklaşımını kullanır. Bu optimizasyon stratejisi, etkin-

liğini belirlemek amacıyla iki yükleme senaryosunda titizlikle test edilmiştir. Optimize edilmiş iç yapı geometrilerinin mekanik davranışları, kapsamlı yapısal testler yoluyla eklemeli imalatla yaygın olarak kullanılan doğrusal iç yapı modelleriyle karşılaştırılmıştır. Testler sonucunda, diğer iç yapıların aksine optimize edilmiş iç yapılar kullanıldığında test numunelerinin mukavemet-ağırlık oranlarında dikkate değer gelişmeler gözlemlenmiştir. Özellikle, ABS numunelerinde yaklaşık %40'lık, 17-4PH Paslanmaz Çelik numunelerinde %55 ile %75 arasında değişen ve 316L Paslanmaz Çelik numunelerinde yaklaşık %30'luk olacak şekilde önemli miktarlarda artış gözlemlendi.

Bu kapsamlı çalışmanın sonuçları, tasarımcılara büyük ölçüde geliştirilmiş mekanik davranışa sahip eklemeli imalat parçaları elde etme imkanı veren bu metodolojinin potansiyelini tartışmasız bir şekilde göstermektedir. Bu araştırma, mekanik performansın geliştirilmesinin tasarım ve üretimde önemli bir husus olduğu eklemeli imalat için önemli bir umut vaat ettiğini göstermektedir.

Anahtar Kelimeler: iç yapı optimizasyonu, mekanik davranış, ergiyik filament ile imalat, metal eklemeli imalat



To my family

ACKNOWLEDGMENTS

I want to extend my heartfelt gratitude to my supervisor, Assoc. Prof. Dr. Ulaş Yaman for his invaluable guidance, boundless patience, and generous assistance throughout my research journey. I am also sincerely grateful to Prof. Dr. Serkan Dağ, Assist. Prof. Dr. Orkun Özşahin, Assist. Prof. Dr. Hakan Çalışkan and Prof. Dr. Oğuzhan Yılmaz for serving on my jury and providing their invaluable comments and suggestions.

I am deeply thankful to my company, ASELSAN Inc., for the opportunity they provided me to undertake this research and for their continuous support in every step of the journey. I am truly fortunate to be part of an organization that values and fosters academic growth and development. I additionally desire to extend my special appreciation to Oğuz Doğan, Serap Aykan, and Mehmet Canberk Bacıkoğlu for the knowledge and perspectives they shared, which illuminated my journey during this research.

Finally, I want to convey my sincerest gratitude to my family for their unending backing, affection, and belief.

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LIST OF ABBREVIATIONS

ABBREVIATIONS

2D	2 Dimensional
3D	3 Dimensional
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
BESO	Bi-directional Evolutionary Structural Optimization
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
DED	Directed Energy Deposition
DLP	Digital Light Processing
DW	Direct Writing
EBM	Electron Beam Melting
ESO	Evolutionary Structural Optimization
FEA	Finite Element Analysis
FFF	Fused Filament Fabrication
FOAM	Field-Oriented Additive Manufacturing
LSM	Level Set Method
MEX	Material Extrusion
M-FFF	Metal Fused Filament Fabrication
MIM	Metal Injection Molding
MWCN-S	Multi-Walled Carbon Nanotubes
PLA	Polylactic Acid
PBF	Powder Bed Fusion
PS	Principal Stress

PSLs	Principal Stress Lines
PSVFs	Principal Stress Vector Fields
SIMP	Solid Isotropic Material with Penalization
SLA	Stereolithography
SLAM	Stress Line Additive Manufacturing
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SS	Stainless Steel
STL	Standard Tessellation Language
TO	Topology Optimization
UTS	Ultimate Tensile Strength
UV	Ultraviolet

CHAPTER 1

INTRODUCTION

Additive manufacturing (AM), often called 3D printing, represents a manufacturing approach based on the successive addition of materials in a single layer and then layer upon layer. The additive nature of this fabrication method offers a distinct advantage in producing intricate structures. This design freedom paves the way for topology optimization. The core objective of this research is the creation of optimal designs by utilizing Principal Stress Lines (PSLs) derived from Finite Element Analysis (FEA). Then, these lines guide the generation of precise toolpaths of a Fused Filament Fabrication (FFF) 3D printer directly. The G-code file generated from the algorithm employed in this study guides the motion of the printer's nozzle.

Furthermore, this investigation extends to manufacturing designed components by the metal Fused Filament Fabrication (M-FFF) methodology. This approach serves to validate the effectiveness of the proposed method. The study comprehensively explores the characteristics and intricacies inherent to this specific fabrication technique.

1.1 Motivation of the Thesis

AM is experiencing a steady surge in popularity, mainly owing to its distinct advantages over conventional fabrication techniques, including enhanced speed, the ability to produce intricate components, reduced material waste, and more. Initially, in the early years of 3D printing, the main aim was to fabricate parts for prototyping purposes, so *rapid prototyping* was generally equivalent to 3D printing. However, in recent years, the primary objectives of AM have evolved from rapid prototyping to

manufacturing functional parts thanks to substantial advancements in the field. This progression has led to the pursuit of fabricating components with superior mechanical properties from a mechanical standpoint.

The fundamental motivation behind this thesis is the aspiration to leverage AM to generate structurally performative designs. This goal is accomplished by integrating PSLs within the design domain. PSLs offer the distinct advantages of rapid implementation and ease of control. Additionally, generating motion trajectories of the 3D printer directly using PSLs is handy. The nozzle of the 3D printer tracks them to obtain components endowed with enhanced mechanical behavior. This is the primary reason to focus on the FFF method since controlling the toolpaths in FFF is comparably simpler than in other AM techniques.

Another main drive for conducting this research is to manufacture parts using M-FFF technology, given that the process parameters in the printing stage diverge from the conventional FFF method. Unlike the plastic FFF method, M-FFF necessitates subsequent debinding and sintering steps, which are crucial for eliminating plastic residues within the part and sintering metal powders to transform them into final metal parts. Significant characteristics inherent to the M-FFF were also observed throughout the study.

1.2 Limitations of the Thesis

The algorithm created in this thesis is only valid for 2.5D geometries. Specifically, its applicability extends to shapes that emerge from the extrusion of a 2D surface geometry along its normal direction. Although some effort was put into tailoring the algorithm to accommodate 3D geometries, this attempt has not matured enough to manufacture intricate 3D components.

Furthermore, the algorithm developed in this work utilizes PSLs, and these lines are derived from Principal Stress Vector Fields (PSVFs), a resulting vector field obtained from FEA conducted on the design domain. Additionally, the algorithm requires designated source points, which serve as the PSLs initiation points because these lines cannot be established solely through a vector field. This study selects source points

based on the Principal Stress (PS) distributions obtained from FEA. However, it is pertinent to acknowledge that the process can be improved regarding the source point selection method, ultimately leading to parts with enhanced mechanical properties.

1.3 Layout of the Thesis

The thesis is structured as follows:

Chapter 2 provides an in-depth exploration of literature related to the subject of this thesis. The literature survey comprehensively analyzes AM studies based on field orientations. It further delves into an overview of topology optimization and PSLs-based optimizations, as well as an examination of metal AM technologies.

Chapter 3 explains all the design, fabrication, and testing stages of the plastic parts manufactured by the FFF method. The developed algorithm is explained in detail in the design stage of the test parts. Moreover, the fabrication of these parts is elaborated upon in detail. Lastly, the structural tests performed on these test samples are presented at the end of the section, offering a comprehensive understanding of their performance.

Chapter 4 is devoted to the test parts manufactured by M-FFF technology. This section addresses the fabrication and structural testing stages of these parts. The critical process parameters and outcomes of M-FFF are presented in this section.

Chapter 5 concludes, encapsulates the study's core findings, and evaluates its critical outcomes. Furthermore, some future works are also addressed. This section provides a summary of the thesis.



CHAPTER 2

REVIEW OF THE STATE OF THE ART

This chapter offers an overview of the relevant literature concerning the thesis subject. Initially, a concise introduction to AM technologies is provided, covering the historical evolution of AM, the employed manufacturing techniques, and related terminology.

Subsequently, this chapter digs into the thesis subject's relevant AM research domains. These domains incorporate Field-Oriented Additive Manufacturing (FOAM), Topology Optimization (TO), and Metal AM. Each is examined under distinct subsections, comprehensively presenting various relevant literature sources.

2.1 Introduction

AM, also called 3D printing or rapid prototyping, constitutes a family of manufacturing processes that hold profound significance and utility in fabricating diverse mechanical components. Tracing its origins back to the 1980s [1], Dr. Hideo Kodama invented the first 3D printer in the early 1980s. Dr. Kodama ingeniously employed UV light to polymerize the resin layer by layer to obtain the final part. Subsequently, in 1987, the first 3D printing machine was produced by Chuck Hull [1]. In contrast to conventional subtractive manufacturing techniques, AM incrementally adds material layers to achieve the intended final product.

The design and fabrication pipeline of the 3D printing process can be outlined as follows. Commencing with the creation of 3D geometry, the consecutive transformation into a Standard Tessellation Language (STL) file approximates the geometric

outer boundaries through triangular mesh representations. This STL file, in turn, interfaces with the printer's built-in Computer Aided Manufacturing (CAM) software. The mesh is sliced into a sequence of discrete 2D layers within this software. Hereupon, CAM software generates a G-code file, encapsulating vital printing process details, including printer head toolpaths, extrusion amounts, and more.

AM methodologies find classification into distinct subcategories based on their underlying production paradigms. Noteworthy among these are Material Extrusion (MEX), Photopolymerization, and Powder Bed Fusion (PBF). The eminent manufacturing techniques within these subcategories are FFF, Stereolithography (SLA), and Selective Laser Sintering (SLS).

2.1.1 Fused Filament Fabrication

FFF, or Fused Deposition Modeling, stands as an AM process based on the incremental construction of a component through the successive deposition of molten material layers. This method predominantly utilizes thermoplastic materials, exemplified by Acrylonitrile Butadiene Styrene (ABS) and Polylactic acid (PLA). The process unfolds with a filament, stored in a spool, channeled to a heated extruder embedded within the printer. Subsequently, the extruder ejects the molten filament through a nozzle, producing a layer deposition. Following the completion of a layer, the process iterates anew, layer by layer, until the entire component is constructed. Figure 2.1 offers a visual exposition of the principal components of an FFF printer.

The FFF process offers several noteworthy advantages. It emerges as a more cost-effective and accessible option than other 3D printing methods. In addition, the absence of harsh chemicals, unlike techniques such as SLA, makes the process relatively clean. Furthermore, the printing process can be efficiently carried out using a single workstation, eliminating the requirement for additional equipment. However, the process has some drawbacks. Layer lines on the manufactured parts are generally visible, affecting the surface finish. Moreover, the print's quality, including the final piece's mechanical strength, heavily relies on the precise adhesion between layers [3].

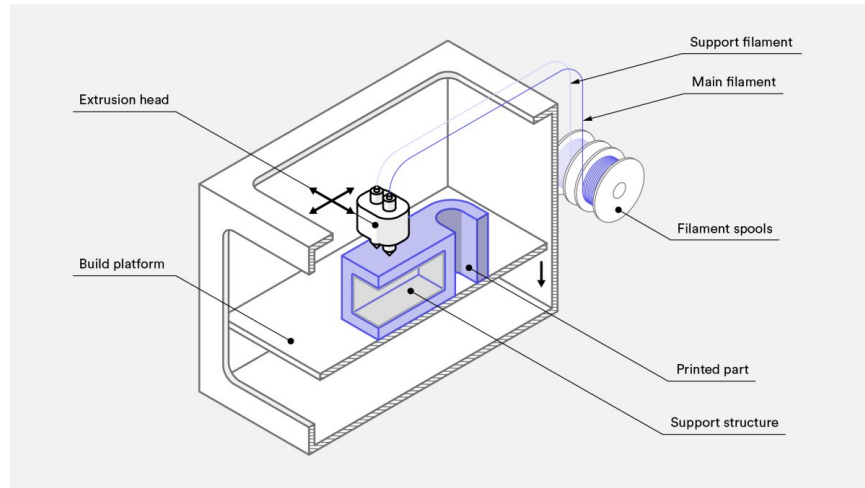


Figure 2.1: Major Components of an FFF printer [2]

2.1.2 Stereolithography

SLA is another significant AM process where an Ultraviolet (UV) laser is focused on a vat of photopolymer resin to cure the resin material layer by layer. The photopolymer resin undergoes photochemical solidification propelled by the agency of UV light, and a single layer of the part is constructed. The build platform is gradually elevated, allowing the laser to progressively shape the photopolymer material into the desired form for each layer. When the printing process is finished, the printed part undergoes a solvent-based washing procedure to remove uncured resin residue from its surfaces. The elemental components of an SLA machine are visually explained in Figure 2.2.

The most notable advantage of SLA is its exceptional precision compared to FFF. This increased precision is attributed to the considerably smaller focus diameter of the laser, in contrast to the nozzle diameter of FFF printers. SLA becomes a favorable choice for parts requiring stringent dimensional tolerances. Although a small focus diameter makes the process more precise, it results in a slower fabrication. For relatively large components, the process duration may extend to several days. In addition, a limited number of photopolymers are applicable for SLA machines, and the material costs are considerably higher than other methods. As a result of these factors, SLA is not widely favored as the leading technology in most engineering applications [5].

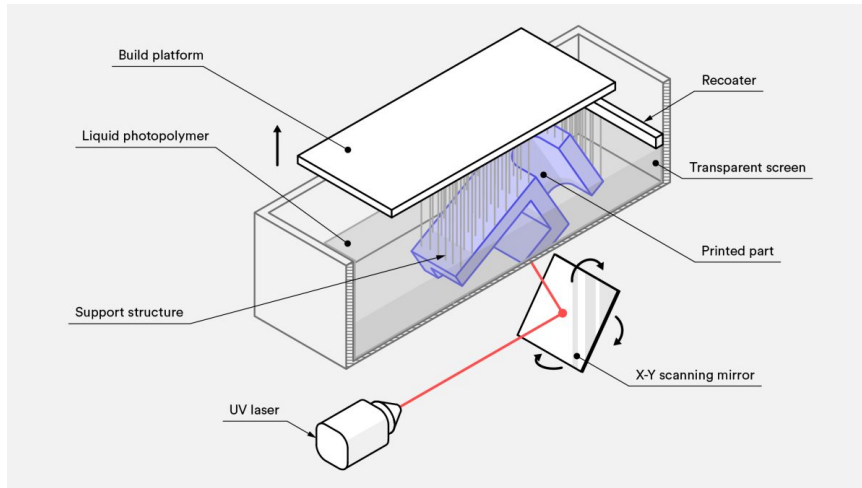


Figure 2.2: The elemental components of an SLA machine [4]

2.1.3 Selective Laser Sintering

SLS plays a pivotal role in AM, utilizing a high-power laser as the power and heat source to sinter polymer powders and fuse them. The process begins by placing powders in a container near the printing surface. Powders are kept in a tank near the print bed and spread across the bed before starting each new layer. These powders are sintered by scanning with a laser in each layer to obtain the desired product. This technique accommodates many materials, including plastics, metals, ceramics, and glass. Figure 2.3 provides a foundational illustration of an SLS machine's architecture.

A unique characteristic of the SLS method is its ability to eliminate the necessity for additional support. The component remains surrounded by the powder bed throughout the process, and the adjacent powder serves as a natural support. This situation simplifies the creation of intricate geometries. Moreover, the SLS process is suitable for small to medium-batch productions due to its enhanced manufacturing capabilities. Additionally, the excess unused powder can be reused in other printing operations.

Parts printed with SLS may require post-processing because these parts have a unique grainy surface finish and internal porosity. However, specific cautions are advised; printing small apertures and large flat surfaces can lead to challenges like warping

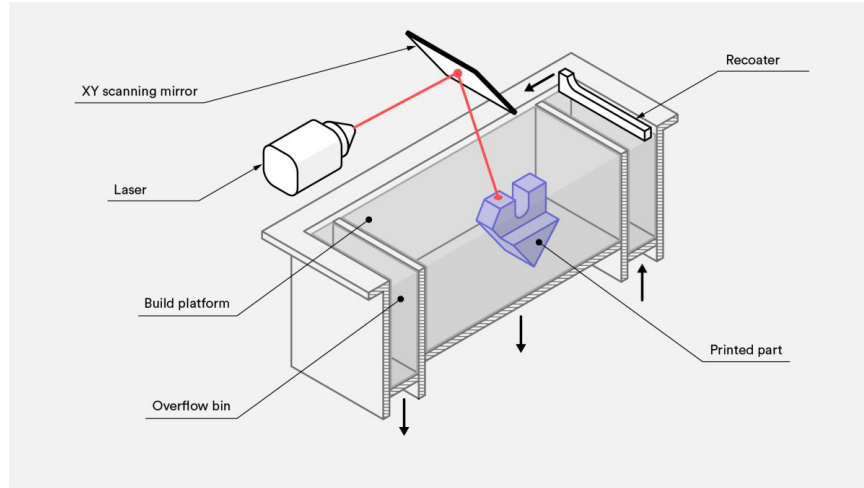


Figure 2.3: The basic structure of an SLS machine [6]

and over-sintering. In addition, it is worth mentioning that the SLS-produced parts' lead times notably exceed those of FFF and SLA methods [6].

2.2 Research Areas of Additive Manufacturing

This section presents some research fields of AM that are highly relevant to this study's subject: FOAM, TO, and Metal AM.

2.2.1 Field-Oriented Additive Manufacturing

Numerous studies delve into AM techniques tailored to the orientation of components in various fields, referred to as *Field Oriented Additive Manufacturing*. These investigations examine the application of magnetic, electric, and acoustic fields. This approach is primarily utilized in manufacturing composite reinforced components, strategically manipulating the alignment of particles or fibers using magnetic, electric, or acoustic fields. Notably, components with discontinuous fiber composites generally demonstrate superior strength and toughness behavior compared to their homogeneous counterparts. This phenomenon finds parallels in nature, such as the cortical bones of mammals and shells of abalones [7]. Drawing inspiration from these natural mechanisms, Martin et al. [7] used magnetic 3D printing to design bioinspired

composite reinforcement structures for enhanced mechanical performance. They constructed a 3D printing framework based on the context of the SLA process under a magnetic field that controls the orientation of ceramic-reinforced particles in the printed material. To demonstrate the robustness of their methodology, they designed different parts, such as composites containing ceramic microparticles aligned with the principal stresses and parts with circular defects having osteon-inspired microstructure. Tensile test results confirmed the improved mechanical strength of these bioinspired composite micro-architectures. Similarly, Yunhai et al. [8] initiated a study centered around bioinspired composites and their mechanical characteristics. Employing a Digital Light Processing (DLP) based printing technique, they attempted to align stainless steel fibers via a magnetic field. Their research thoroughly examined tensile, compressive, and frictional properties in components that displayed different orientations and amounts of fibers. Their findings unveiled that optimal mechanical properties emerged when the fibers were parallel to the loading direction, a similar consequence of Martin's work [7]. On the other hand, perpendicular fiber orientation yielded the most favorable frictional performance.

Regarding electric field-assisted tailoring of polymeric composites, Kim et al. [9] conducted a study that uses field-aided micro-tailoring (FAiMTa) to align micro or nanosized inclusions in a liquid photopolymer through the application of an electric field. This method aimed to achieve locally micro-tailored parts with improved thermal or mechanical properties by manipulating this field's magnitude, direction, and gradient. The study involved the fabrication of orthotropic composite samples, orienting them both parallel and transverse to the tension/compression direction, allowing for a comparison with composites containing randomly distributed inclusions. According to the tests' outcomes, samples with fibers oriented parallel to the tension/compression direction demonstrated a 10-20% increase in elastic modulus compared to samples with randomly distributed inclusions. Conversely, the samples with perpendicular orientation experienced a 10% reduction in elastic modulus. Similar to [7] and [8], Yang et al. [10] also took inspiration from biological architectures for mechanically superior design. They utilized electrically assisted 3D printing to align the structure's Multi-Walled Carbon Nanotubes (MWCNT-S). This alignment was guided by the intricate Bouligand-type structure found in nature. Researchers also compared

components with different rotation angles in terms of their impact resistance. Significantly, their work extended to creating an artificial meniscus through electrically assisted 3D printing. This innovative approach resulted in an artificial meniscus with enhanced mechanical properties, effectively mitigating tear-related issues.

In the context of AM guided by acoustic fields, Collino et al. [11] employed acoustic fields to excite microfluidic print nozzles, thereby altering the microstructure of composite filaments within extrusion-based procedures. Particles in ink are aligned and packed with the help of a coupled piezoelectric actuator. Tensile tests were conducted for the mechanical characterization of base ink and Silicon Carbide (SiC)/epoxy inks. Results indicated improved modulus and strength but decreased ductility compared to the base ink. The study also exhibited that acoustic focusing is advantageous for depositing ordered two-phase material with a single nozzle. Due to its material-agnostic nature, it is highly suitable for many multiphase inks and 3D printing methodologies. In a similar study to [11], Wadsworth et al. [12] conducted a similar investigation in the domain of ultrasonic Direct Writing (DW) aimed at fabricating engineered materials with controlled microstructures. Their methodology is based on coupling DW 3D printing with ultrasound-directed self-assembly. Within their setup, fibers within a liquid photopolymer resin were aligned through an acoustic radiation force field before extrusion. Samples were prepared to assess the electrical and mechanical characteristics of the fabricated parts. Interestingly, the alignment of carbon fibers within a sample has a relatively minor impact on macroscopic mechanical behavior. Remarkably, according to the measured moduli of the DW samples, these samples displayed greater flexibility compared to well-known electrical conductors such as copper or gold. This discovery offered a new outlook on the mechanical characteristics of these engineered materials.

2.2.2 Topology Optimization

2.2.2.1 Topology Optimization Overview

TO is a structural design methodology aimed at achieving optimal material distribution across a design domain, intending to maximize structural performance while

adhering to defined loads, boundary conditions, and constraints. Its prominent advantage lies in its capacity to avoid predefined configurations, distinguishing it from other optimization methods, such as sizing and shape optimization. This approach is precious for creating lightweight, high-performance components and finds significant applications in aerospace, automotive, and related industries.

TO has gained popularity in tremendous amounts since the seminal work by Bendsøe and Kikuchi in 1988 [13]. Although the concept began with mechanical performance concerns, it has expanded to cover various physical disciplines, including fluid dynamics, thermal analysis, and electromagnetics.

Several TO methods have been put forward since Bendsøe and Kikuchi; however, three of them have gained significant prominence: the density-based methods, the Evolutionary Structural Optimization (ESO), and the Level Set Method (LSM) [14].

Density-based methods are based on converting a binary 0-1 discrete optimization problem into a continuous one. This is achieved by utilizing the homogenization technique, which, although powerful, can involve intricate mathematical processes. To address these complexities, Bendsøe and Sigmund [15] introduced a density-based approach called Solid Isotropic Material with Penalisation (SIMP). The approach is based on penalizing element elastic modulus according to density variables assigned to finite elements referred to as solid isotropic microstructures. SIMP serves as a prominent illustration of density-based methods.

The ESO method, initially proposed by Xie and Steven [16], employs a heuristic approach that progressively eliminates inefficient materials to attain optimized topology. Yang et al. [17] and Querin et al. [18] extended this concept with the Bi-directional Evolutionary Structural Optimization (BESO), allowing both the addition and removal of material within the design domain for further design refinement.

An alternative approach, the Level Set Method, was introduced by Wang et al. [19]. This method relies on the implicit description of the material domain, utilizing level-set functions to represent structural boundaries. Level set functions are updated by solving the Hamilton-Jacobi equations iteratively to yield the desired material configuration. Mei and Wang [20] demonstrated the effectiveness of their methodology

in multi-material and multi-constraint optimization problems, extending its use from rigid structural design to include compliant mechanisms and material design.

2.2.2.2 Optimization Based on Principal Stress Lines

In addition to TO, researchers have explored optimizing infill patterns within structures to improve mechanical performance. One approach they have adopted is generating lines that follow the principal stress trajectories within a structure, referred to as the Principal Stress Lines (PSLs) approach. This method stands out for its computational efficiency compared to other optimization techniques. Additionally, the line-based nature of PSLs aligns effectively with AM, as these lines can be readily transformed into toolpaths for AM machines without requiring slicing operations.

Kwok et al. [21] suggested a structural topology design method utilizing PSLs within the structure. Kwok's team developed an algorithm for topology optimization using PSLs building upon Michell's theorem, which suggests that the optimal weight structure aligns members along principal stress directions. In other words, the members should be subjected to only axial loads, i.e., no shear stress should be present on the members [22]. Their approach was applied to diverse design domains, such as cantilever and bridge structures, yielding results that closely resembled solutions to Michell's problems. Drawing inspiration from this approach, Wojciechowski [23] aimed to achieve optimal material distribution by computationally determining principal stress trajectories, employing a streamlined-inspired strategy. While their study established a connection between PSLs and Michell structures, the mechanical performance of the designed structures was not validated through physical testing. Tam and Mueller [24] utilized PSLs to create paths for filament deposition in the FFF process, naming this technique Stress-Line Additive Manufacturing (SLAM). Utilizing a six-axis robot arm, they applied their methodology to complex 2.5D surface geometries and planar cases. The primary contribution of this research lies in the demonstration that when integrated with robot-enabled techniques, SLAM has excellent potential for the design of intricate geometries.

Daynes et al. [25] proposed a novel approach to optimizing lattice core structures using isostatic lines aligned with principal stress directions. These isostatic lines aided

in obtaining functionally graded lattice structures. Isostatic lines, aligned with principal stress directions, proved beneficial in achieving optimal cell alignment, size, and shape. As a result of the study, they reported a 101% and 172% increase in strength and stiffness, respectively, compared to uniform lattice core. Gao et al. [26] developed an approach for creating a ground structure for truss topology optimization using principal stress trajectories on the structure. They obtained the first and third principal stress trajectories of the structure, and intersections of these trajectories became the ground structure's nodal points. This streamlined approach led to accelerated solution convergence during optimization due to the reduced number of nodes and bars in the ground structure.

Inspired by Kwok's work [21], Sales [27] studied a line-based topology optimization approach focused on efficiently generating tool paths for AM. As a progression of Kwok's work, the study's main aim is achieving topology optimization during toolpath planning by considering toolpath characteristics of the AM processes. Tensile tests indicated that specimens with PSLs as infill patterns exhibited around 50% higher supported load compared to other infill patterns (triangle, tri-hexagon, and grid). For further advancements, the optimization of printing order was also studied in this work. The effect of printing order was observed by printing some of the samples beginning from tensile PSLs and some by starting from compressive PSLs. As a result, printing order optimization mitigated discontinuities and achieved a 16.4% increase in mechanical strength. They also addressed concerns related to material overlapping by investigating extrusion rate and line width.

2.2.3 Metal Additive Manufacturing

Additive Manufacturing is *the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies*, as defined by ASTM International's characterization [28]. AM processes can be classified into several subcategories based on various criteria. These include the initial state of the input material—such as molten filament, powder, liquid, or solid layers—alongside the differentiation between direct and indirect processes dictated by the bonding method. Furthermore, selecting

foundational materials, polymers, ceramics, and metals also plays a pivotal role in classification [29].

Metal AM processes have emerged as a cornerstone in various manufacturing areas, including aerospace, automotive, tooling, and healthcare. Significant advantages of Metal AM are its cost and lead time reductions, more design freedom for engineers to produce complex geometries for lightweight and topology optimization, and consolidation of multiple parts. Nevertheless, it must be acknowledged that Metal AM has some drawbacks in dimensional accuracy and surface finish, limited materials, part certification, and unique quality control requirements [30].

The prevailing Metal AM processes involve Selective Laser Melting (SLM), Electron Beam Melting (EBM), Directed Energy Deposition (DED), and M-FFF.

SLM is an AM methodology that relies on melting metal powders by laser with high-power density and fusing them to obtain desired parts; it resembles SLS employed for plastics. This method makes it possible to manufacture nearly completely dense parts with mechanical properties akin to bulk metals. The flexibility of SLM is particularly evident in its ability to work with non-ferrous metals like aluminum, titanium, and copper. However, high energy usage during the process may result in high thermal stresses and shrinkage on components manufactured by this method [31].

EBM, another widely used Metal AM process, shares similarities with SLM as both are carried out in a bed of metal powders. The main difference comes from the energy source for melting these powders; EBM uses an electron gun instead of the lasers employed in SLM. This distinction results in faster build rates in EBM compared to SLM. Although build rates are faster in EBM, the process requires a vacuum environment, and the electrical conductivity of metals limits the material diversity suitable for this manufacturing method.

Another well-known Metal AM process is DED, which centers on melting the material deposited by a nozzle in a powder or wire form. This is achieved through a concentrated energy source like lasers, electron beams, or plasma arcs. DED is particularly effective for adding material to or repairing existing components, but building new parts is also applicable. Although DED enables manufacturing highly complex

and relatively large parts, resulting surface finish and limited material compatibility pose challenges [32].

The above paragraphs explain some of the most used Metal AM techniques, SLM, EBM, and DED. Although they have considerable demand, these methods necessitate energy-intensive lasers or beams to fuse metal powders, making these processes highly energy-consuming. Additionally, chambers used in SLM and EBM have to provide a controlled atmosphere or preserve high temperatures during the printing process. Therefore, a substantial investment is essential for metal powders, equipment, and maintenance, which restricts their application areas to cost-insensitive industries [33]. At this point, the M-FFF method emerges as a more cost-effective solution. M-FFF is a newly developed technology based on printing filaments composed of metal/polymer composites having substantial metal powder content. Specially equipped 3D printers can extrude these filaments through a nozzle, mirroring the FFF process employed with plastics. The part obtained in this stage is called the *Green Part*. However, to get the desired metal part, the polymer in the green part must be removed by the debinding process, resulting in the *Brown Part*. The ultimate step involves the sintering process that fuses metal powders into the final M-FFF part. Refer to Figure 2.4 for an illustrative depiction of the M-FFF process.

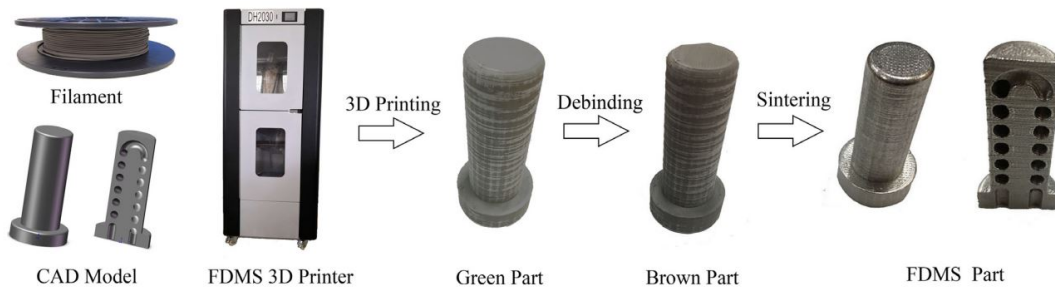


Figure 2.4: A schematic of the M-FFF process [33]

As described in the preceding paragraph, M-FFF technology may become a prospective alternative to other Metal AM methods thanks to its significant advantages. Consequently, recent years have seen a notable increase in research efforts centered around this approach. These studies have specifically focused on examining the mechanical performance of parts manufactured by this technique and determining optimum process parameters.

Liu et al. [33] conducted a study investigating the mechanical properties of the parts manufactured using the M-FFF technique. Their focus centers on four main mechanical attributes: hardness, yield strength, tensile strength, and elongation at break of final sintered components. Additionally, they focused on their microstructural characteristics and observed relative density and shrinkage. Their findings revealed that the mechanical properties of the parts produced by M-FFF fall behind those documented for parts produced via SLM in the existing literature. This difference was attributed to their specimens' low relative density and high porosity. They reported a porosity level of 7.77%, indicating substantial porosity. Consequently, their study concluded that M-FFF technology appears more suitable for functional purposes than parts demanding substantial structural performance. In alignment with this perspective, Carminati et al. [34] followed a similar trajectory, focusing on the mechanical characterization of 316L Stainless Steel (SS) parts fabricated by M-FFF. Their study also concentrated on the influence of process parameters on the mechanical attributes of these components. Initially, they tried to identify the optimal process parameters (layer thickness, nozzle temperature, print speed, and infill pattern) to achieve specimens with the highest density, namely 95%. Subsequently, they subjected parts produced using these parameters to mechanical tests, including tensile, compressive, and resilience assessments. Results were compared with the properties of monolithic AISI 316L SS. Tensile testing unveiled yield strength approximately 36% lower and Ultimate Tensile Strength (UTS) 20% lower than those of the monolithic sample, echoing the findings of Liu et al. [33]. The study conducted by Caminero et al. [35] revealed significant insights regarding determining the optimum process parameters of M-FFF. Their attention centered on how mechanical and geometric properties change concerning the printing parameters: build orientation, feed rate, layer thickness, and nozzle diameter. Notably, nozzle diameter and build orientation emerged as the most influential parameters among the four. Furthermore, increasing nozzle diameter leads to lower porosity and improved mechanical properties; nevertheless, it causes diminished geometric accuracy in the samples. While the measured relative density of the parts can reach up to 99.5% and the parts demonstrated mechanical properties comparable to the Metal Injection Molding (MIM) process, changing process parameters for enhancing geometric accuracy may result in higher porosity, leading to diminished mechanical performance. This trade-off positions the M-FFF

process as better suited for components designed for moderate loading conditions, aligning with the findings of both Liu [33] and Carminati [34].

Inspired by similar objectives as [35] and [34], Tosto et al. [36] studied the influence of printing parameters on the mechanical attributes of the parts manufactured by M-FFF. Different from [35] and [34], they extended their study to bending properties alongside tensile characteristics. They evaluated the impact of nozzle temperature, layer thickness, and flow rate on these attributes. Their results highlighted that increased mechanical properties could be attained via a higher flow rate, larger layer thickness, and lower nozzle temperature. Also, the statistical analysis identified the flow rate as the most dominant parameter on tensile and bending properties. Using their optimized parameter set, they obtained 316L SS samples with 513 MPa UTS and nearly 60% elongation at break. Compared to other studies, these values are comparable to MIM-produced parts, and the UTS value obtained from this study is approximately 15%-20% lower than those reported by SLM. Also, the 513 MPa UTS value exceeded the minimum tensile strength confirmed for bulk AISI 316L SS by some steel suppliers in the market. Their work indicated that M-FFF might become a competitive method in the market with the help of further developments in debinding, sintering, and post-processing techniques.

In addition to these studies focusing on the mechanical properties and printing parameters of M-FFF for 316L SS, Suwanpreecha [37] et al. conducted a study exploring the physical, microstructural and mechanical attributes of 17-4PH SS parts manufactured by M-FFF. They tried to observe the effect of specimen layout on these properties as in [35]. They printed tensile test specimens in three different layouts: flat, side, and vertical. According to the results of this work, specimen layouts significantly influence tensile properties and relative density, contrary to the hardness of the specimens. Optimal performance in relative density and tensile properties was observed in flat printed samples, while the least favorable result was observed in the vertical one. Examination of fracture surfaces revealed noticeable defects and voids along the perimeter walls of the vertical samples, magnifying stress concentration and layer delamination. Discrepancies between flat and side samples were attributed to larger voids in the side-printed specimens, rendering them more vulnerable to fractures.

2.3 Closure

Advancements in AM in recent years have empowered engineers to manufacture parts with complex geometric details. This transformation has opened opportunities to apply optimization strategies to attain mechanically superior designs. As discussed in the literature review, numerous studies focused on implementing optimization methods to obtain optimal geometries for heightened mechanical efficiency. Nonetheless, there is a lack of research considering the inherent characteristics of AM processes.

This study makes a notable contribution by introducing a novel approach: using lines aligned with principal stress directions within the geometry. This approach forms the basis for developing suitable toolpaths for the 3D printer, thereby bypassing the conventional slicing process. Another advantage of this approach is the integration of the design and production phases of FFF 3D printing.



CHAPTER 3

LINE BASED INFILL OPTIMIZATION FOR ADDITIVE MANUFACTURING

In this chapter, the adopted methodology that guided the entire study is described. The process is detailed, starting with the design and manufacturing phases of the test parts. This phase includes conducting FEA to obtain PSLs within the design domain. Following this, a G-code file is generated in alignment with PSLs, facilitating the fabrication of the intended component. After this, the chapter outlines the structural tests conducted to evaluate the mechanical effectiveness of the test parts.

3.1 Design and Fabrication of the Test Parts

The fundamental objective of this study is to enhance the structural integrity of parts manufactured using the FFF 3D printing method. For this purpose, the study concentrates on optimizing the infill structure of the parts for superior mechanical behavior. Recognizing the orientation-dependent nature of the FFF process, this study expands its scope to encompass geometry and manufacturing strategy optimization. Therefore, an optimization strategy is proposed that considers not only the effect of geometry but also the effect of manufacturing strategy.

A promising avenue explored within this study involves the generation of an infill pattern based on PSLs within the structure. Aligning the infill pattern with PSLs is expected to result in parts with enhanced strength. Additionally, the line-based nature of this approach facilitates the control of toolpaths for the FFF 3D printer, thereby streamlining the manufacturing process.

Two types of well-known structural cases were utilized to demonstrate the effectiveness of this algorithm: the Messerschmitt-Bölkow-Blohm (MBB) Beam and Cantilever Beam, depicted in Figure 3.1 and Figure 3.2, respectively. Structural tests were conducted to compare the mechanical performance of these optimized parts with parts featuring commonly employed infill patterns in the FFF method, namely triangular and grid infills.

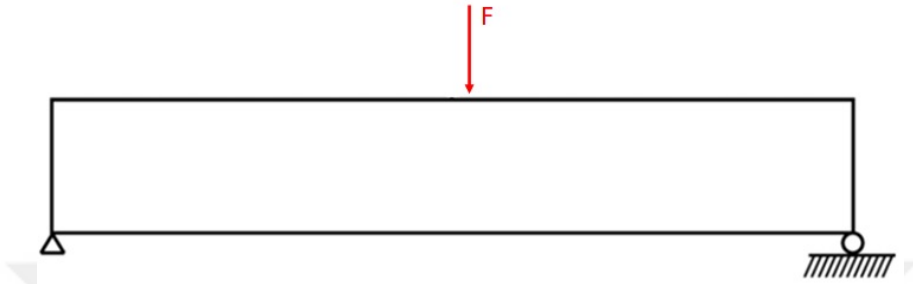


Figure 3.1: MBB Beam

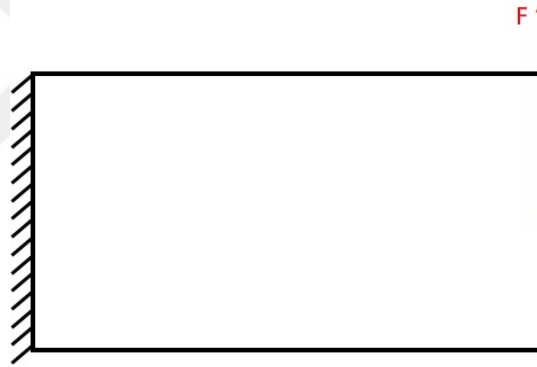


Figure 3.2: Cantilever Beam

3.1.1 Theory

This section offers a comprehensive explanation of the theory behind PSLs. However, it is crucial to introduce the concept of principal stress briefly before diving into this topic.

A continuum body can be divided into infinitesimal elements to obtain the state of stress for each point. In typical structural engineering scenarios, when an individual plane is considered, the state of stress can be expressed by two normal stress and one

shear stress component. These normal and shear stress components can change according to the plane's orientation. Achieving zero shear stress alongside maximum or minimum normal stresses is possible at specific plane orientations. These orientations are known as the principal stress directions. The formula governing the orientations of maximum and minimum normal stresses is provided in Equation 3.1. The equation has two roots, two angles separated by 90° from each other. One angle corresponds to the direction of maximum normal stress, while the other angle corresponds to the direction of minimum normal stress.

$$\tan 2\theta_p = \left(\frac{2\tau_{xy}}{\sigma_x - \sigma_y} \right) \quad (3.1)$$

When considering a continuum body, if a sufficient number of principal stress planes are identified for different points on the body, the principal stress fields can be constructed by connecting these projections. Two distinct approaches are employed to establish trajectories grounded in the internal stresses of a body: direct and iterative methods. Direct methods can take the form of analytical or graphical techniques. Direct methods are either analytical or graphical, which means either theoretical constraints are satisfied mathematically or analytical formulations are characterized geometrically for optimum material distribution. A prominent example of a direct analytical approach is Michell's optimal truss derivation [22]. Michell's theorem expresses that to attain a structure of minimum weight, its members must align with principal stress directions, thereby exclusively accommodating tension or compression without shear.

Nonetheless, specific analytical formulations from this approach apply to limited scenarios, emphasizing the significance of numerical and iterative methods in constructing stress lines. Using FEA, principal stress directions for a specific point on the continuum body can be determined. The process involves initiating from this point and drawing a line segment according to the prevailing vector field. Subsequently, additional lines extend from the endpoint of this segment, gradually forming a polyline until the domain's boundary is reached. Once this polyline is complete, another trajectory starts from a source point, and the iterative process continues.

The algorithm developed in this thesis adopts a similar FEA-based methodology to

determine PSLs on the structure. These PSLs then serve as guidance for determining the motion trajectories of the FFF 3D Printer.

3.1.2 Algorithm Overview

This section explains the algorithm developed in this study. The algorithm initiates with establishing an FEA model tailored to a specific load case. Following this, the analysis yields a subset of PSLs within the design domain—lines that will govern the motion trajectory of the 3D printer. After this process, another FEA is conducted to deduce the distributions of maximum and minimum principal stresses across the design domain. These distributions serve to determine the intensity of PSLs in different regions. The intensity of these lines is arranged by translating readily available PSLs by a certain amount to increase the thicknesses of these paths in the final structure.

Once all paths are established, a final G-code is generated. This G-code file serves as a roadmap for the movement of the 3D printer nozzle, facilitating the fabrication of parts using an FFF 3D printer. The fundamental framework of the algorithm is presented in Figure 3.3. Two different structural cases are employed to demonstrate the algorithm's effectiveness: the MBB Beam and the Cantilever Beam. The following subsections detail the fundamentals of the part design process within these two distinct load cases.

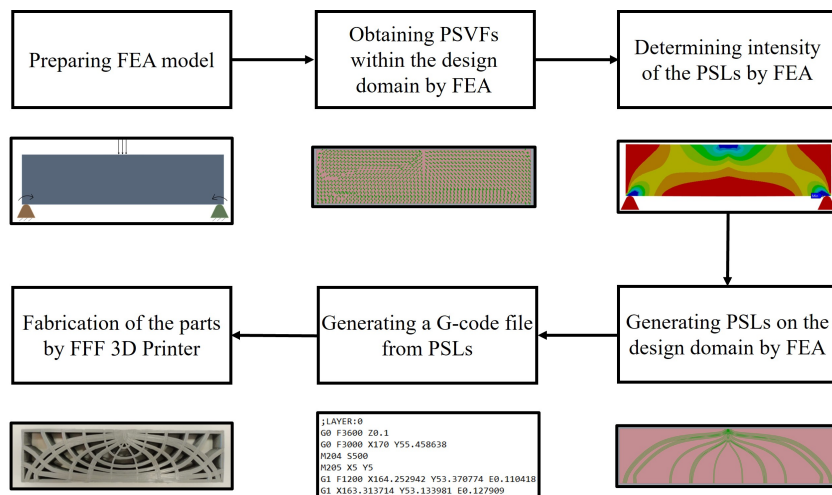


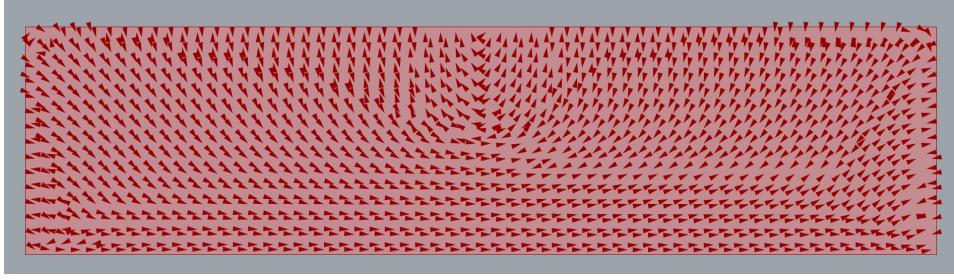
Figure 3.3: Pipeline of the algorithm

3.1.2.1 MBB Beam

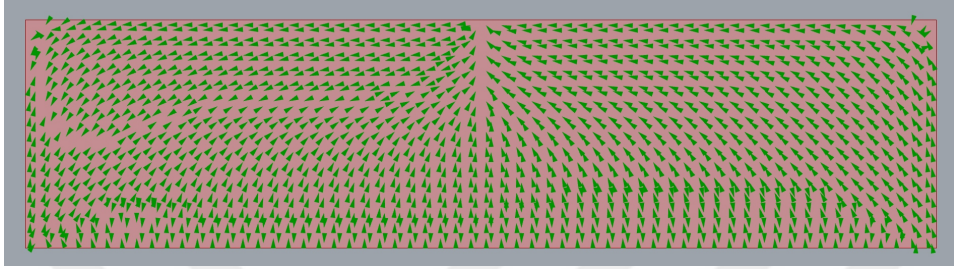
The initial step involves creating a 2D surface geometry measuring 120 mm by 30 mm, serving as the design space for optimization in Grasshopper 3D—a powerful parametric design tool within the Rhinoceros 3D suite. Subsequently, a 2 mm by 2 mm mesh is generated on this surface to facilitate FEA. As boundary conditions, a rotation degree of freedom is assigned to the bottom left corner of the beam, and a translation degree of freedom is given to the bottom right corner. Additionally, a force is applied at the midpoint of the top edge, mimicking the load and boundary conditions outlined in Figure 3.1. Furthermore, a specific material has been designated for this analysis. Combining these, the FEA model for this load condition is prepared, and the analysis is solved in Karamba 3D, an add-on of Grasshopper 3D for FEA.

The analysis yields vector results on the shell, including principal force and principal stress vector fields, directly within Karamba 3D. As depicted in Figure 3.4, the PSVFs acquired for the MBB Beam illustrate the trajectories of maximum and minimum principal stresses on the geometry corresponding to the load case examined. This insight also provides a visual representation of stress distribution across the structure. Afterward, equipped with a vector field spanning the design area, supplying appropriate starting points (source points) makes it possible to obtain trajectories that follow principal stress within the structure, referred to as PSLs.

As an initial approach, PSLs are constructed by selecting source points that are equally apart from each other along the beam's edges. This results in a homogenous distribution along either the bottom or top edge. PSLs can be categorized as either tensile or compressive, depending on whether the maximum or minimum principal stress vector field is employed during line construction. When the top edge of the beam is employed as source points for tensile lines, the resultant tensile PSLs are illustrated in Figure 3.5a. Similarly, if the bottom edge of the beam is used as source points for compressive lines, the corresponding compressive PSLs are shown in Figure 3.5b.

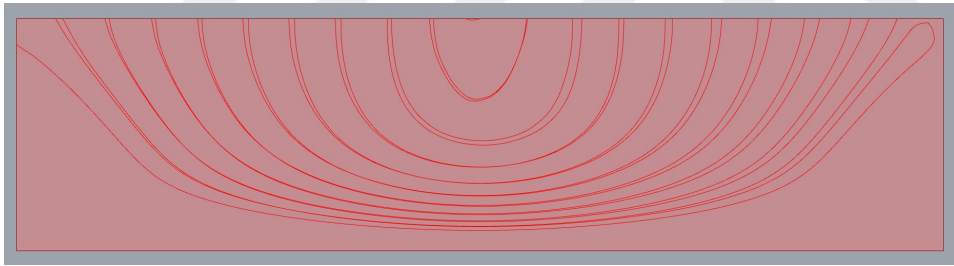


(a) Maximum PSVF

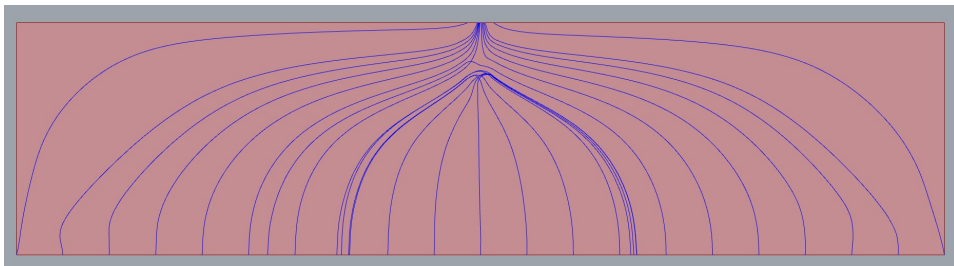


(b) Minimum PSVF

Figure 3.4: Maximum and minimum PSVFs for MBB Beam



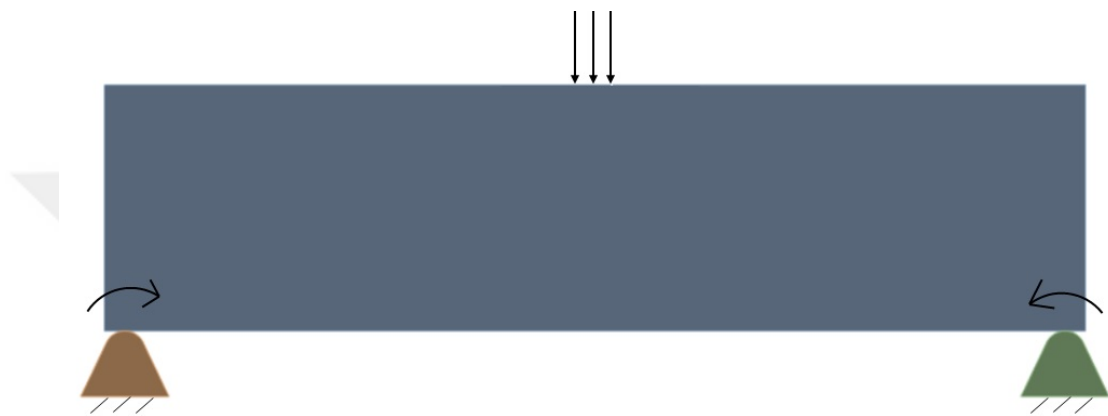
(a) Tensile PSLs



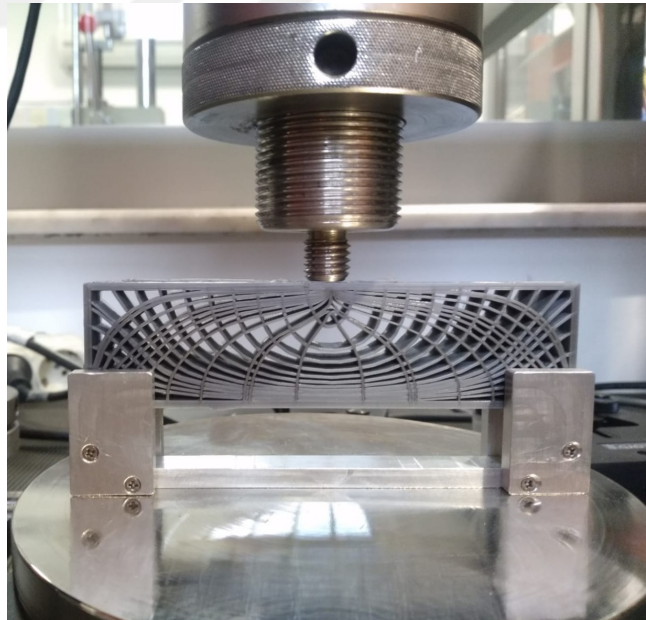
(b) Compressive PSLs

Figure 3.5: Tensile and compressive PSLs generated by homogeneous source distribution

The optimal selection of source points is pivotal in deriving optimal geometries by this method, as these points influence the trajectories by serving as the starting points for the paths. At this stage, the results of the static structural analyses from ANSYS are integrated. The beam is modeled as an entire block, with two supports simulated at the beam's base to replicate real-world structural testing conditions. The supports are defined with a rotational degree of freedom in the regions where they interface with the beam. A distributed force is also applied at the middle of the top edge. The analysis model and structural test configuration are depicted in Figure 3.6.



(a) Analysis model

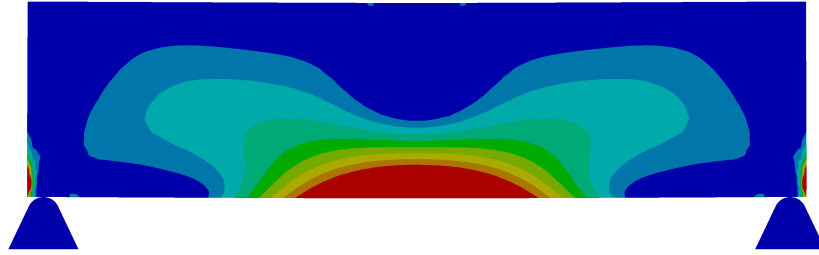


(b) Test setup

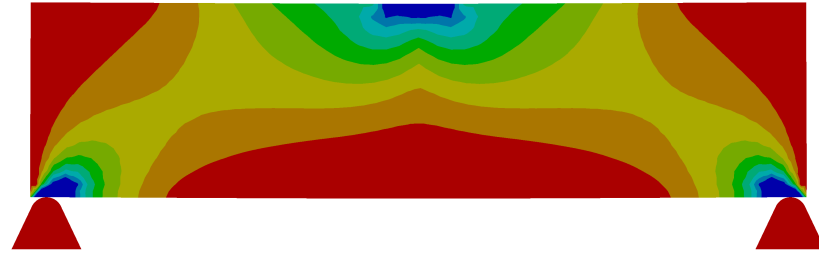
Figure 3.6: The analysis model and the test setup for the MBB Beam

The analysis outcomes are then employed to establish the maximum and minimum Principal Stress (PS) distributions across the beam. These distributions guide the determination of PSLs intensity. In regions where the maximum PS is high and the minimum PS is low, the number of PSLs is increased for enhanced strength. The areas with high maximum PS values, as indicated by the red regions in the maximum PS distribution of the beam (Figure 3.7a), require a denser arrangement of tensile PSLs. Similarly, regions with low minimum PS values, depicted in blue within the minimum PS distribution (Figure 3.7b), necessitate higher compressive PSLs intensity. The resulting PSLs, displayed in Figure 3.8, are subsequently integrated as input into the G-code file. This file dictates the toolpath and manufacturing parameters of the FFF 3D printer.

Each PSL shown in Figure 3.8 is represented by a polyline comprising multiple line segments. Coordinates of endpoints of these line segments serve as guidance for the 3D printer's toolpath. Furthermore, the length of these segments governs the amount of extrusion along these toolpaths. The thickness of these lines corresponds to the nozzle diameter of 0.6 mm, considering that the printer's nozzle traverses these paths just once. Supplementary printing parameters, including nozzle temperature, bed temperature, and print speed, are also integrated into the algorithm to formulate the appropriate G-code file. This file is subsequently sent to the printer, and Figure 3.9 presents the manufactured part printed by this methodology.

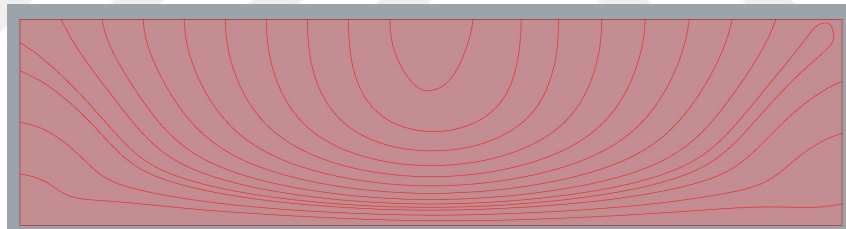


(a) Maximum PS distribution

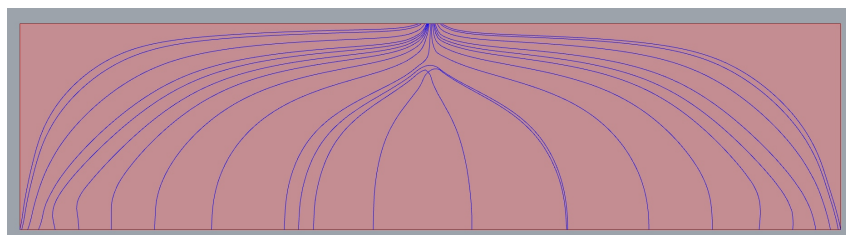


(b) Minimum PS distribution

Figure 3.7: Maximum and minimum PS distributions on the MBB Beam



(a) Tensile PSLs based on maximum PS



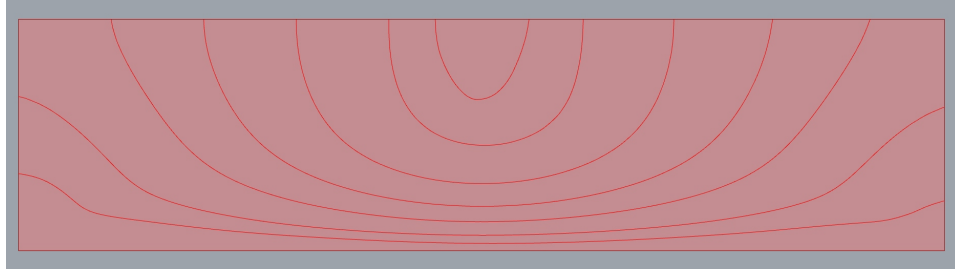
(b) Compressive PSLs based on minimum PS

Figure 3.8: Tensile and compressive PSLs generated by using PS distributions

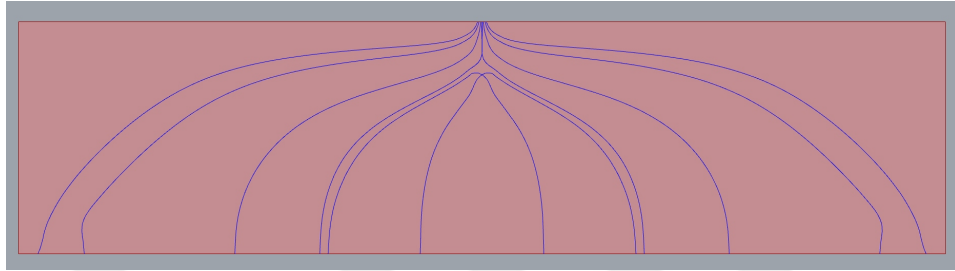
As detailed in the upcoming section on structural tests, the part resulting from the PSLs shown in Figure 3.9 resulted in inferior strength behavior due to weak connection points between these lines, rendering them susceptible to failure. This vulnerability might arise from the intrinsic nature of PSLs, which primarily endure axial loads (tensile or compressive) and are thus prone to buckling. Consequently, reinforcing these lines becomes crucial in specific regions to establish robust paths to counteract buckling. Due to these reasons, the algorithm evolved to increase the thickness of the lines for the regions of high max. PS and low min. PS, instead of increasing the number of independent, spaced-apart lines. Figure 3.10 presents the condensed versions of PSLs, their thicknesses adjusted by the prevailing high maximum PS and low minimum PS values across the design domain. To strengthen these lines, the readily available lines are translated 0.5 mm to both sides—accounting for the 0.6 mm nozzle diameter—to allow a 0.1 mm overlap for eliminating detachment. Figure 3.11 demonstrates the final generated toolpath encompasses these translated lines alongside boundary lines. The printed part produced through these toolpaths is presented in Figure 3.12.



Figure 3.9: The manufactured part with a layer thickness of 0.6 mm



(a) Tensile PSLs created by updated source points



(b) Compressive PSLs created by updated source points

Figure 3.10: PSLs created by updated source points

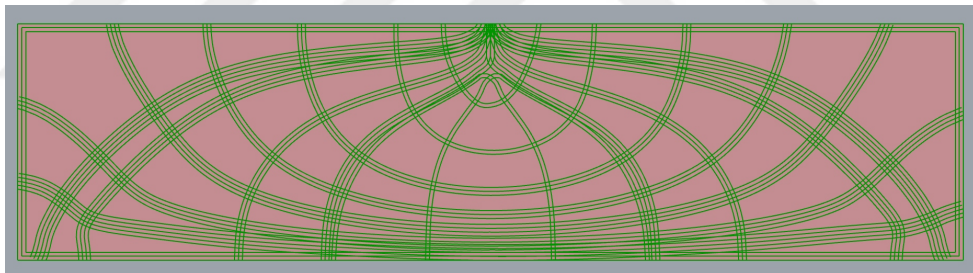


Figure 3.11: Final trajectories of the optimized geometry for the MBB Beam

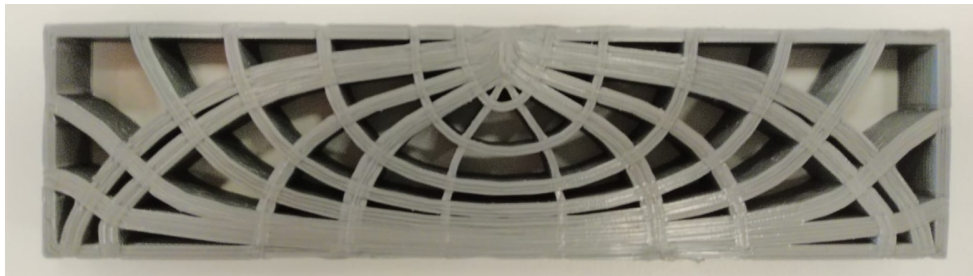


Figure 3.12: The MBB Beam manufactured part with the optimized infill pattern

3.1.2.2 Cantilever Beam

This second example follows a methodology analogous to that of the MBB Beam. Initially, an 80 mm by 50 mm surface geometry is defined as a design space. Before the analysis, the geometry is discretized into one mm-sized elements. To simulate the fixed boundary conditions, translation and rotation degrees of freedom of the left edge of this beam are restrained. Following the structural scenario depicted in Figure 3.2, an upward force is applied from the midpoint of the right edge of the beam to simulate the load case. Material properties are assigned for the FEA. Subsequently, the maximum and minimum PSVFs resulting from this analysis are presented in Figure 3.13.

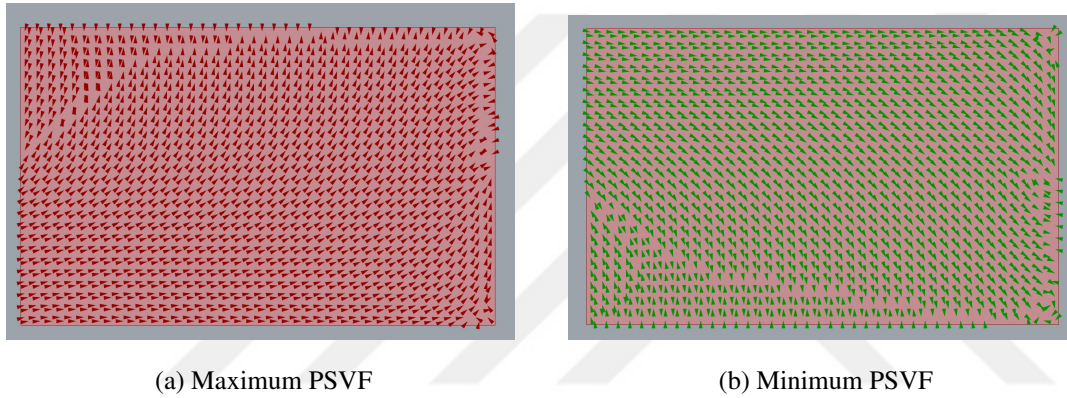


Figure 3.13: Maximum and minimum PSVFs for Cantilever Beam

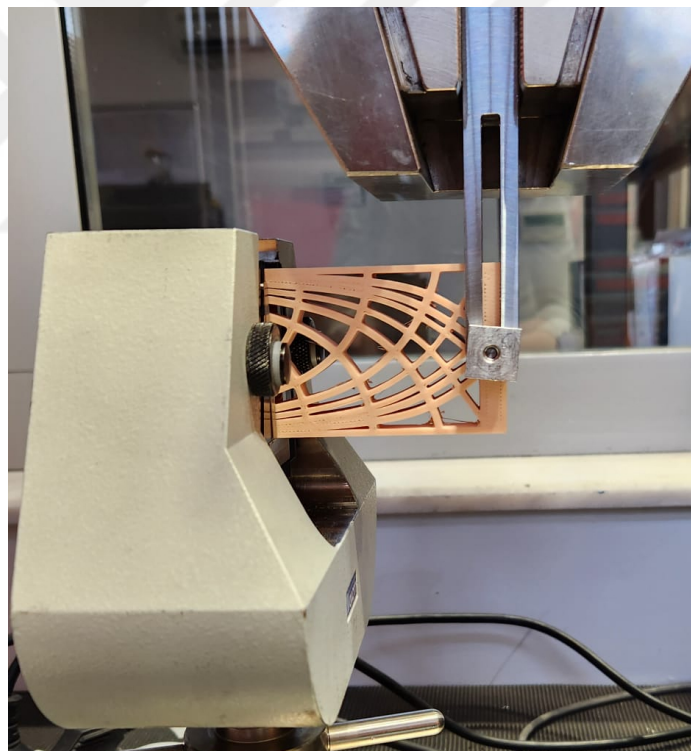
As in the case of the MBB Beam, a structural analysis is performed to optimize source point locations. A model representing the entire block of the beam is created, with an 8 mm segment fixed on the left side to simulate the boundary conditions of the actual test. For the load scenario, an upward force is applied through the hole on the right side of the beam. The analysis model, along with the physical testing setup, is depicted in Figure 3.14.

From the results of this analysis, both maximum and minimum PS distributions are obtained (Figure 3.15). Regions highlighted in red within Figure 3.15a signify areas of high maximum PS values, indicating the need for greater density of tensile PSLs. Conversely, blue-colored areas in Figure 3.15b correspond to the low minimum PS

values, signaling the requirement for increased density of the compressive PSLs in these regions. The generated PSLs, starting from appropriate source points, are portrayed in Figure 3.16. Subsequently, Figure 3.17 displays the version of PSLs with augmented line thicknesses.

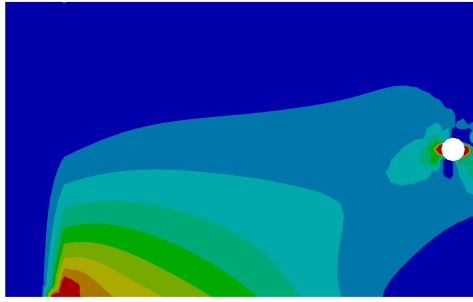


(a) Analysis model

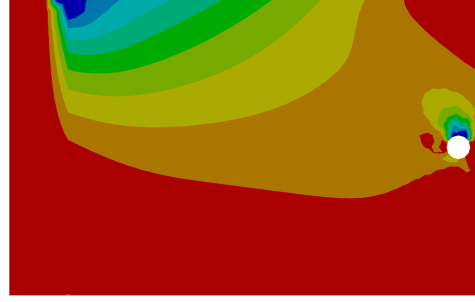


(b) Test setup

Figure 3.14: The analysis model and the test setup for the Cantilever Beam



(a) Maximum PS distribution



(b) Minimum PS distribution

Figure 3.15: Maximum and minimum PS distributions on the Cantilever Beam

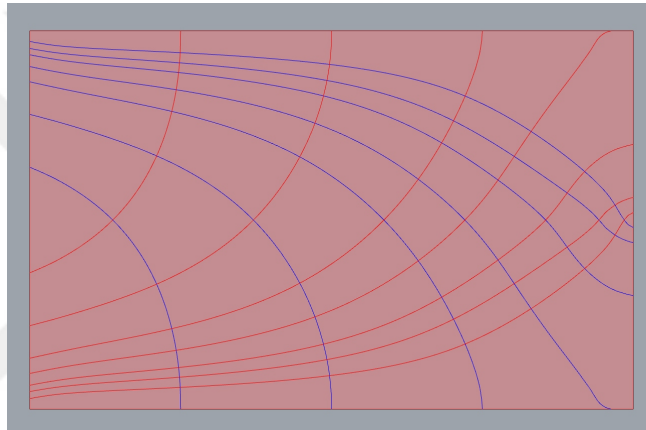


Figure 3.16: Tensile and compressive PSLs

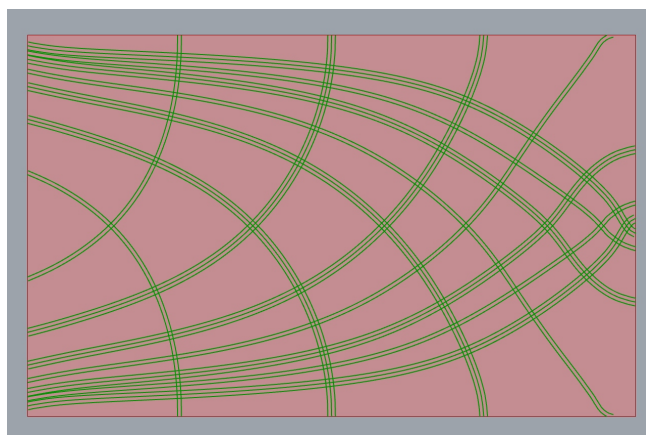


Figure 3.17: Toolpaths for the infill structure

Once the infill structure of the part is determined, it is essential to establish the appropriate boundaries that adhere to the requirements for testing. These boundaries should meet the requirements to be used in testing. Consequently, the 8 mm segment on the right side of the beam is designed to be solid, featuring a central hole. This design choice aims to mitigate stress concentration that might arise due to the application of the force in this area, thus preventing potential undesired failures. Similarly, the fixed boundary condition is addressed by filling an 8 mm segment on the left side of the beam to ensure optimal clamping. Nevertheless, as evidenced by the outcomes of the structural tests, this modest clamping area proves insufficient for robust clamping. As a result, this solid region is expanded to a width of 23 mm for more effective clamping. With the incorporation of these optimized boundary designs, the comprehensive toolpath is illustrated in Figure 3.18. Subsequently, the manufactured part, fabricated with these optimized infill geometries, is presented in Figure 3.19.

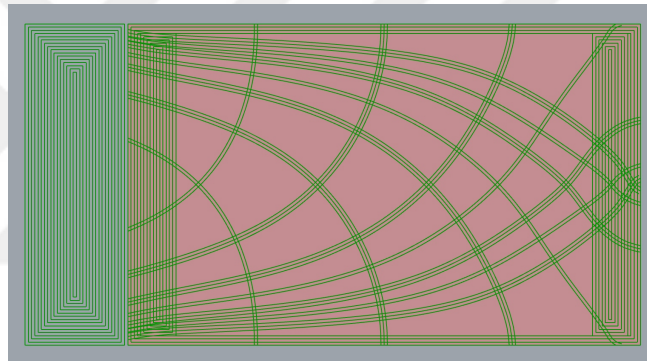


Figure 3.18: The whole toolpath for the optimized part

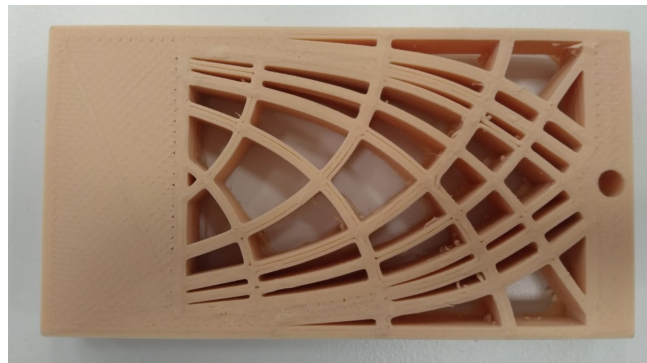


Figure 3.19: The manufactured Cantilever Beam with optimized infill patterns

3.1.3 Fabrication of the Test Parts

This section presents the fabrication of the test parts for the MBB and the Cantilever Beams.

3.1.3.1 MBB Beam

As described in the *Algorithm Overview* section, two distinct parts were designed using the PSLs approach for the MBB Beam case. Figure 3.21a exhibits the initial part fabricated with PSLs of uniform thickness. This configuration employed PSLs distributed according to the structure's maximum and minimum PS distribution, resulting in many independent PSLs. Their thickness matched the nozzle diameter, set as 0.6 mm, due to the M-FFF process's requirement for a hardened steel nozzle. This nozzle size was maintained for both the ABS test parts and the metal parts to ensure consistency.

Figure 3.21b illustrates the other part manufactured using PSLs within the design domain. This version incorporated fewer source points compared to the first variant. However, the thicknesses of the PSLs in this part were customized based on the maximum and minimum PS distribution obtained from the FEA. Two variations of this geometry were printed, differing in the printing order of the PSLs. One was manufactured by printing the tensile PSLs first, while the other prioritized the compressive PSLs. This divergence in printing order aimed to explore whether the sequence of PSLs printing influences the structural strength. Another test sample employing this optimized infill geometry was manufactured using the G-code generated through Cura. The main objective of producing this test sample is to compare the parts fabricated using the newly developed algorithm with those created through the conventional slicing process in Cura.

Throughout the manufacturing of the MBB Beam parts, an additional four parts were produced for a comprehensive structural performance comparison with the PSLs-based designs. These parts featured common triangular and grid infill patterns. Two were designed using ANSYS's SpaceClaim and imported as STL files into Ultimaker Cura for slicing. The remaining two parts had their infill patterns generated directly

within Cura, commonly used CAM software for the FFF method. This allowed for a comparative analysis of infill patterns created using different strategies. Notably, the infill of the SpaceClaim-designed part was printed as a *wall* within Cura, while the infill produced directly in Cura was printed as an *infill*.

In total, eight different test parts were manufactured for subsequent testing. The Ultimaker 3 Extended printer (Figure 3.20) was employed for fabrication using ABS material. To ensure a consistent basis for comparison, the same 3D printing parameters were applied across all the parts, as detailed in Table 3.1. Figure 3.21 visually demonstrates all the parts manufactured for the upcoming tests.

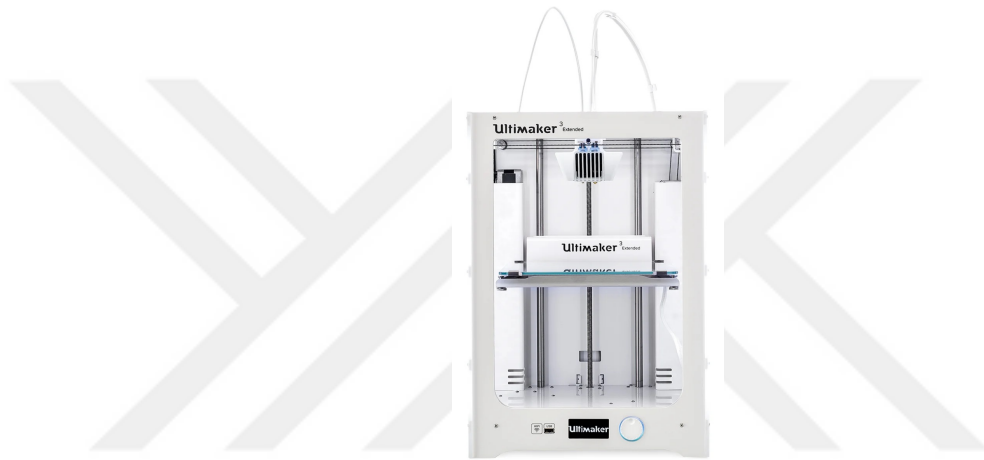


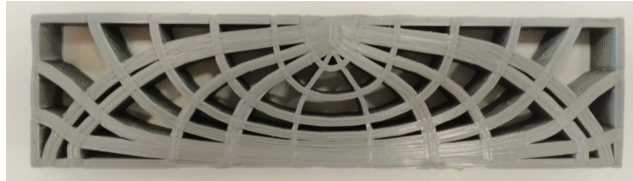
Figure 3.20: Ultimaker 3 Extended printer [38]

Table 3.1: Printing parameters of the ABS samples

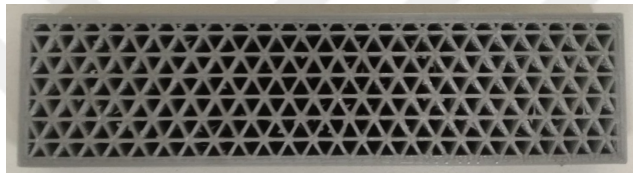
Parameters	Value	Units
Nozzle Diameter	0.6	mm
Layer Height	0.2	mm
Nozzle Temperature	230	°C
Bed Temperature	85	°C
Filament Diameter	2.85	mm
Printing speed	1200	mm/min



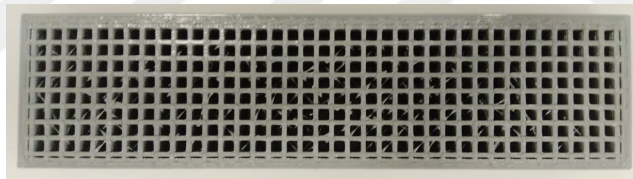
(a) Manufactured part with a layer thickness of 0.6mm



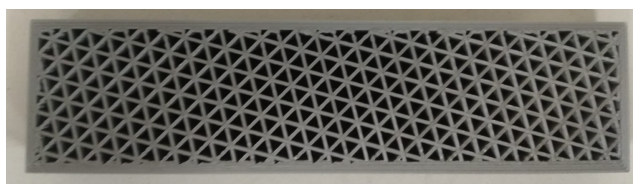
(b) Manufactured part with variable thickness (printed twice as tensile PSLs are printed first and compressive PSLs are printed first)



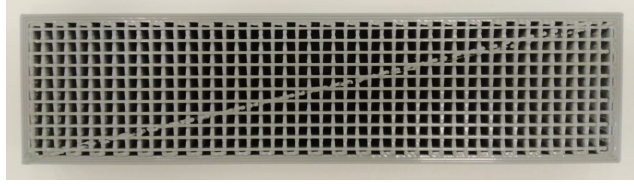
(c) Triangular infill from SpaceClaim



(d) Grid infill from SpaceClaim



(e) Triangular infill from Cura



(f) Grid infill from Cura



(g) Optimized infill fabricated using Cura

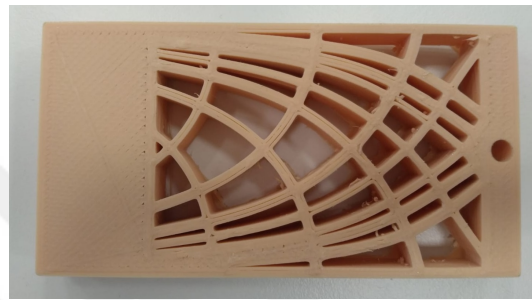
Figure 3.21: Test parts for the MBB Beam made of ABS

3.1.3.2 Cantilever Beam

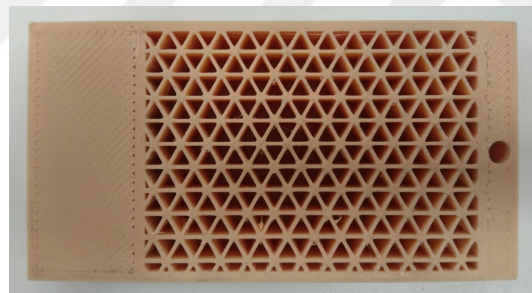
To demonstrate the effectiveness of this algorithm, tests were also performed for the Cantilever Beam case. First, the PSLs approach generated an optimized geometry as depicted in the *Algorithm Overview* section. PSLs within the design domain were identified, and their thicknesses were aligned with the maximum and minimum PS distribution across the design domain. The primary goal was to utilize this toolpath to generate a suitable G-code file for printing, similar to the MBB Beam case. However, in this scenario, the connection points of these lines posed challenges in achieving satisfactory mechanical behavior in the printed part. Moreover, the beam region designated for a fixed boundary condition constitutes a large area without voids. When using the algorithm's G-code to print this region, the extruded material becomes significantly denser than in other parts, leading to an uneven comparison between infill structures. As a solution, this optimized geometry was imported into Cura as an STL file, where slicing operations were conducted (Figure 3.22a). Although this approach relinquishes control over the nozzle's toolpath, it provides an opportunity to validate the optimization method's effectiveness.

Additionally, mirroring the approach taken with the MBB Beam case, two more parts were printed for comparison in terms of structural performance. Both parts were

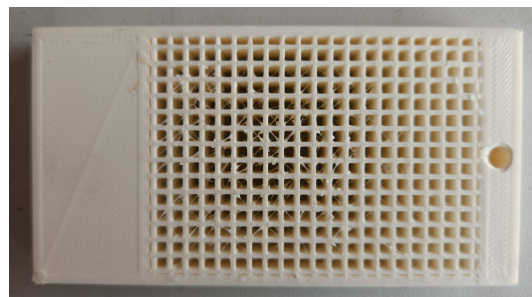
designed in SpaceClaim, and their respective STL files were imported into Cura for slicing operations. These parts feature common triangular and grid infill patterns. Just like the test parts for the MBB Beam case, the same printer and printing parameters (Table 3.1) were employed to fabricate these test parts. It is important to note that while these parts were intended to have a hole on their right side for force application, they were not printed with this hole. The hole is drilled after printing to account for any inaccuracies due to shrinkage during the FFF process. Figure 3.22 provides an overview of all the parts produced for the structural tests.



(a) Optimized part manufactured via Cura's G-code



(b) Triangular infill from SpaceClaim



(c) Grid infill from SpaceClaim

Figure 3.22: Test parts for the Cantilever Beam made of ABS

3.2 Structural Tests

This section explains structural tests carried out to assess the mechanical performance of the test parts. Lloyd Instruments LR100K plus tension-compression testing machine was employed for conducting these tests (Figure 3.23).



Figure 3.23: The test machine

3.2.1 MBB Beam

This section broadly explains the structural tests performed on the MBB test samples. Figure 3.24 offers a visual exposition of the test setup. As depicted in the figure, an additional part is designed for this test to provide rotation boundary conditions on the bottom corners of the test parts (Figure 3.25). In this test, a universal testing machine was utilized in the compression mode, with downward force applied from a circular region on the tip of the threaded piece shown in the figure. The main objective of this test is to compare the flexural strengths of the manufactured parts. To achieve this goal, the variation in applied force at the tip of the threaded piece was recorded as the test machine underwent vertical deflection, leading to the acquisition of force vs. deflection graphs. The loading was progressively increased until the fracture of the test parts, at which point the applied force value was identified as the strength limit of the test parts.

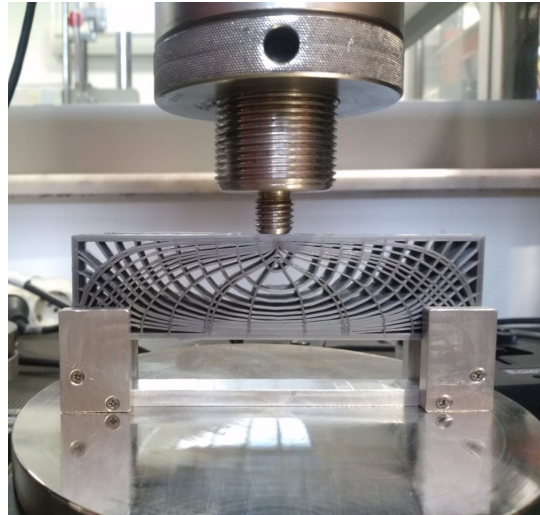


Figure 3.24: MBB Beam test setup



Figure 3.25: Part designed for boundary conditions

A detailed explanation of each test part is provided below.

1. Part with 0.6 mm thickness of PSLs

- This part is designed using numerous PSLs whose thicknesses are arranged as 0.6 mm. This signifies that the 3D printer's nozzle moves along these distinct lines once during printing.

2. Part with variable PSLs thickness and compressive PSLs are printed first.

- In this part, a limited number of PSLs are initially generated to enhance the thickness of the final infill trajectories. These lines are then translated based on the maximum and minimum PS distributions within the design domain, resulting in variable thickness infill paths. In this part, compressive PSLs are printed first.

3. Part with variable PSLs thickness and tensile PSLs are printed first.
 - Similar to the second part, this one also employs the same PSLs and the variable thickness infill pattern. However, in this case, the tensile PSLs are printed before the compressive ones.
4. Part with triangular infill designed in SpaceClaim
 - This part is characterized by a triangular infill pattern generated using SpaceClaim, the 3D modeling software.
5. Part with grid infill designed in SpaceClaim
 - Utilizing SpaceClaim, this test sample is designed with a grid infill pattern, distinct from the triangular pattern in the previous part.
6. Part with triangular infill generated in Cura
 - Similar to the fourth part, this test part employs a triangular infill pattern. However, the pattern is generated directly within the slicing software Cura.
7. Part with grid infill generated in Cura
 - As the fifth part, this test sample features a grid infill pattern. This pattern is generated using Cura.
8. Part with variable PSLs thickness whose trajectories are generated in Cura.
 - The same infill pattern as in Parts 2 and 3 is employed in this part. The distinguishing factor here is that the G-code is generated in Cura. As a result, the nozzle's trajectories do not directly follow PSLs; instead, a different path is used for fabrication.

3.2.1.1 Results

Eight distinct samples were tested in this configuration, and their respective force vs. deflection curves are detailed in Figure 3.26. Figure 3.27 demonstrates parts manufactured utilizing different infill strategies, each depicted in separate graphs.

Additionally, Table 3.2 provides the weights of the test parts, the force thresholds at which the onset of fracture occurs, and the resultant strength-to-weight ratios of these parts. The original components and their corresponding fracture shapes are represented from Figure 3.28 to Figure 3.35.

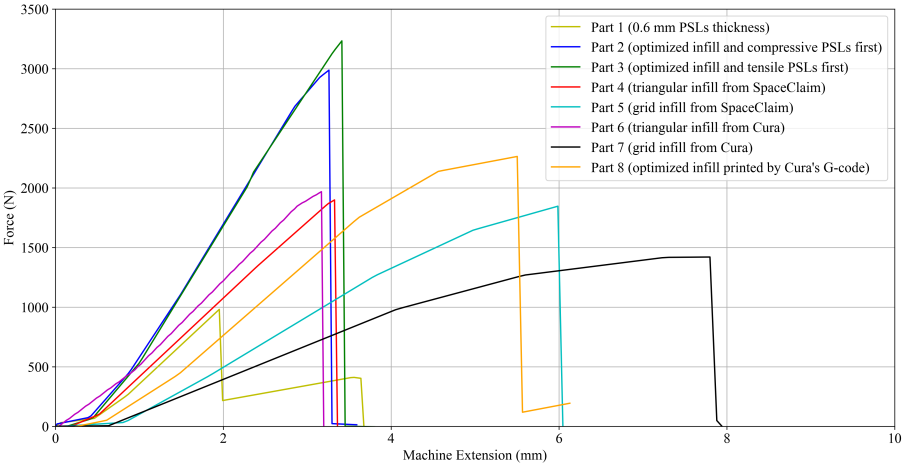


Figure 3.26: Force vs. deflection plots for all the MBB Beams made of ABS

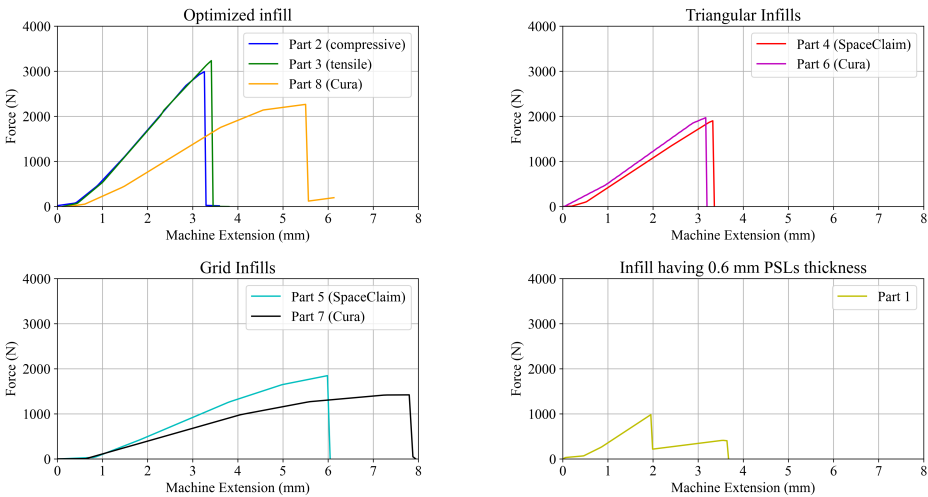


Figure 3.27: Force vs. deflection plots based on infill structures for all the MBB Beams made of ABS

Table 3.2: MBB Beam test results for all the ABS samples

Part Number	Weight (g)	Max. Force (N)	Strength-to-Weight Ratio (N/g)
1	24.0	981	40.9
2	30.0	2988	99.6
3	29.4	3233	110
4	25.2	1900	75.4
5	26.2	1846	70.5
6	27.2	2147	78.9
7	25.5	1420	55.7
8	24.8	2264	91.3

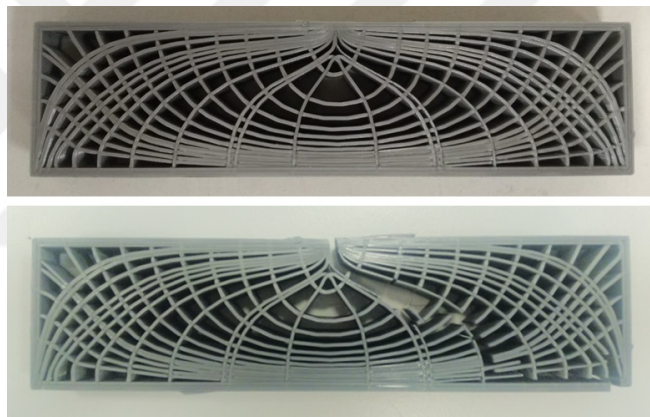


Figure 3.28: MBB Beam Part 1 and its fracture shape

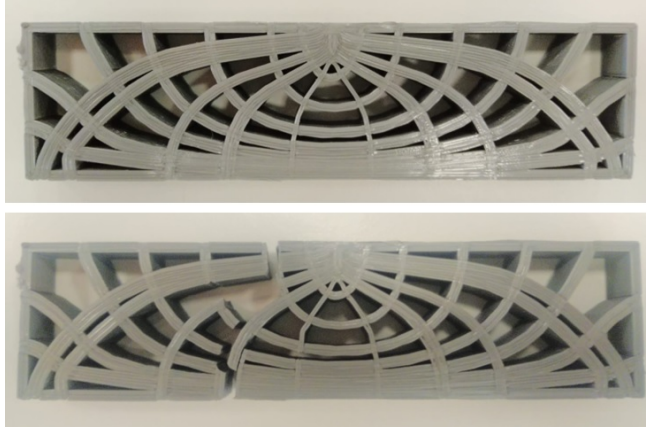


Figure 3.29: MBB Beam Part 2 and its fracture shape

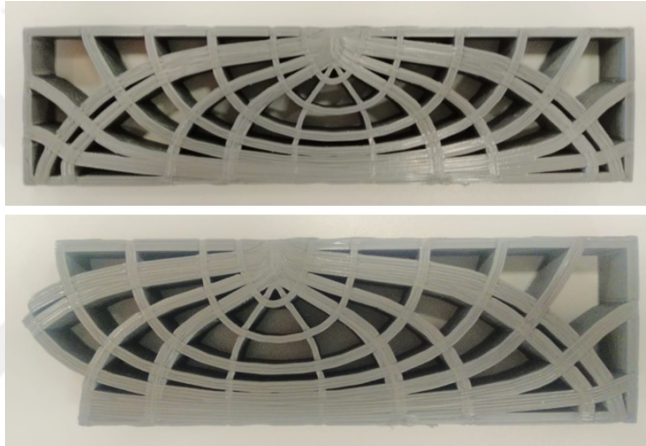


Figure 3.30: MBB Beam Part 3 and its fracture shape

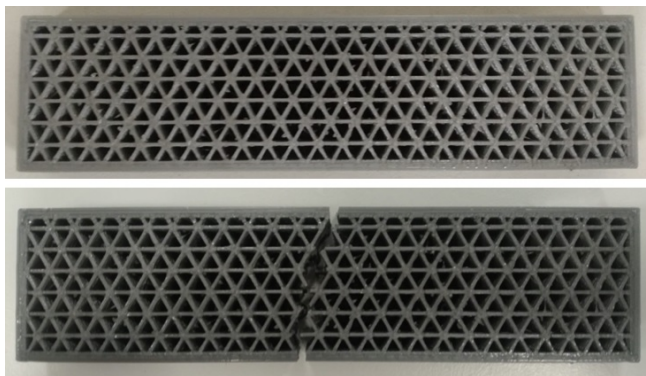


Figure 3.31: MBB Beam Part 4 and its fracture shape

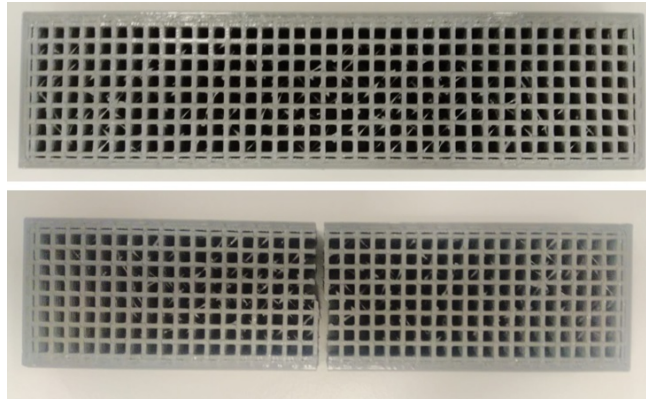


Figure 3.32: MBB Beam Part 5 and its fracture shape

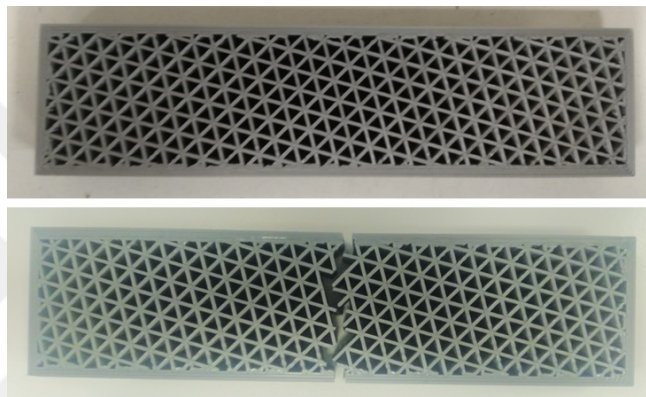


Figure 3.33: MBB Beam Part 6 and its fracture shape

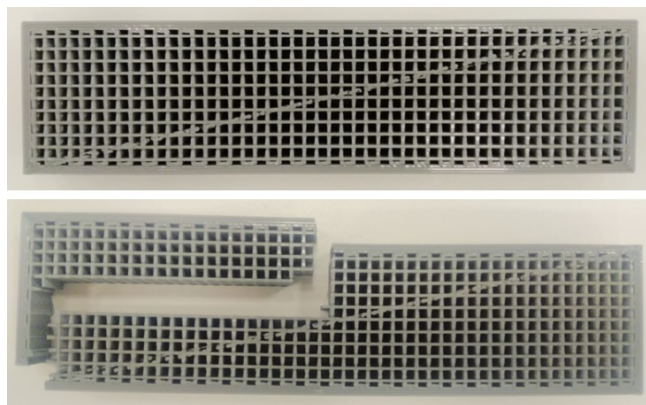


Figure 3.34: MBB Beam Part 7 and its fracture shape



Figure 3.35: MBB Beam Part 8 and its fracture shape

3.2.1.2 Conclusions

The conclusions drawn from the tests performed on the MBB Beam samples made of ABS are as follows.

- The highest force values at the point of fracture were observed for Parts 2 and 3, whose infill structures were generated according to the PSLs-based optimization algorithm. Despite having higher weights, these parts achieved significantly better strength-to-weight ratios than the other samples (99.6 N/g and 110 N/g). This suggests that the optimization algorithm effectively improved the mechanical strength of the parts.
- Comparison between Parts 2 and 3 revealed that the printing order of PSLs influences the strength of the parts. Part 3, where tensile PSLs were printed first, exhibited better mechanical performance. This indicates that the order in which the PSLs are printed affects the final strength of the part, aligning with the findings from other studies.
- Part 1, which featured PSLs with a thickness of 0.6 mm, displayed the weakest performance among all the samples. This could be attributed to two reasons. Firstly, thin PSLs that carry only axial loads are more prone to buckling. Secondly, the intersection points of these thin lines might not have been appropriately formed during the extrusion process.

- The other test samples having regular infill patterns (triangular and grid) demonstrated similar strength-to-weight ratios between each other. Parts with grid infill patterns displayed more extension before fracture than the other test samples, making them better candidates for applications demanding ductility.
- Furthermore, Figure 3.26 and Figure 3.27 demonstrate that similar infill patterns have analogous slopes of the curves in force vs. deflection plots, especially for triangular and optimized infills. This suggests that similar infill geometries result in nearly the same stiffness behavior.
- Significantly higher forces were measured at the fracture point in the parts featuring optimized infill patterns compared to the other samples. This can be attributed to the optimized infill aligning with the PSVFs within the structure, thereby enhancing their load-carrying capacity. It's worth noting, however, that this increased strength also resulted in lower ductility for these samples, as there typically exists an inverse relationship between ductility and strength in most engineering materials [39]. Conversely, the samples featuring grid infill patterns exhibited higher deformations than the other test parts. This suggests improved ductility but indicates a lower load-carrying capacity for these test samples due to the trade-off between strength and ductility inherent in their mechanical behavior.
- Additionally, Figure 3.26 and Figure 3.27 illustrate a nonlinear behavior observed in Parts 5, 7, and 8 as deflections reach higher values. This behavior can be attributed to the escalating geometric nonlinearity that becomes more pronounced with increasing deflections.
- Lastly, the strength-to-weight ratio of the parts having optimized infill pattern was compared with a full solid beam to observe enhancement in this ratio. A relevant study by Kandemir et al. [40] involved the fabrication of a filled specimen using ABS material. They conducted a three-point bending test, analogous to the MBB Beam test in this study, and recorded a force value of 2276 N at 3 mm deflection for a specimen weighing 37.7 grams. This translates to a strength-to-weight ratio of 60.3 N/g.

In contrast, in this thesis, the force value measured at 3 mm deflection for Part

3 reached approximately 2800 N. Consequently, the strength-to-weight ratio for Part 3 at this 3 mm deflection was calculated as 95.2 N/g. Remarkably, this signifies a nearly 58% improvement in the strength-to-weight ratio when employing the optimized infill pattern, as opposed to filling the interior of the part. This highlights the advantages of the optimized infill pattern in achieving superior strength-to-weight performance.

3.2.2 Cantilever Beam

This section presents structural tests performed on the Cantilever Beams. The test setup is depicted in Figure 3.36. The setup involves a clamp that secures the left side of the part to establish a fixed support condition. The testing machine operates in tension mode, applying a tension load to the beam. A hole is incorporated into the test parts in line with the loading configuration. A pin is inserted into this hole, and an additional component is designed to make contact with this pin. This arrangement facilitates the transmission of force from the testing machine to the pin, resulting in an upward force being applied to the middle of the right edge of the test part.

The primary objective of these tests was to compare the strengths of the different test part configurations and infill patterns for the Cantilever Beam samples. As for the MBB Beam tests, the applied force was incrementally increased until the test parts fractured. Throughout the testing process, force vs. deflection curves were generated to characterize the behavior of the parts under loading. The experimental results aimed to provide valuable insights into the relative structural performance of the various test part configurations, shedding light on the effectiveness of the optimized infill structures and infill patterns in the context of the Cantilever Beam scenario.

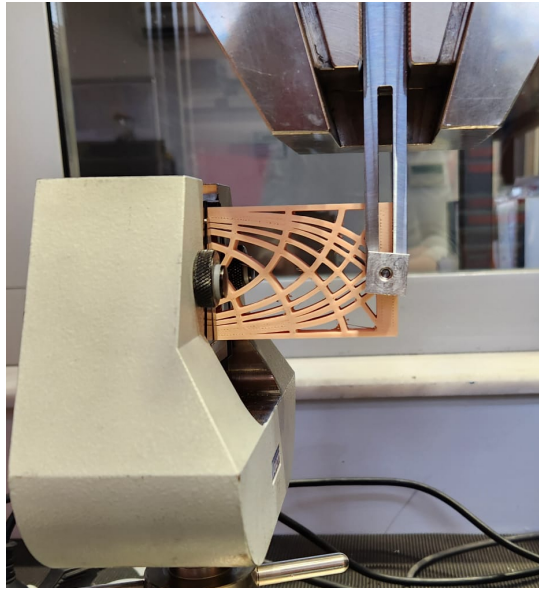


Figure 3.36: Cantilever Beam test setup

The Cantilever Beam test parts are detailed as follows.

1. Part with PSLs-based optimized infill whose G-code is generated by Cura.
 - This test part features an optimized infill structure derived from PSLs. The G-code for fabricating this part is produced using Cura. Unlike some of the PSLs-based samples in the MBB Beam case, where the printer's nozzle directly followed PSLs for motion guidance, here, Cura generates the toolpath automatically. This means the printer's nozzle trajectory does not strictly adhere to the PSLs as in the MBB Beam case.
2. Part with triangular infill designed in SpaceClaim
 - This test part employs a triangular infill pattern designed in SpaceClaim.
3. Part with grid infill designed in SpaceClaim
 - For this test sample, a grid infill pattern created in SpaceClaim is utilized.

3.2.2.1 Results

Under this configuration, three different parts were subjected to testing. These parts were equipped with PSLs-based optimized, triangular, and grid infill. The force vs. deflection plots depicting their behaviors are shown in Figure 3.37. Also, Table 3.3 exhibits the weights of the parts, the force values recorded at the fracture, and the corresponding strength-to-weight ratios of these parts. The test parts and their respective fracture patterns are also presented from Figure 3.38 to Figure 3.40.

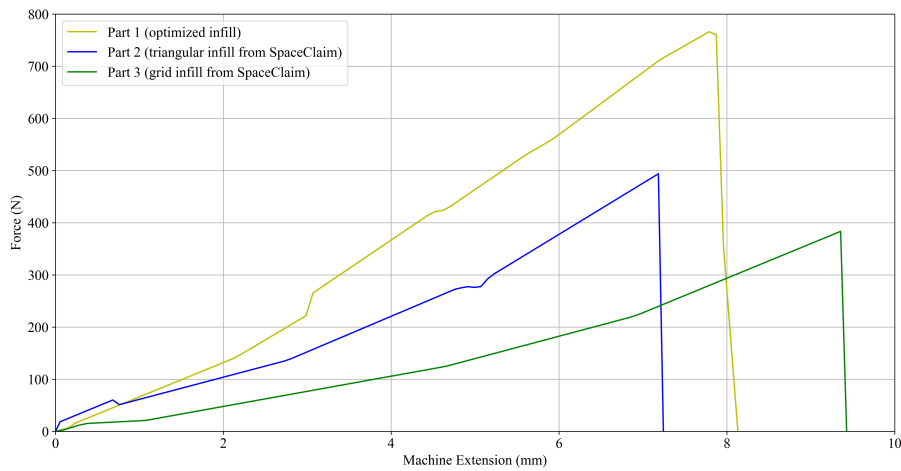


Figure 3.37: Cantilever Beam force vs. deflection plots for all the ABS samples

Table 3.3: Cantilever Beam test results for all the ABS samples

Part Number	Weight (g)	Max. Force (N)	Stregth-to-Weight Ratio (N/g)
1	32.0	760	23.8
2	29.2	495	16.9
3	32.2	385	11.9

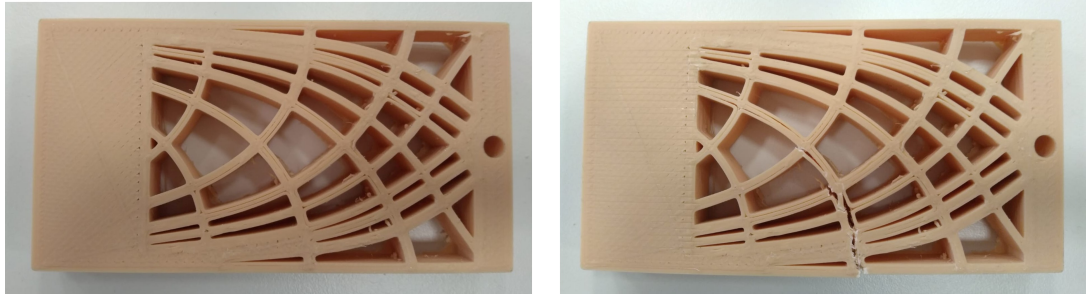


Figure 3.38: Cantilever Beam Part 1 and its fracture shape

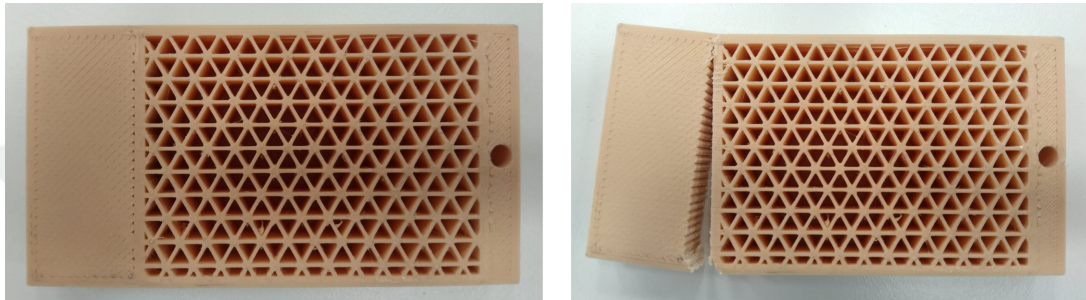


Figure 3.39: Cantilever Beam Part 2 and its fracture shape

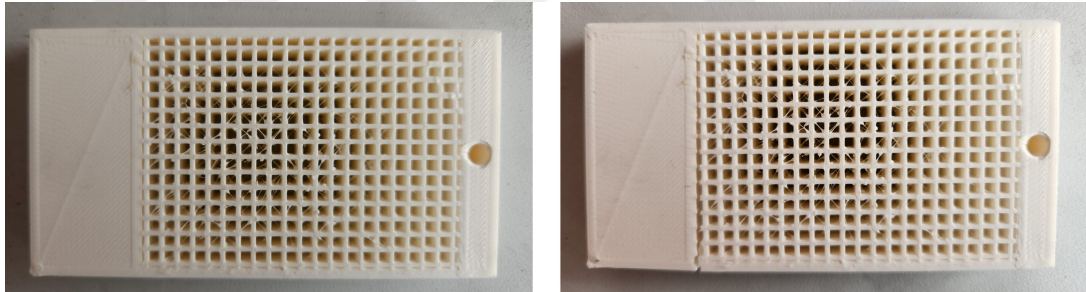


Figure 3.40: Cantilever Beam Part 3 and its fracture shape

3.2.2.2 Conclusions

The conclusions drawn from the Cantilever Beam test samples manufactured using ABS material are as follows.

- Part 1, which features the optimized infill structure and is sliced using Cura, demonstrated the best mechanical performance among all the samples. It ex-

hibited a force of 760 N at the fracture point, resulting in a strength-to-weight ratio of 23.8 N/g. This ratio was nearly 40% higher than that of Part 2, which features a triangular infill pattern. Part 2 also showcased an enhanced strength-to-weight ratio compared to Part 3, which employs a grid infill.

- Unlike the MBB Beam case, Part 2, with triangular infill created in SpaceClaim, exhibited a distinct strength-to-weight ratio compared to Part 3, which featured a grid infill pattern also generated in SpaceClaim. The strength-to-weight ratio difference between these two parts was approximately 42%.
- Similarly, in the Cantilever Beam tests, the component with a grid infill pattern exhibited greater ductility compared to the samples with different infill patterns, as observed in the MBB Beam tests.

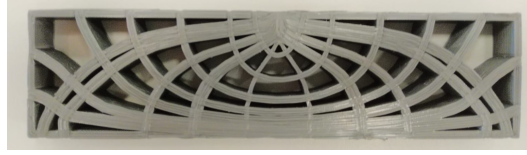
3.3 Structural Analyses

In this section, structural analyses of the test parts are presented. In addition to testing, the mechanical performance of these test parts was also compared by structural analyses. These analyses were conducted in ANSYS Workbench 2023R1.

The algorithm used in this thesis generates lines to be used as trajectories of the 3D printer in one layer, and by using these lines, a G-code file is generated that follows these lines in all layers. Because of the conversion of lines directly into commands for the printer, no CAD file is generated in this algorithm. Therefore, a 2D or 3D geometry should be created from these lines for structural analyses. First, the lines obtained from the algorithm were imported into SpaceClaim, the 3D modeling software of ANSYS, to prepare the geometry for the analysis. A 2D surface geometry was created from these lines according to the thicknesses on the final part. The reason for using 2D surface geometry is that the MBB and Cantilever Beam loading conditions are in-plane. Therefore, plane stress analysis is suitable for these load cases. For example, Figure 3.41 shows a geometry created for the analyses and its manufactured version.



(a) Geometry created for the analysis



(b) Its manufactured version

Figure 3.41: The analysis geometry and the printed part

In addition to test parts generated from PSLs, other test parts with triangular and grid infill were manufactured for comparison purposes. The infill patterns of some of these parts were created in Cura. After importing an STL file, Cura generates infill patterns for these parts while selecting printing parameters. However, these parts cannot be exported from Cura as a CAD file format and imported into ANSYS for analyses. Therefore, some test parts' infill patterns were created in SpaceClaim to conduct structural analysis on these parts.

Due to the in-plane loading condition, 2D plane stress analyses were conducted on the test parts. Although the FFF 3D printing process has some factors that can influence analyses, such as the directionality of printing, these factors were not included in the analyses. For more accurate analyses, some of the material properties should be determined from material characterization tests. However, for the scope of this thesis, isotropic material properties for ABS material were employed to compare only the mechanical performance of different infill patterns, and a linear elastic material model was used in these analyses.

Plastic ABS (high-impact) material in the material library of ANSYS is used for the test parts. Its material properties, such as density, Young's Modulus, Poisson's ratio, yield strength, and ultimate tensile strength, are tabulated in Table 3.4.

Table 3.4: Material properties of Plastic ABS (high-impact)

Property	Value	Units
Density	1030	kg/m ³
Young's Modulus	1.628	GPa
Poisson's Ratio	0.4089	-
Tensile Yield Strength	27.4	MPa
Tensile Ultimate Strength	36.3	MPa

3.3.1 MBB Beam

Linear static analyses were conducted in three parts for the MBB Beam case. These are PSL-based optimized infill, triangular infill, and grid infill. To simulate a real structural test scenario, two supports were modeled at the bottom corners of the part to simulate rotation freedom at these regions. Remote displacements were defined in these regions, allowing only the rotation degree of freedom of the beam on the z-axis with respect to the supports. A distributed forcing was applied on the middle of the top edge of the beams. The same amount of force (200 N) was used for all analysis cases for comparison purposes.

Figure 3.42 shows the analysis model for optimized infill as an example.

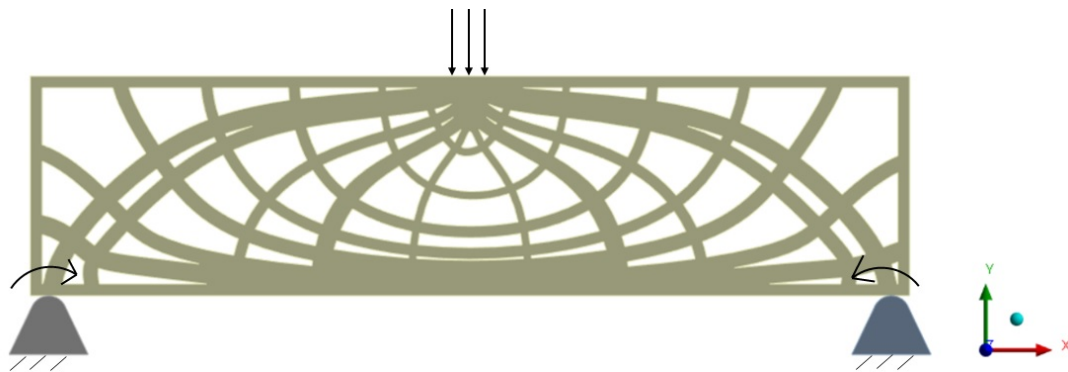


Figure 3.42: MBB Beam analysis model

3.3.1.1 Results

As the results of the structural analyses, total deformation and equivalent Von-Mises stress distributions on the test parts are determined. These results are presented in Figure 3.43 and Figure 3.44.

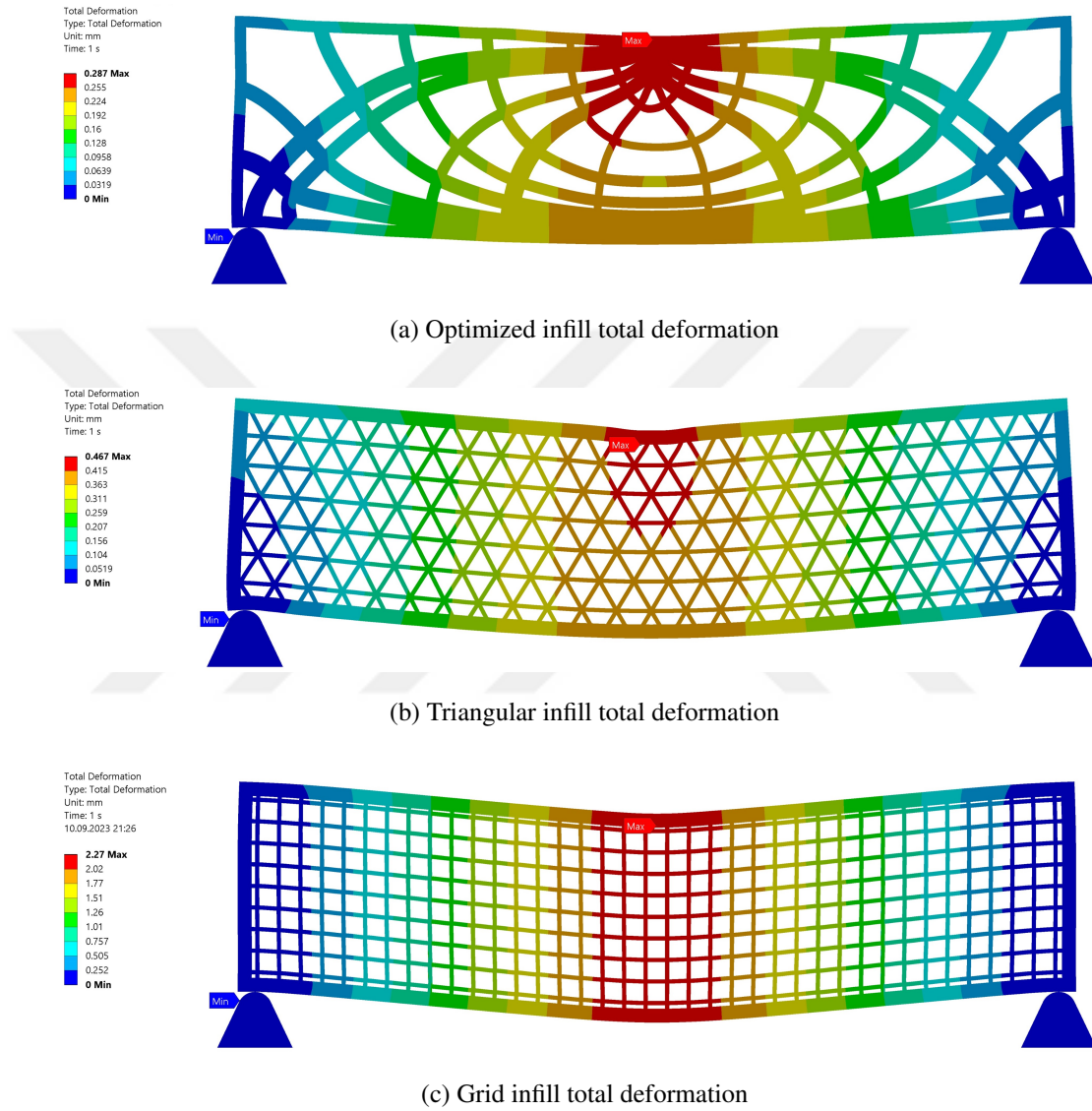
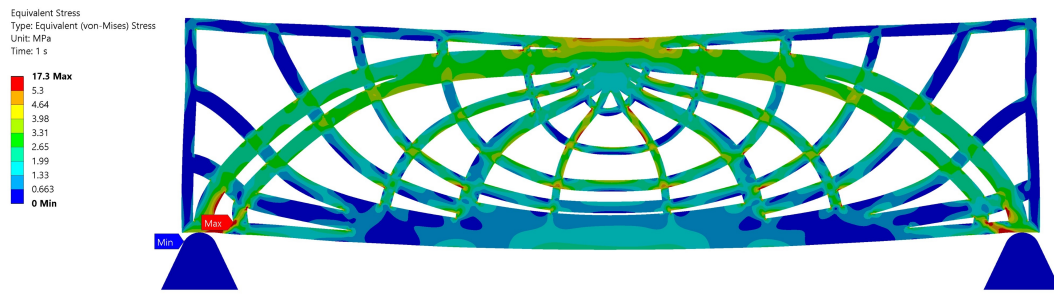
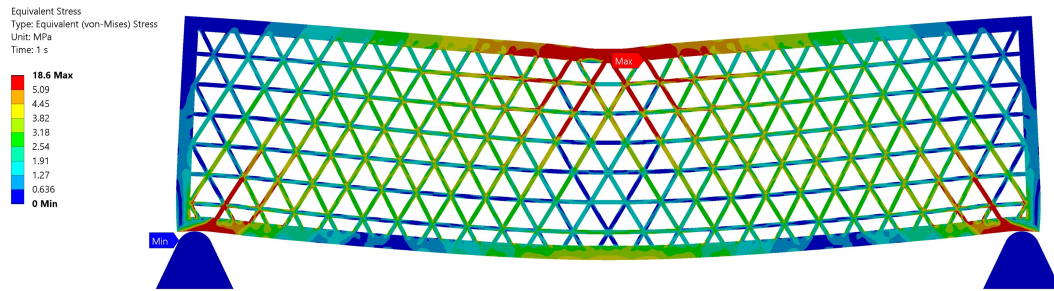


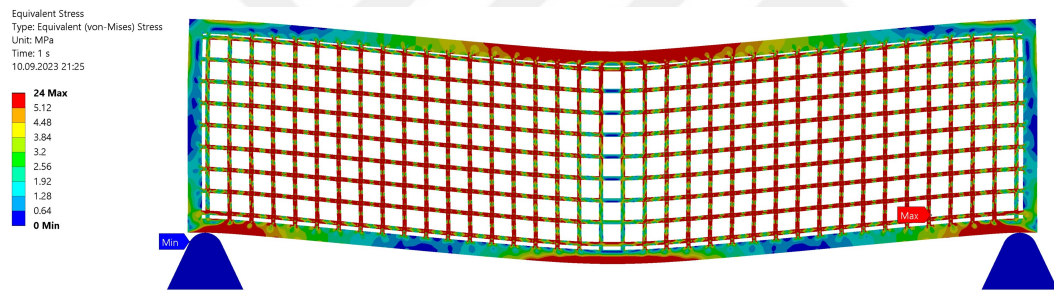
Figure 3.43: Total deformation results for MBB Beam test parts



(a) Optimized infill equivalent Von-Mises stress



(b) Triangular infill equivalent Von-Mises stress



(c) Grid infill equivalent Von-Mises stress

Figure 3.44: Equivalent Von-Mises stress results for MBB Beam test parts

3.3.2 Cantilever Beam

Like the MBB Beam case, linear static analyses were performed for the Cantilever Beam case. The parts used in these analyses employ PSL-based optimized, triangular, and grid infill. As in the actual structural tests, the left portion of the beam is fixed during the analyses. Also, an upward force was given in the upper half edge of the hole at the right side of the beam. The same amount of force (200 N) was used for all analysis cases for comparison purposes.

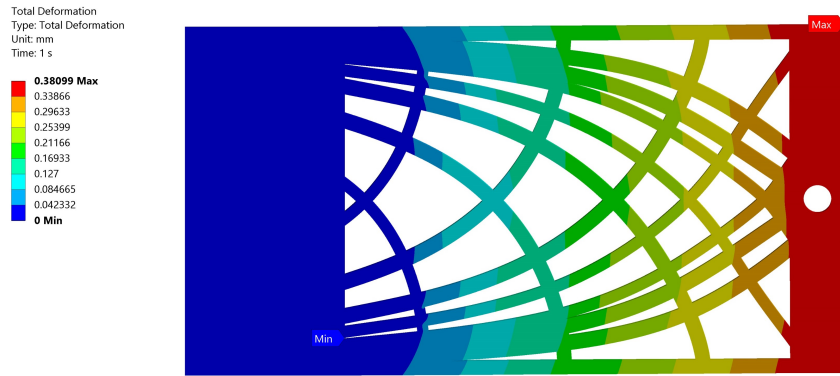
Figure 3.45 shows the analysis model for optimized infill as an example.



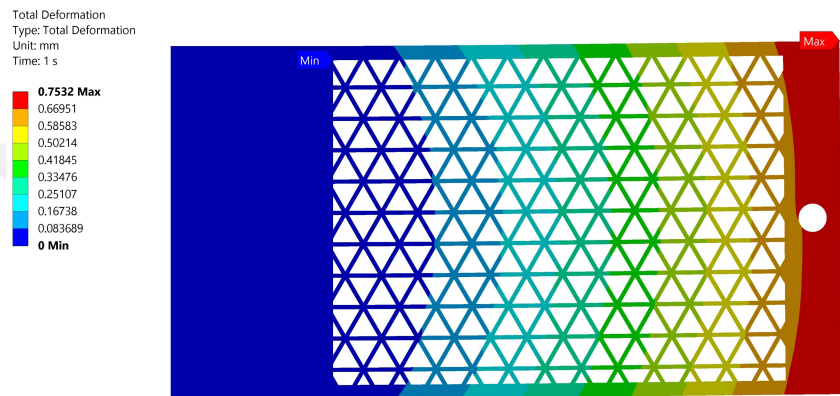
Figure 3.45: Cantilever Beam analysis model

3.3.2.1 Results

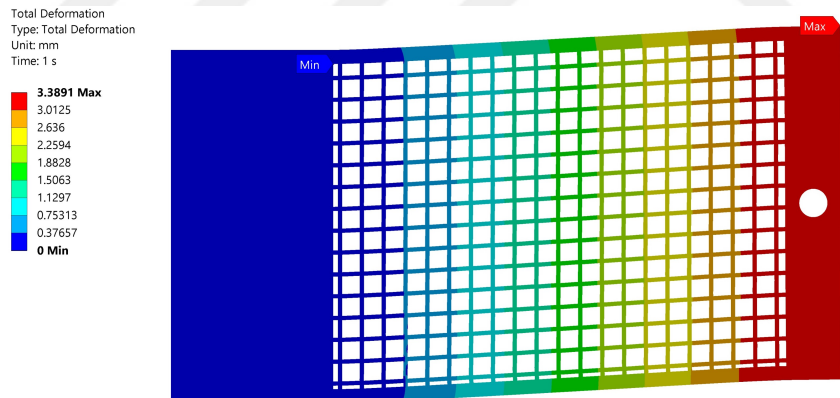
As the results of the structural analyses, total deformation and equivalent Von-Mises stress distributions on the test parts were determined. These results are presented in Figure 3.46 and Figure 3.47.



(a) Optimized infill total deformation

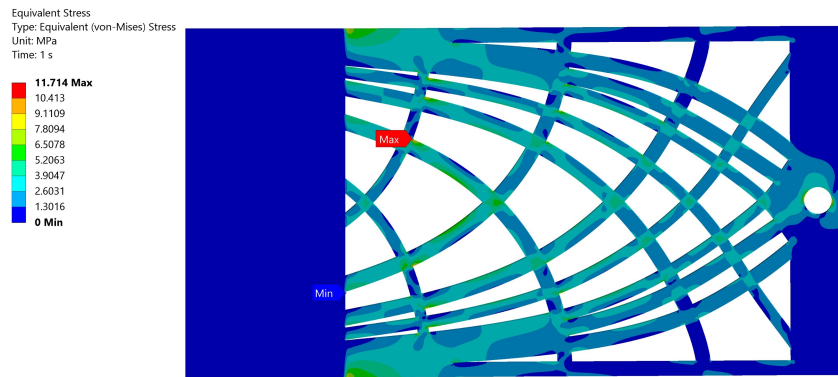


(b) Triangular infill total deformation

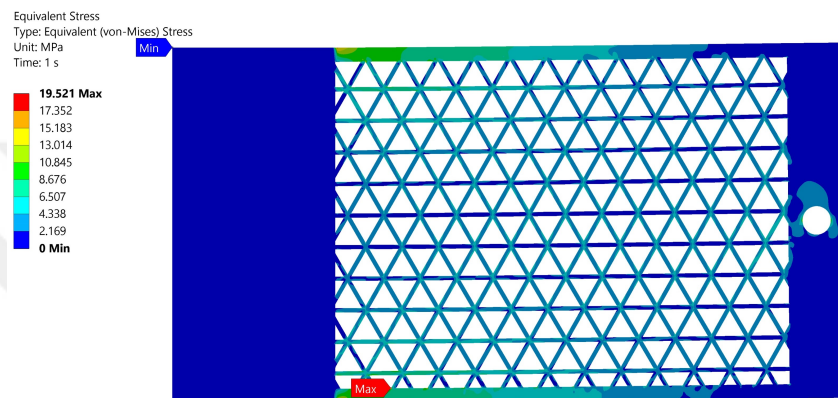


(c) Grid infill total deformation

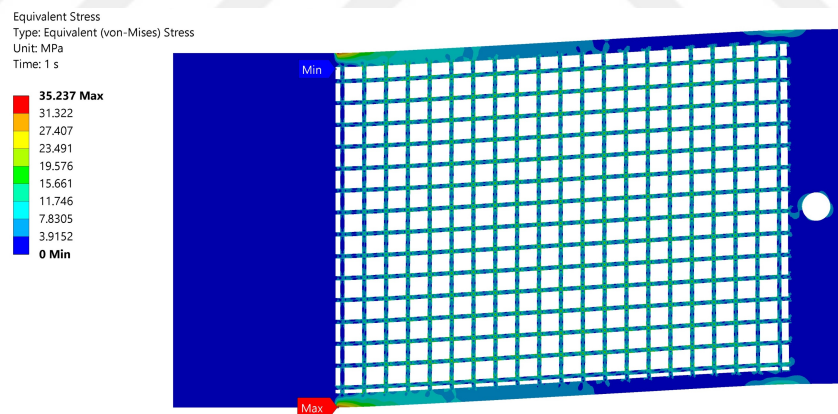
Figure 3.46: Total deformation results for Cantilever Beam test parts



(a) Optimized infill equivalent Von-Mises stress



(b) Triangular infill equivalent Von-Mises stress



(c) Grid infill equivalent Von-Mises stress

Figure 3.47: Equivalent Von-Mises stress results for Cantilever Beam test parts

3.3.3 Conclusions

The conclusions drawn from the structural analyses of the MBB Beam and Cantilever Beam test samples are presented below.

- While these analyses were preliminary and aimed at comparing structural performances of samples with different infill patterns, the total deformation outcomes of the samples mirrored the trends depicted in Figure 3.26 and Figure 3.37. Notably, when an equivalent amount of force was applied to the test samples, the least deformations were observed in parts employing PSLs-based optimized infills. Conversely, the highest deformations were recorded in samples featuring the grid infill patterns.
- In terms of equivalent Von-Mises stress values, a comparison between parts utilizing different infill patterns revealed that samples with the grid infill pattern exhibited the highest stresses, in contrast to those employing triangular and optimized infill structures. While stress results were similar for samples with optimized and triangular infills in the MBB Beam case, it's noteworthy that parts with optimized infill patterns displayed lower stresses than those with triangular infills.

CHAPTER 4

METAL FUSED FILAMENT FABRICATION OF TEST PARTS

This chapter is devoted to the parts manufactured by the M-FFF method. This fabrication technique was implemented to manufacture the metal versions of the test parts explained in the previous chapter. The reason for choosing this manufacturing approach lies in incorporating a material extrusion process within an FFF 3D printer during its initial phase. This permits control of the path of the extrusion and to intervene in the printing order. The test parts were fabricated with two different metal filaments, which are 17-4PH SS and 316L SS. The components made with the 17-4PH SS filament were printed using a Metal X 3D printer developed by Markforged. After printing, a debinding stage involving a solvent and subsequent sintering process in a furnace produces 17-4PH SS metal components. In this manufacturing process, the STL files of the test parts were supplied to the company, and the manufacturer company carried out all the stages, from printing to sintering. Apart from this, these test parts were also fabricated by using BASF Ultrafuse 316L SS filament. As opposed to manufacturing with 17-4PH SS filament, the printing stage was accomplished in this production by the readily available Ultimaker 3 Extended printer in the laboratory. This allows for control over the G-code used for printing the initial shape and observing how different toolpaths affect the strength of the test components. Subsequent sections provide more details on these M-FFF manufacturing methods, the resulting test components, and the subsequent structural evaluations conducted on these specimens.

4.1 17-4PH Stainless Steel Test Parts

As outlined in the preceding chapter, two structural scenarios, namely the MBB Beam and the Cantilever Beam, were examined to showcase the algorithm's efficacy. For these scenarios, samples with different infill patterns were manufactured with ABS material to compare their structural performance with the outcomes presented in Chapter 3. Correspondingly, identical components were produced utilizing the M-FFF technique and 17-4PH SS material. Subsequent structural assessments were conducted to compare these infill patterns. Since the manufacturing process involved supplying the STL files to the manufacturer, controlling the sequence of printing these samples was impossible. Therefore, the comparison primarily pertains to the infill patterns employed in the specimens. Detailed explanations of these parts are provided below. Additionally, Figure 4.1 and Figure 4.2 showcase the 17-4PH SS test components.

1. MBB Beam with optimized infill

- This MBB Beam example incorporates an optimized infill pattern based on PSLs, and the software manages its printing sequence.

2. MBB Beam with triangular infill

- This component features a triangular infill structure that was generated using SpaceClaim.

3. MBB Beam with grid infill

- The infill design for this part utilizes a grid pattern created in SpaceClaim.

4. Cantilever Beam with optimized infill

- This Cantilever Beam test sample is obtained by a PSLs-based optimized infill pattern whose printing order is controlled by the software.

5. Cantilever Beam with triangular infill

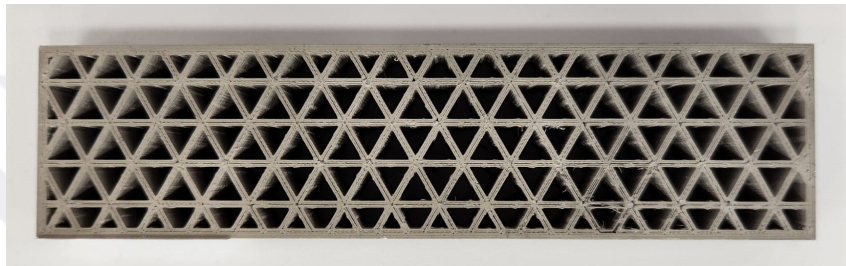
- This test component is fabricated with a triangular infill structure designed using SpaceClaim.

6. Cantilever Beam with grid infill

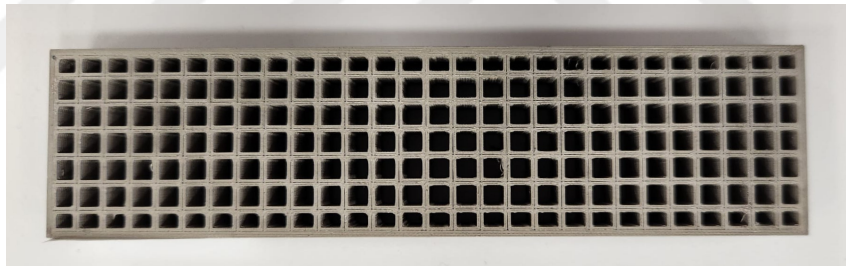
- The test sample employs a grid infill pattern generated in SpaceClaim.



(a) Part 1: MBB Beam having optimized infill

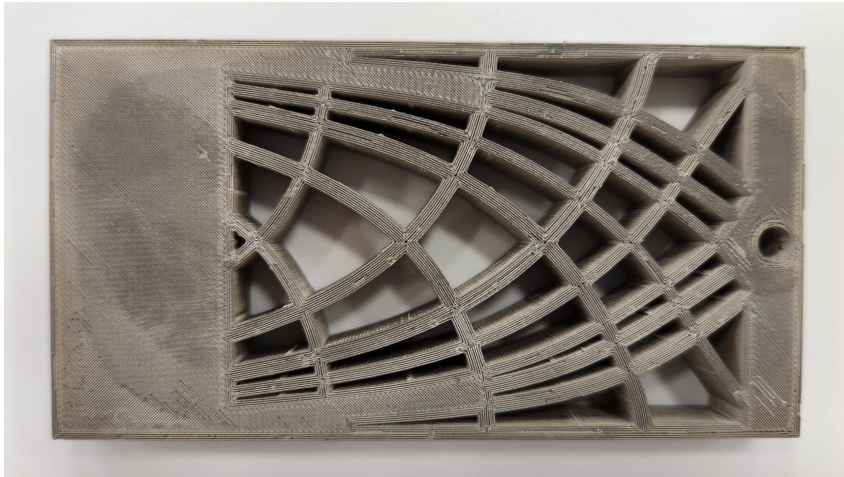


(b) Part 2: MBB Beam having triangular infill

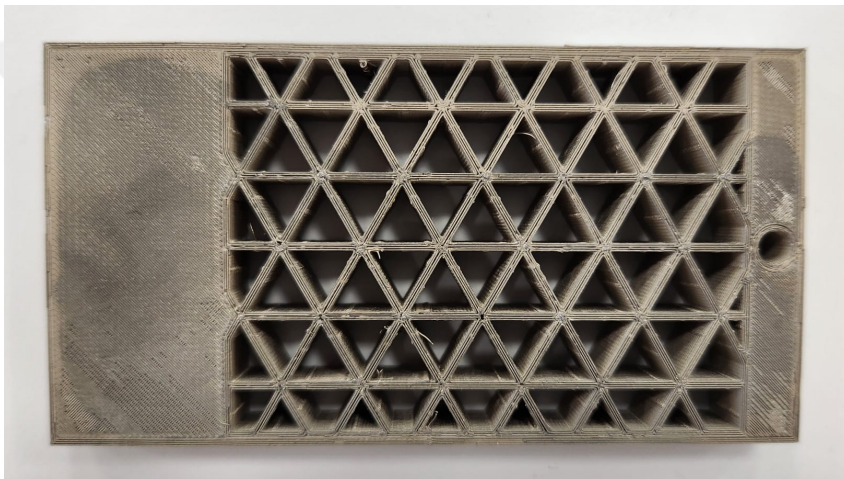


(c) Part 3: MBB Beam having grid infill

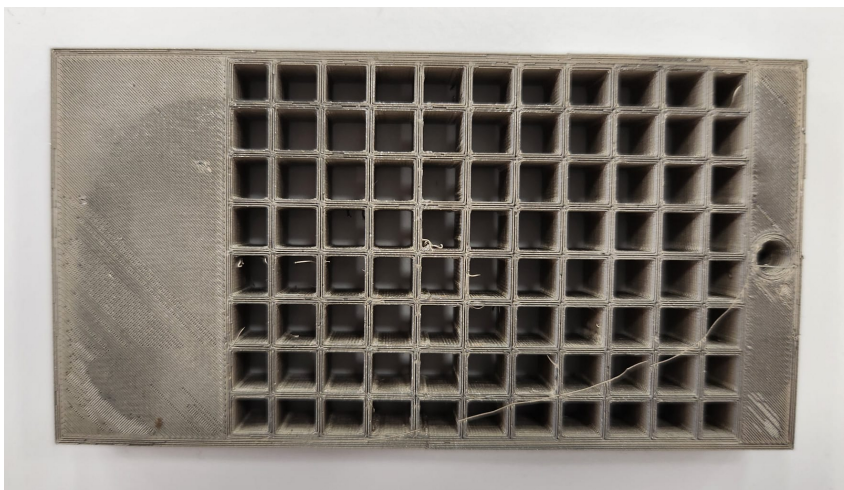
Figure 4.1: 17-4PH SS MBB Beam test parts



(a) Part 4: Cantilever Beam having optimized infill



(b) Part 5: Cantilever Beam having triangular infill



(c) Part 6: Cantilever Beam having grid infill

Figure 4.2: 17-4PH SS Cantilever Beam test parts

4.1.1 Structural Tests

The identical structural tests on the ABS specimens were carried out on the MBB and the Cantilever Beam components manufactured by 17-4PH SS. However, certain adjustments were introduced on the test setups due to the greater strength of metals compared to ABS. The testing arrangement for the MBB Beam is illustrated in Figure 4.3. In contrast to the procedures for the ABS samples, the portion designed to replicate rotational boundary conditions (evident at the base of the printed part in Figure 4.3) is fabricated from AISI 4140 steel to account for its enhanced strength. The Cantilever Beam's testing configuration is displayed in Figure 4.4. This depiction demonstrates how the upward movement of the testing apparatus is conveyed to the specimen through a component manufactured from AISI 4140 steel. Moreover, due to its remarkable tensile strength, the pin material between the hole in the component and the force-transmitting steel component is chosen as 12.9-grade steel.

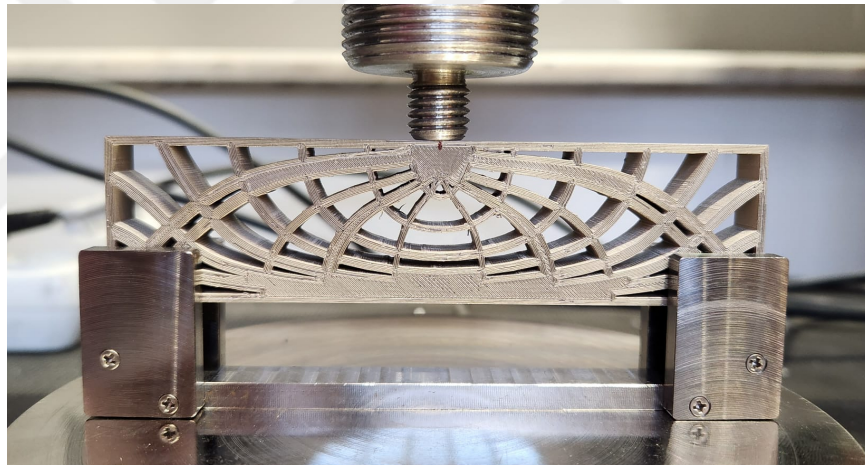


Figure 4.3: 17-4PH SS MBB Beam test setup

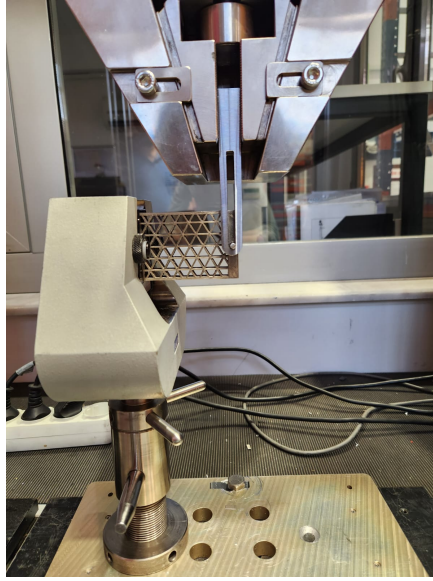


Figure 4.4: 17-4PH SS Cantilever Beam test setup

4.1.1.1 Results

This section presents the structural test results for the parts in Figure 4.1 and Figure 4.2. The force vs. deflection curves for these test specimens are visualized in Figure 4.5 and Figure 4.7. Notably, in Figure 4.7, the Cantilever test sample with the optimized infill pattern did not exhibit a clear fracture point. The test was halted at an extension of approximately 20 mm due to the high tensile load and potential risks to the test fixture and machine apparatus. As a result, the force value measured at this point was considered the force limit or maximum load-bearing capacity of this specific part.

Supplementary information, including the weights of the parts, the force values measured at the point of fracture, and the corresponding strength-to-weight ratios, are tabulated in Table 4.1 and Table 4.2. In addition, the fracture shapes exhibited by these test samples can be observed in Figure 4.6 and Figure 4.8.

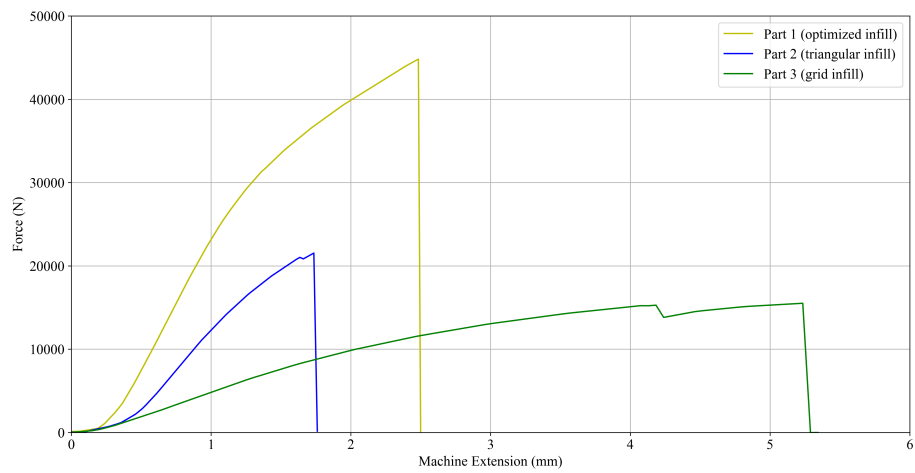
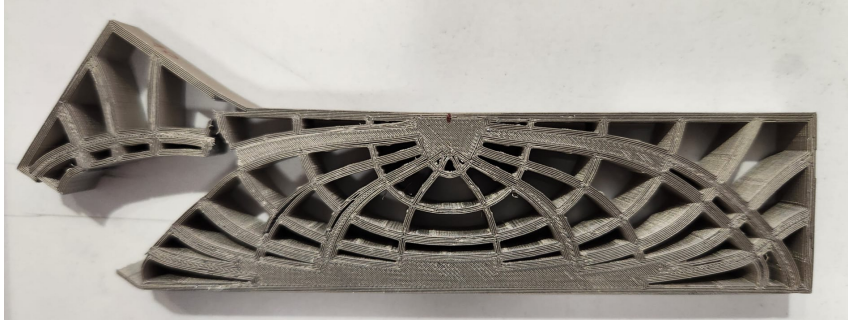


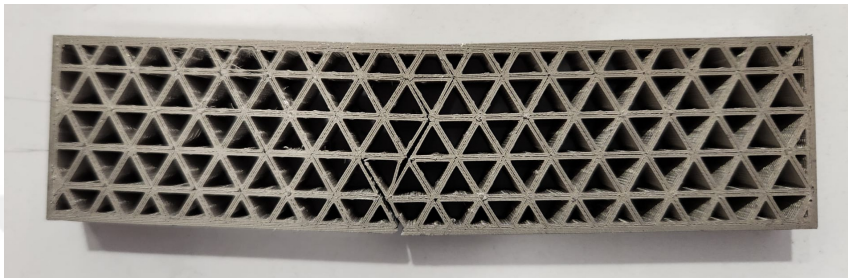
Figure 4.5: MBB Beam force vs. deflection plots for all the 17-4PH SS samples

Table 4.1: MBB Beam test results for all the 17-4PH SS samples

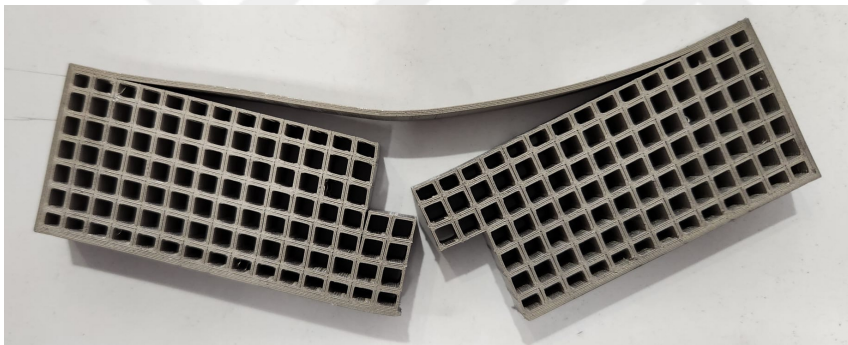
Part Number	Weight (g)	Max. Force (N)	Strength-to-Weight Ratio (N/g)
1	149	44800	300.7
2	126	21500	170.6
3	124	15500	125.0



(a) Fracture shape of Part 1



(b) Fracture shape of Part 2



(c) Fracture shape of Part 3

Figure 4.6: Fracture shapes of the MBB Beam 17-4PH SS test parts

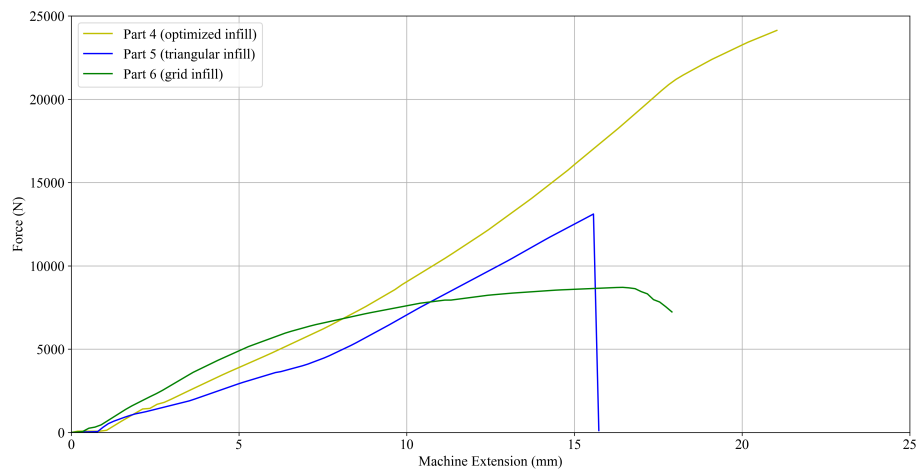
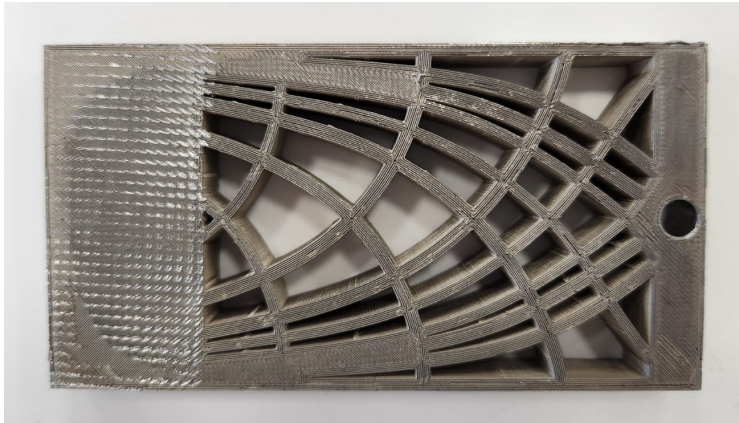


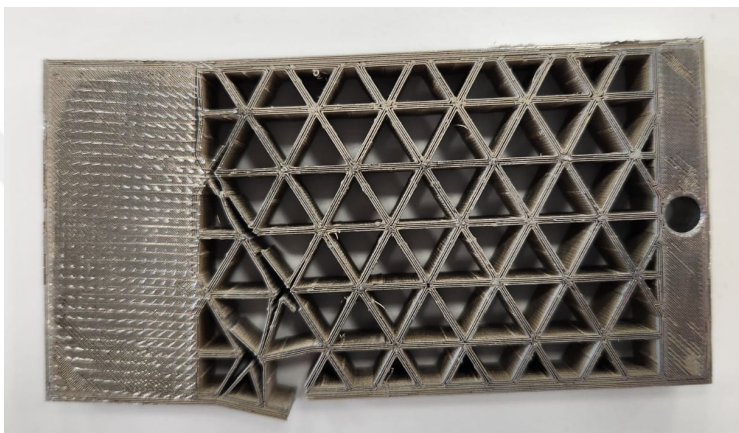
Figure 4.7: Cantilever Beam force vs. deflection plots for all the 17-4PH SS samples

Table 4.2: Cantilever Beam test results for all the 17-4PH SS samples

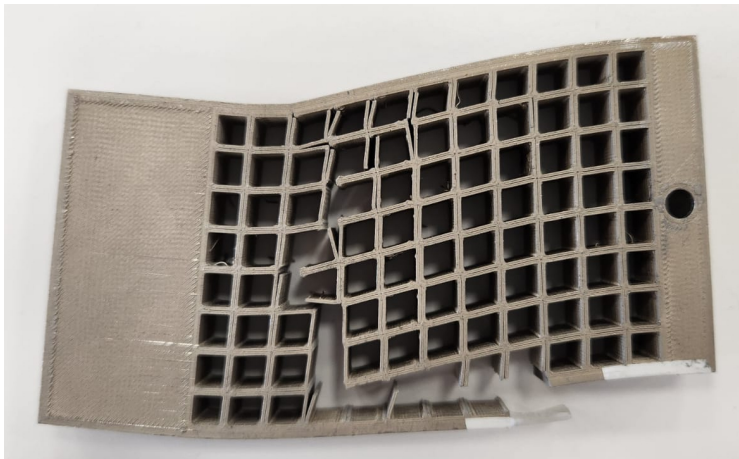
Part Number	Weight (g)	Max. Force (N)	Strength-to-Weight Ratio (N/g)
4	244	24100	98.8
5	207	13100	63.3
6	201	8700	43.3



(a) Deformed shape of Part 4



(b) Fracture shape of Part 5



(c) Fracture shape of Part 6

Figure 4.8: Distorted shapes of the Cantilever Beam 17-4PH SS test parts

4.1.1.2 Conclusions

The outcomes of the structural tests for the parts manufactured by 17-4PH SS are summarized as follows.

- Similar to the findings from the tests on ABS samples, the test parts produced by 17-4PH SS material exhibited improved strength-to-weight ratios when utilizing the optimized infill patterns. The enhancement in this ratio was 75% for the MBB Beam case and 55% for the Cantilever Beam case.
- The improvement in strength-to-weight ratios was even more substantial for the test samples manufactured with 17-4PH SS material compared to ABS samples. This suggests that the effectiveness of the optimization approach is particularly pronounced for highly brittle materials.
- As it is described in the results section, the force-deflection graph illustrated in Figure 4.7 does not exhibit a distinct fracture point for the Cantilever Beam test sample designed with the optimized infill pattern. This outcome is attributed to the decision to halt the test to mitigate potential risks associated with the high tensile load being applied. As a result, the force value measured at approximately 20 mm deflection was considered the maximum load-bearing capacity for this test sample. This precaution was taken to ensure the safety of the testing equipment and apparatus. This scenario underscores the substantial improvement in strength that the optimized infill pattern offers, preventing the part from reaching a point of failure even under the high tensile load applied during the test.
- Consistent with previous findings, the test parts employing triangular infill structure demonstrated higher strength-to-weight ratios than parts featuring grid infills. This underscores the importance of infill pattern selection in determining mechanical performance.
- The ductile nature of the parts featuring grid infill patterns was also evident in these tests, especially in the MBB Beam case. This characteristic is visually noticeable in the force vs. deflection graph shown in Figure 4.5.

4.2 316L Stainless Steel Test Parts

In addition to the parts manufactured by 17-4PH SS, the MBB Beam and the Cantilever Beam test parts were fabricated by 316L SS filament. The primary motivation for selecting this filament was utilizing the readily available Ultimaker 3 Extended printer within the laboratory for printing. This approach enables the manipulation of the 3D printer's toolpath and facilitates the observation of how diverse printing toolpaths impact the strength of the parts created through the M-FFF method.

While the printing stage of M-FFF bears similarities to FFF, there are particular distinctions to be aware of during printing. Firstly, M-FFF necessitates a wear-resistant and hardened nozzle for printing. Hence, CC 0.6 Ultimaker Print Core was utilized for the printing process. This particular nozzle, featuring a diameter of 0.6 mm, matches the nozzle used for printing ABS test specimens. This uniformity in nozzle choice is maintained across all the test parts within this study for consistency. Secondly, due to the debinding and sintering stages integral to the M-FFF process, the printed part must be printed with slightly larger dimensions in all directions to attain the final metal part with the intended dimensions. User guideline of Ultrafuse metal filaments by BASF [41] was taken as a reference for using proper oversizing factors to compensate for shrinkage. The specifics regarding the process of shrinkage compensation will be elaborated upon in the subsequent subsection. Lastly, some of the printing parameters necessitate adjustment. For instance, nozzle and bed temperatures must exceed the values utilized for the ABS samples. Table 4.3 outlines several printing parameters employed during the printing phase of the 316L SS test specimens. Additionally, the produced test parts for the MBB Beam and the Cantilever Beam can be observed in Figure 4.9 and Figure 4.10, respectively.

Table 4.3: Printing parameters of 316L SS test samples

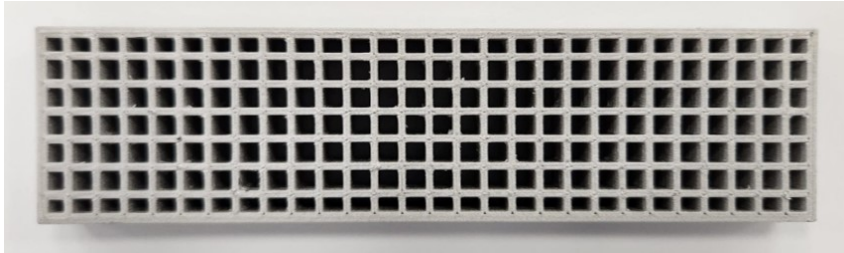
Parameters	Value	Units
Nozzle Diameter	0.6	mm
Layer Height	0.2	mm
Nozzle Temperature	240	°C
Bed Temperature	95	°C
Filament Diameter	2.85	mm
Printing Speed	1200	mm/min

4.2.1 Shrinkage in 316L Stainless Steel Test Samples

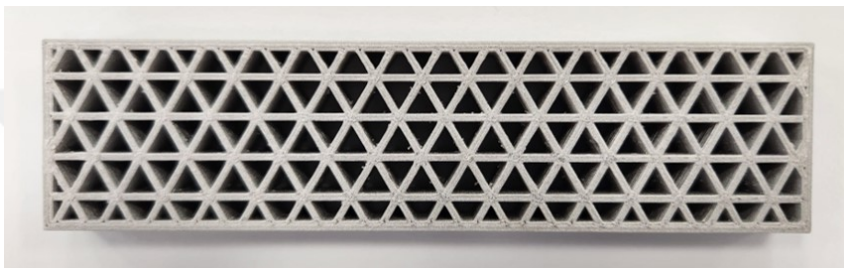
This section provides an in-depth explanation of the shrinkage compensation process applied to the components printed using Ultrafuse 316L SS filament. As previously mentioned, the M-FFF process involves three key stages: printing, debinding, and sintering. The debinding stage involves the removal of binding materials from the *Green Part*, which is the outcome of the printing phase. This debinding process results in a shrinkage of the Green Part, transforming it into the *Brown Part*. Furthermore, during the sintering stage, the metal powders within the Brown Part are fused, further reducing overall dimensions, albeit to a lesser extent than the debinding stage.

The user guideline provided by BASF for Ultrafuse metal filaments [41] offers calculations and insights into shrinkage and oversizing factors. Consequently, recommended oversizing factors for this process are suggested by BASF as 20% in the x-direction, 20% in the y-direction, and 26% in the z-direction. Following these guidelines, the test samples printed using the 316L SS filament in this study are scaled by these specified percentages before printing. For example, an MBB Beam fabricated in this study should possess dimensions of 120 mm in the x-direction, 30 mm in the y-direction, and 10 mm in the z-direction. Upon measurements, the samples exhibited measurements close to these intended dimensions. As a result, the shrinkage compensation recommendations provided by BASF yielded components with dimen-

sions that closely align with the intended measurements. Although the measurements displayed some variance in the final dimensions, this situation can be attributed to the observed warpage in some of the test samples.



(a) Part 1: MBB Beam having grid infill



(b) Part 2: MBB Beam having triangular infill

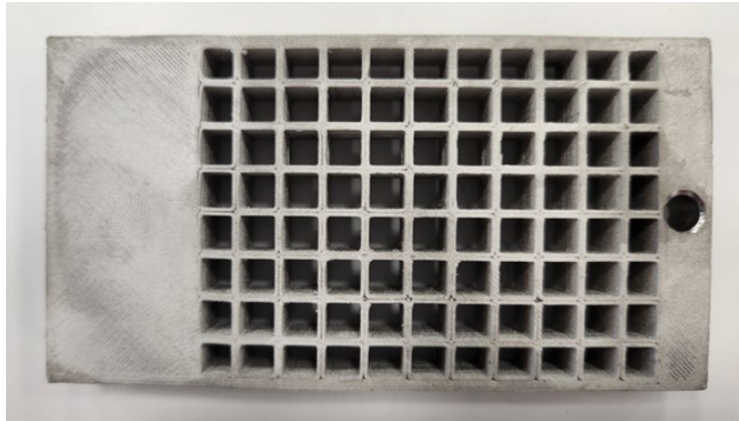


(c) Part 3: MBB Beam having optimized infill whose G-code is created by Cura

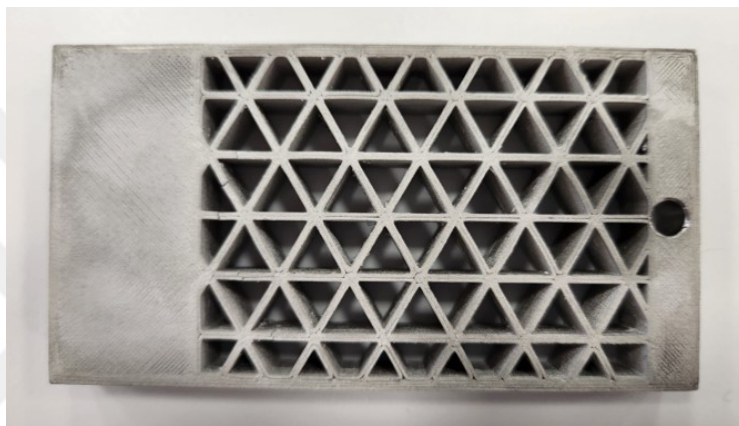


(d) Part 4: MBB Beam having optimized infill whose G-code is created by the algorithm

Figure 4.9: 316L SS MBB Beam test parts



(a) Part 5: Cantilever Beam having grid infill



(b) Part 6: Cantilever Beam having triangular infill



(c) Part 7: Cantilever Beam having optimized infill whose G-code is created by Cura

Figure 4.10: 316L SS Cantilever Beam test parts

4.2.2 Structural Tests

The identical structural tests on the ABS and 17-4PH SS test components were also performed on the 316L SS test specimens. The fixtures that simulate boundary conditions and facilitate force transmission remain consistent with those used in the 17-4PH SS sample tests.

4.2.2.1 Results

As illustrated for the previous tests, Figure 4.11 and Figure 4.12 display the force vs. deflection curves for the MBB and the Cantilever Beam 316L SS test specimens, respectively. In contrast to the earlier tests conducted on ABS and 17-4PH SS samples, the 316L SS samples exhibited a markedly ductile behavior. This characteristic resulted in substantial deformations without experiencing any fractures. Consequently, the force values on the graphs tend to maintain a consistent trend after a certain degree of deformation. To address this behavior, dashed lines have been introduced onto the graphs to indicate the deflection values at which the measured force values are evaluated. These specific values were 6 mm for the MBB Beam and 20 mm for the Cantilever Beam. Accordingly, the force values recorded in Table 4.4 and Table 4.5 signify the measured force values at these corresponding deflection points. Alongside these force values at specific deflections, the tables showcase the weights of the components and their corresponding strength-to-weight ratios. Furthermore, the distorted shapes of these specimens are depicted in Figure 4.13 and Figure 4.14.

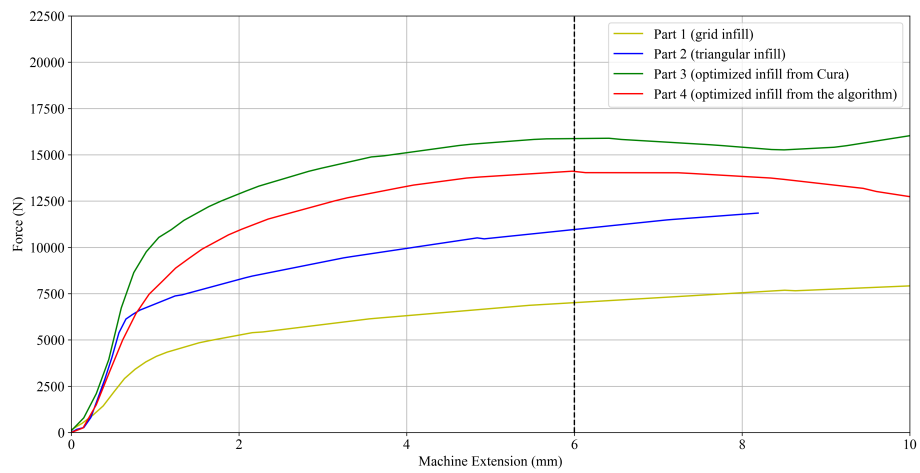


Figure 4.11: MBB Beam force vs. deflection plots for all the 316L SS samples

Table 4.4: MBB Beam test results for all the 316L SS samples

Part Number	Weight (g)	Force (N)	Strength-to-Weight Ratio (N/g)
1	136	6900	50.7
2	152	10900	71.7
3	170	15900	93.5
4	160	14100	88.1

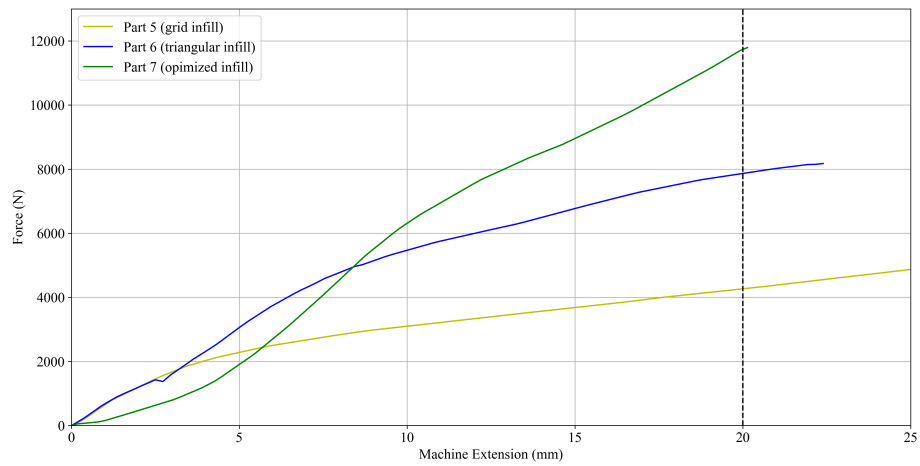


Figure 4.12: Cantilever Beam force vs. deflection plots for all the 316L SS samples

Table 4.5: Cantilever Beam test results for all the 316L SS samples

Part Number	Weight (g)	Force (N)	Strength-to-Weight Ratio (N/g)
5	205	4300	21.0
6	210	7900	37.6
7	245	11900	48.6



(a) Deformed shape of MBB Beam having grid infill



(b) Deformed shape of MBB Beam having triangular infill

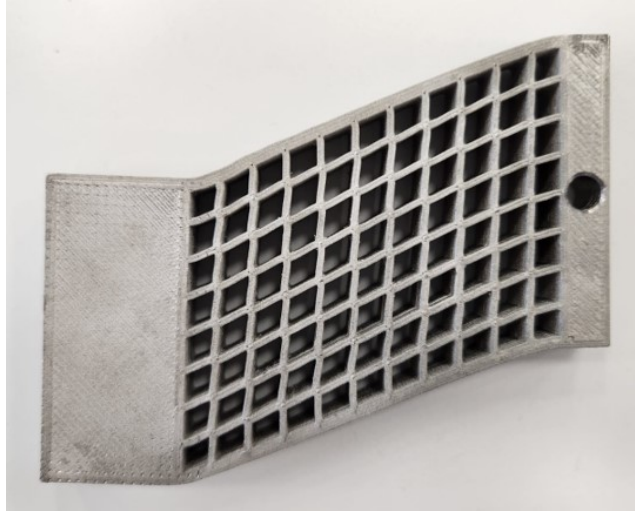


(c) Deformed shape of MBB Beam having optimized infill whose G-code is created by Cura

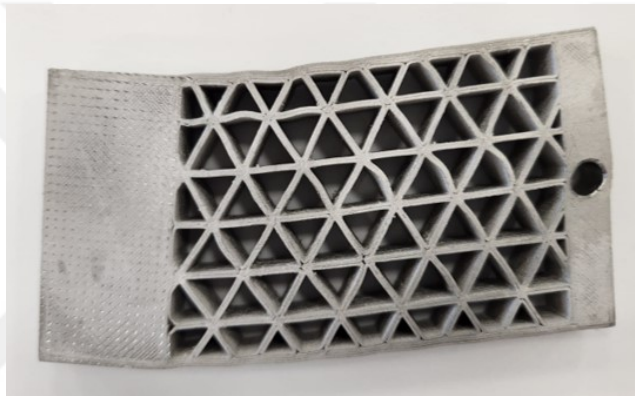


(d) Deformed shape of MBB Beam having optimized infill whose G-code is created by the algorithm

Figure 4.13: Deformed shapes of the MBB Beam 316L SS test parts



(a) Deformed shape of the Cantilever Beam having grid infill



(b) Deformed shape of the Cantilever Beam having triangular infill



(c) Deformed shape of the Cantilever Beam having optimized infill whose G-code is created by Cura

Figure 4.14: Deformed shapes of the Cantilever Beam 316L SS test parts

4.2.2.2 Conclusions

The conclusions drawn from the structural tests on the parts manufactured using 316L SS material are outlined as follows.

- Contrary to the previous tests conducted on ABS and 17-4PH SS samples, these specific test parts showcased a distinctly ductile behavior. This characteristic is particularly evident when examining the force-deflection curves, as these curves show a lack of any increase in force corresponding to an increase in deflection. This behavior indicates the material's ductile response under the applied loading conditions.
- Due to the absence of a distinct fracture point in these samples, the load-carrying capacities of these parts were determined based on specific displacement values: 6 mm for the MBB Beam and 20 mm for the Cantilever Beam. When comparing the force values measured at these deflections, it was evident that parts with optimized infill structures exhibited a roughly 30% improvement in strength-to-weight ratios compared to other infill patterns. However, this increase was less significant than in tests conducted on ABS and 17-4PH SS samples. This outcome suggests that optimized infills' effectiveness diminishes when the test parts' ductile behavior becomes more prominent.
- Additionally, similar to the previous tests conducted on ABS and 17-4PH SS samples, the slopes of the parts with grid infill patterns are lower than those with optimized and triangular infills. Moreover, parts featuring optimized infill structures resulted in the highest slopes in force vs. deflection plots. This outcome highlights grid infills' high ductile behavior and the optimized infills' high brittle characteristics in this material context.



CHAPTER 5

DISCUSSION & CONCLUSIONS

This last chapter of the thesis serves as a concluding part of this study. This chapter comprises three sections: summary, discussions, and future works.

5.1 Summary

This section provides a comprehensive overview of the preceding chapters in this thesis.

Chapter 1 served as an introduction, outlining the key motivations behind the research endeavor. Additionally, it acknowledged the limitations inherent in the proposed methodology. The section concluded by offering a concise outline of the thesis structure.

Chapter 2 is a dedicated exploration of the pertinent literature concerning the subject of the study. Commencing with a brief overview of prevalent AM techniques in the industry, it subsequently delved into an exhaustive literature survey. This survey highlighted studies most related to the thesis, encompassing FOAM, TO, and Metal AM. The chapter concluded with a closure part, emphasizing the study's principal contributions to the existing literature.

Chapter 3 delves into the methodology developed throughout the study. It provides the theory behind the research and the implementation procedure of the algorithm into two different load cases in detail. This chapter also offers an in-depth focus on the manufacturing stages of the test samples utilizing ABS material. Also, the structural tests performed on these samples to assess the performance of the proposed optimiza-

tion approach are detailed. The chapter provides a comprehensive presentation of the test results and conclusions.

Chapter 4 is dedicated to the fabrication and testing stages of the test samples manufactured by the M-FFF process. In addition to detailing this manufacturing method's inherent challenges and intricacies, it thoroughly depicts samples produced from 17-4PH SS and 316L SS filaments. The chapter also presents test results and insights into the performance of these samples.

5.2 Discussions

This thesis introduces an innovative infill optimization methodology for designing parts to improve mechanical properties for material extrusion AM. The core of this approach lies in a novel line-based infill optimization algorithm that operates within the design domain employing PSLs. To prove the effectiveness of the proposed method, two different structural cases, MBB and Cantilever Beam, were selected. A series of test samples were subsequently manufactured for structural evaluation. Specific test samples were constructed using the PSLs-based optimized geometry for the infill structures. These samples were compared with counterparts featuring triangular and grid infill patterns, focusing on their mechanical behaviors.

Importantly, this study focused on the FFF method that generally uses plastic polymers and extended its scope to M-FFF technology. This attention to M-FFF is significant due to the novelty of this manufacturing process, which still holds many unknowns. The limited information regarding the mechanical performance of components produced through M-FFF has hindered its application in end-product manufacturing. In addition, M-FFF serves as a promising candidate for implementing the proposed algorithm thanks to its toolpath-based nature, similar to FFF. In the preliminary stages of this work, the test samples were first fabricated by the FFF method with ABS filament. Following mechanical testing on these ABS samples, the same parts were reproduced using M-FFF, utilizing 17-4PH SS and 316L SS materials.

The results of structural testing highlight that the parts composed of optimized infill structures exhibited enhanced strength-to-weight ratios compared to the samples

having linear infill patterns. In the case of the ABS test samples, the optimized geometry resulted in nearly a 40% increase in this ratio. This improvement was even more pronounced in the 17-4PH SS test samples, where the ratio ranged from 55% to 75%. Similarly, the test samples manufactured by 316L SS filaments demonstrated a nearly 30% increase in this ratio. These findings indicate that the enhancement in strength-to-weight ratios is more pronounced for materials with brittle nature. It is worth mentioning that the highly ductile nature of 316L SS test samples prevented fracture occurrences during the tests, resulting in force vs. deflection plots demonstrating a continuous trend where force values remained nearly unchanged despite increased deflection.

In addition, the test samples with triangular infills exhibited improved strength-to-weight ratios than those with grid infill patterns in all tests. Therefore, even a selection between linear infill patterns significantly determines the strength-to-weight ratios and overall mechanical behavior. Besides, the printing order of tensile and compressive PSLs in the infill structure impacted the parts' strength. Printing tensile PSLs before compressive PSLs resulted in better mechanical performance. This suggests that the printing sequence influences the interactions between PSLs and the overall structural integrity of the part.

Furthermore, force vs. deflection plots also provide insights into the ductility behaviors of distinct infill patterns. By comparing the slopes of the curves, it is evident that parts featuring grid infill structures exhibit the lowest slopes, indicating enhanced ductility. On the other hand, parts with optimized infills display the highest slopes, suggesting improved brittleness. Likewise, the optimized parts fabricated by Cura's G-code resulted in enhanced ductility compared to those manufactured by the algorithm's G-code. In addition, the strength-to-weight ratios of the optimized parts obtained through G-codes of Cura and the algorithm generally yielded approximate results for the MBB Beam tests. This inquiry was a central focus of the thesis: whether the printing path that aligned directly with PSLs on the structure could result in components with superior mechanical behaviors to those printed by ordinary printing trajectories defined by slicing software. This printing path adjustment did not yield considerable improvements in mechanical behaviors.

To conclude, this research successfully developed and validated an optimization algorithm for infill pattern generation in MEX AM, contributing to advancing Metal AM techniques. The algorithm's ability to enhance the strength-to-weight ratios of 3D printed parts was evident across different materials and geometries. This work underscores the importance of intelligent infill design in improving the mechanical performance of AM parts. The line-based nature of this optimization approach finds application not only in MEX AM techniques but also extends to DED and bioprinting processes.

5.3 Future Works

This section discusses potential directions for future research and development based on the findings of this study.

While this study focused on 2.5D geometries, the fundamental principles of aligning deposition paths with stress trajectories can undoubtedly be extended to complete 3D parts. 3D printing technologies allow for intricate and complex geometries, and optimizing deposition paths in three dimensions could lead to even more advanced and high-performance parts.

Additionally, aligning material deposition with stress trajectories is particularly interesting when considering composite materials like carbon fiber-reinforced filaments. By aligning the direction of the fibers with stress trajectories, it is possible to attain components with enhanced strength and stiffness in specific directions, making them ideal for applications where directional properties are crucial. Similarly, the approach could be adapted for multi-material 3D printing, where different materials are deposited layer by layer to achieve specific material properties or functionalities. Aligning deposition paths with stress trajectories for different materials could result in parts with complex material gradients and tailored properties.

As mentioned earlier, optimizing source point selection is a crucial aspect of this PSLs-based optimization approach. Further research could delve into developing more advanced algorithms or methodologies to optimize source point placement. This could involve techniques from optimization theory, machine learning, or even

genetic algorithms to determine the optimal placement of source points for specific performance criteria.

As inferred from the results of the structural tests, the alignment of printing trajectories with PSLs did not yield a substantial enhancement in the strength-to-weight ratio. This outcome can be attributed to suboptimal printing parameters within the G-code produced by the algorithm, in contrast to those generated by Cura. Further comprehensive optimization of printing parameters could facilitate the design of components with improved mechanical performance.

In addition to these potential further studies, tensile test specimens featuring different infill patterns can be fabricated for tensile testing. The outcome of these tests would enable the determination of stress-strain curves for these samples, which is instrumental in establishing a stress and strain relationship independent of sample size. While sample dimensions influence force-deflection curves, stress-strain curves would prove invaluable for non-dimensional characterization purposes.



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