Exploring flexible structures in 3D-printed bio-based materials for specific product applications

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MASTER THESIS

JONAS IHREBORN

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Abstract

This master thesis investigates possibilities to use additive manufacturing in the form of Fused Filament Fabrication (FFF) with the material Polylactic Acid, to replace polyurethane foams for less environmental impact. The mechanical properties of foam are difficult to mimic and there are few or no materials that are similar, hence the great challenge to replace it. The idea of using a flexible structure instead of a flexible material is not a new one and can be seen in the field of mechanical springs for example. A lot of inspiration have been taken from other scientific areas of relevance through reviewing literature as well as previous projects in the field at LTH. By studying and testing different structures from previous projects as well as designing new structures a collection of samples was created for a study. The goal of the study was to test the different structures in a specific load condition to determine their flexibility by measuring the elongation. During testing and printing, drawbacks of using a simple AM method revealed itself with a lot of print failures and lack of print quality. Adapting to appearing problems new designs as well as new printing settings were necessary to reach structures that were suitable for testing. The study resulted in several findings of which parameters could affect the flexibility and how they can be altered for desired results for different end use cases. The feasibility of using FFF as a method for replacing polyurethane is discussed as well as further research options needed to reach a sustainable and profitable solution.

Keywords: Design, Additive Manufacturing, Polyurethane Foams, Flexible Structures, Product Development

Sammanfattning

Det här examensarbetet undersöker möjligheterna att använda additiv tillverkning i form av Fused Filament Fabrication (FFF) i miljövänliga material som ett mer miljövänligt alternativ till polyuretan. Polyuretan används i stor utsträckning, speciellt i möbelindustrin, tack vare sina unika mekaniska egenskaper men dess fossila ursprung, giftiga produktionsprocess och svårighet att återvinna gör det till ett miljöskadligt material. Att ersätta materialet är en betydande utmaning då få alternativ visar motsvarande kombination av flexibilitet och dämpande egenskaper. Ett sätt att lösa det här problemet är att skapa flexibilitet genom strukturell design snarare än genom materialval. Genom litteraturstudier, analys av tidigare forskningsprojekt samt inspiration från relaterade områden utvecklades och testades ett antal 3D printade strukturer. De tillverkades med FFF-teknik och undersöktes under kontrollerad belastning för att mäta deformation och bedöma flexibilitet. Arbetet påvisade flera begränsningar hos den använda tillverkningsmetoden som bland annat fel vid utskrifter och kvalitetsproblem vilket krävde justeringar av både skrivarparametrar och geometrisk utformning. Resultaten visar att parametrarna väggtjocklek, cellstorlek och geometrisk orientering har en betydande inverkan på strukturernas mekaniska egenskaper. Studien belyser därmed hur designval kan användas för att anpassa flexibilitet efter specifika användningsområden. Avslutningsvis diskuteras möjligheterna att tillämpa FFF för att ersätta polyuretan i exempelvis möbelindustrin samt vilka fortsatta forskningsinsatser som krävs för att uppnå en hållbar och ekonomiskt konkurrenskraftig lösning.

Nyckelord: Design, Additiv Tillverkning, Polyuretan Skum, Flexibla Strukturer, Produktutveckling.

Acknowledgments

This project has been a journey filled with new challenges and learning experiences, and it would not have been possible to complete without the help and encouragement from those around me. Conducting this thesis as a single author has at times been demanding, which makes me especially grateful to my supervisor Axel Nordin for his continuous guidance, thoughtful feedback, and for being a valuable discussion partner throughout the process. His insights and support have been crucial in shaping both the direction and outcome of this work.

A special thanks goes to Jonas Ihreborn AB for their collaboration and for contributing with valuable insights from an industrial perspective, which helped connect the theoretical findings to real applications in the furniture industry.

Lund, October 2025
Sebastian Evander

Contents

1 Introduction

This master thesis is a part of the project STEPS. The goal of this part of the STEPS project is to find 3D printed lattice structures in sustainable plastics to mimic the properties of polyurethane. The main focus is to improve the environmental impact since polyurethane is a fossil based material with negative environmental features such as toxic chemicals in production, difficult to recycle and non-biodegradable. The applications of polyurethane are broad but the main focus for this thesis is the furniture industry where it is used for its excellent flexibility during compression. In this master thesis a furniture company called Jonas Ihreborn AB is involved to utilize potential results. Previously in the STEPS project, structures have been tested in polyamide materials in a broad series of structures for 3D printing in a Selective Laser Sintering(SLS) printer. SLS is a technology suited for small prints such as prototypes and its main purpose in the project is merely to test the structures. Producing furniture in SLS technology is currently not feasible because SLS printing has limitations in size and price, furthermore, Large Scale Additive Manufacturing(LSAM) is based on material extrusion technologies such as Fused Filament Fabrication(FFF).

1.1 STEPS Programme

The STEPS project's annual report for 2022 presents a comprehensive overview of its progress, with an emphasis on material properties and advances in the realm of polymers. The report presents a diverse range of initiatives and collaborative efforts aimed at enhancing the properties of polymers and their applications.[1]

Mission 4, led by Jonas Ihreborn AB and involving collaboration with Lund University and Nordic Sugar, stands out for this master thesis. This mission explores 3D printed foam, leading to the creation of various examples that highlight the structural properties of different materials and their morphology. These activites were presented at the NordDesign conference and a detailed project report authored by Florian Ventur.[2] The mission involved an evaluation of fused deposition modeling, resulting in valuable insights documented in a Master's thesis by Samuel Bengtsson.[3]

The STEPS report emphasizes the project's commitment to encourage development of material science and plastics technology for positive environmental impacts. By making interdisciplinary collaborations possible and engaging with stakeholders, the STEPS project hopes to enable innovative methodologies and techniques to improve the performance and sustainability of materials.

In addition to the previous works done in the STEPS programme, this thesis will contribute by focusing on methods for FFF that can be adapted and developed for LSAM. While similar previous work has used SLS printing, the step towards extrusion-based methods is important to enable industrially feasible applications. By exploring design strategies and process parameters this thesis can provide results that enable the use of environmentally friendly materials instead of fossil based materials such as polyurethane for furniture applications.

1.2 Limitations

For the project a series of assumptions and limitations needed to be made to constrict the project to a reasonable extent.

In the project the testing and designing will be strictly limited to FFF printing since it is the cheapest and most accessible AM method as well as the most commonly used method for LSAM. It will also be limited to one material to decrease the number of variables and to simplify testing and analyzing of results. However the material have some requirements that should be fulfilled. The material will be chosen in the beginning of the project preferably in cooperation with The Industry Sweden and Jonas Ihreborn.

- It should not be fossil-based.
- No toxic chemicals used in production.
- It should not be sensitive to UV light.
- The material is preferably recyclable.

1.3 Objectives

1.3.1 Test the previous results from SLS printing in FFF printing.

In the study by Sinclair [1], the exploration of flexible structures using 3D-printed bio-based materials is presented. The goal of the research is to closely mimic the properties of foam through AM methods. The study investigates various design configurations, as seen in figure 1, and material compositions to achieve the desired level of flexibility, lightweight, and structural integrity. The results demonstrate the potential of 3D-printing to create complex and adaptable structures that show foam-like behavior. The findings highlights the influence of material parameters and printing settings on the mechanical properties of the flexible structures. The use of bio-based materials also aligns with sustainable design practices. The results presented from the study by Sinclair [1] will be tested with FFF printing and will be adjusted to better suit the properties of FFF printing.

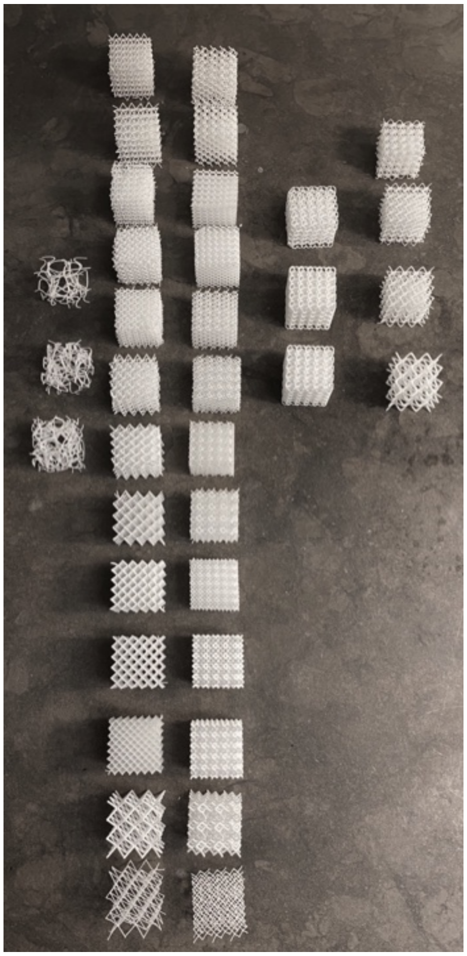


Figure 1: Designed and tested structures from the study by Sinclair. [4]

1.3.2 Try new structures as well as alternating existing structures to achieve satisfying results.

Using previous projects as inspiration new structures will be generated testing different geometric shapes and patterns. With the limitations in mind the new structures is designed to suit the simple ability of material extrusion and therefore some simplifications are needed. When a suitable amount of shapes and patterns are reached they will be optimized to improve the results. Optimization will include wall thickness and pattern variations. Testing the structures will show the importance of geometry and wall thickness and how they can be used to achieve desired results.

To define satisfying results the following critera should be fulfilled:

- Can be printed using FFF technology without print failures or support material
- Reasonable stability during compression tests without visible breakage
- Stiffness values in the interval of 2-5 N/mm for 30 mm test cubes based on data provided from Ihreborn

1.3.3 Evaluate the feasibility for the results in end consumer applications.

The greatest advantage of FFF printing is the fact that it is much cheaper than other AM methods. This makes it the most feasible method for production of end consumer applications. Using the results from previous objectives the feasibility of using FFF for producing foam like products in furniture will be tested by producing a simple prototype of a chair cushion. Furthermore what type of applications is suited will be discussed and also how it can be implemented.

1.4 Disposition

A short summary of the structure of this thesis and what is focused on within each section of the report.

- Section 2 explains the details of the working method of the study, the process, what equipment and what material was used.
- Section 3 focuses on explaining the literature areas that are covered such as Material Extrusion, Deployable structures and features of additive manufacturing and how this thesis can complement current research in the area.
- Section 4 defines what specifications the ideas or designs should fulfill.
- Section 5 explains how the different designs were generated and where the inspiration came from.
- Section 6 explains the testing of structures and the thinking process for evaluating the test.
- Section 7 presents the results.
- Section 8 discusses the reliability of the results and how they can affect potential use cases.
- Section 9 explains the overall findings and what conclusions can be drawn from the thesis and what future works could expand in the area.

2 Methodology

Since the Master Thesis is a part of an on going project a lot of resources and results within the project are available. However the goal is to test these results with a new technology and therefore new tests will be performed similar to previous tests. To base the assumptions, results and designs in theory a thorough literature review is needed. Most sources will be found through LUBsearch since it is an excellent platform for finding scientific articles, however google scholar and other web searches will also be used. The main goal is to find reliable information and to identify what results already exists within the project area to avoid unnecessary work. Since the area of Additive Manufacturing is constantly making new strides recent studies are of great importance for the project and will be prioritized.

2.1 Equipment

For the project a simple desktop printer is used called Creality Ender 3, which is a material extrusion or FFF printer in a price group of around 200$. For the project it is a good representative of cheaper and more simple technology and will exemplify how printer settings and design needs to be adapted to the limitations of the manufacturing equipment. It is also a good example to test the feasibility of the results towards end consumer application manufactured through LSAM.

2.2 Testing

The tests will mainly consist of compression tests to evaluate flexibility, deformation and other parameters. To print existing structures with a new technology some modifications might be needed and therefore a process of learning relevant software such as Rhinoceros 3D and Grasshopper will be performed. Furthermore new structures will also be designed and tested considering the different characteristics of FFF in contrast to SLS. Besides physical tests, digital tests will be performed in the concept development phase using a program provided by the department. In contrast to normal simulation functions which usually tests for stiffness this program will simulate for flexibility. Since a high degree of movement and deformation generally is not preferred, functions simulating for this is not that common. The program is based on the Karamba plug-in for Grasshopper and is written to simulate tests of flexible lattice structures. The program will be used to test a wide range of structures as a type of screening method. In combination with the software a visual and physical screening method is also used in the system level design phase to decrease the number of potential structures. The physical method is basically a compression test using the hands which was very effective to get a rough estimate of the structure's flexibility. The visual method is based on the visual results from initial prints and during simple compression tests checking for any deficiencies or failures that can be used to rule out that structure.

The structures with successful results from the concept development and system level design phases will be printed and tested with compression tests using the digital measuring tool seen in figure 2 below. With the measuring tool it is possible to decide a force to compress with and measure the elongation achieved with that force using *Hooke's law* as explained in the literature review. Using a caliper the structures can be measured before and after compression to evaluate if any plastic deformation can be seen.

Figure 2: Digital measurement equipment used for the project.

2.3 The Generic Product Development Process

The generic product development process is a structured framework consisting of six phases to provide a systematic way to develop a product from initial idea to implementation in production. It was chosen for the master thesis to act as a guidance for the complete project and was an inspiration on what activities to perform. A big part of the project is to design new structures as well as finding designs that could be implemented towards end-consumer products thus the generic development processes was a suitable choice of model. Since it is not part of the scope of the thesis to implement any product in production, phase 6 is not performed.[5]

To visualize the method a process chart based on *The generic product development process* is drawn to show the steps of the thesis and how they depend on each other. The green diamonds are decision points where important decisions were made together with supervisors and other stakeholders.

2.3.1 Planning Phase

The planning phase forms the foundation for the entire development process to establish a clear direction by defining objectives, setting limitations and benchmarking with other relevant work.

In this thesis, the planning phase was shaped through a combination of benchmarking and a literature review. Benchmarking served as a method to evaluate existing solutions and outcomes of previous projects, which provided the basis for defining realistic objectives. A systematic literature review allowed the project to be positioned within current research and literature, ensuring that the objectives were not only relevant but could also provide new results to the area.

Benchmarking further played a central role in setting the limitations of the project. By comparing technologies, materials, and methods, it was possible to establish limitations that made the scope of the project reasonable but still enabling relevant results.

2.3.2 Concept Development

The concept development phase focuses on generating and evaluating different solutions consequently deciding the direction of the development work. During the phase customer needs are interpreted and product concepts are developed to face those needs. Through an iterative process the concept can be developed through finding new solutions and evaluating their feasibility. By starting with a very broad idea or thought this phase is used to narrow down the concept to a product or solution that is feasible and possible to achieve and develop.

For the master thesis the most important part of the concept was testing the limitations of the printer technology as well as calibrating the printer settings. In parallel ideas of the structures was generated and the printer settings and designs could be evaluated simultaneously through simple testing. In an iterative process the settings were optimized but the generation of the ideas was also narrowed down as the limitations would become clearer and clearer. In this phase precise or advanced testing was not necessary as the main purpose was to find suitable printer settings but also it was used as a screening method which is more effective using faster and easier testing.

2.3.3 System Level Design

At the system level design phase the broad exploration of alternative solutions from the concept phase is focused toward establishing key design features and defining the overall product structure. The goal is to take broad conceptual ideas and turn them in to a more organized product structure that can be further detailed and optimized.

While the concept development phase was focused on testing the printer settings the system level design phase was focused on performing the initial testing and evaluation of the designs. Using inspiration from previous projects a set of initial geometries and structures was created and tested. These designs were deliberately experimental and was used as a screening process to narrow down potential structures effectively.

Using visual evaluation and simple compression tests it was possible to identify clear limitations of the printer method, material and the initial designs. Testing and designing iteratively in this phase led to an important decision point simplifying the design features.

2.3.4 Detail Design

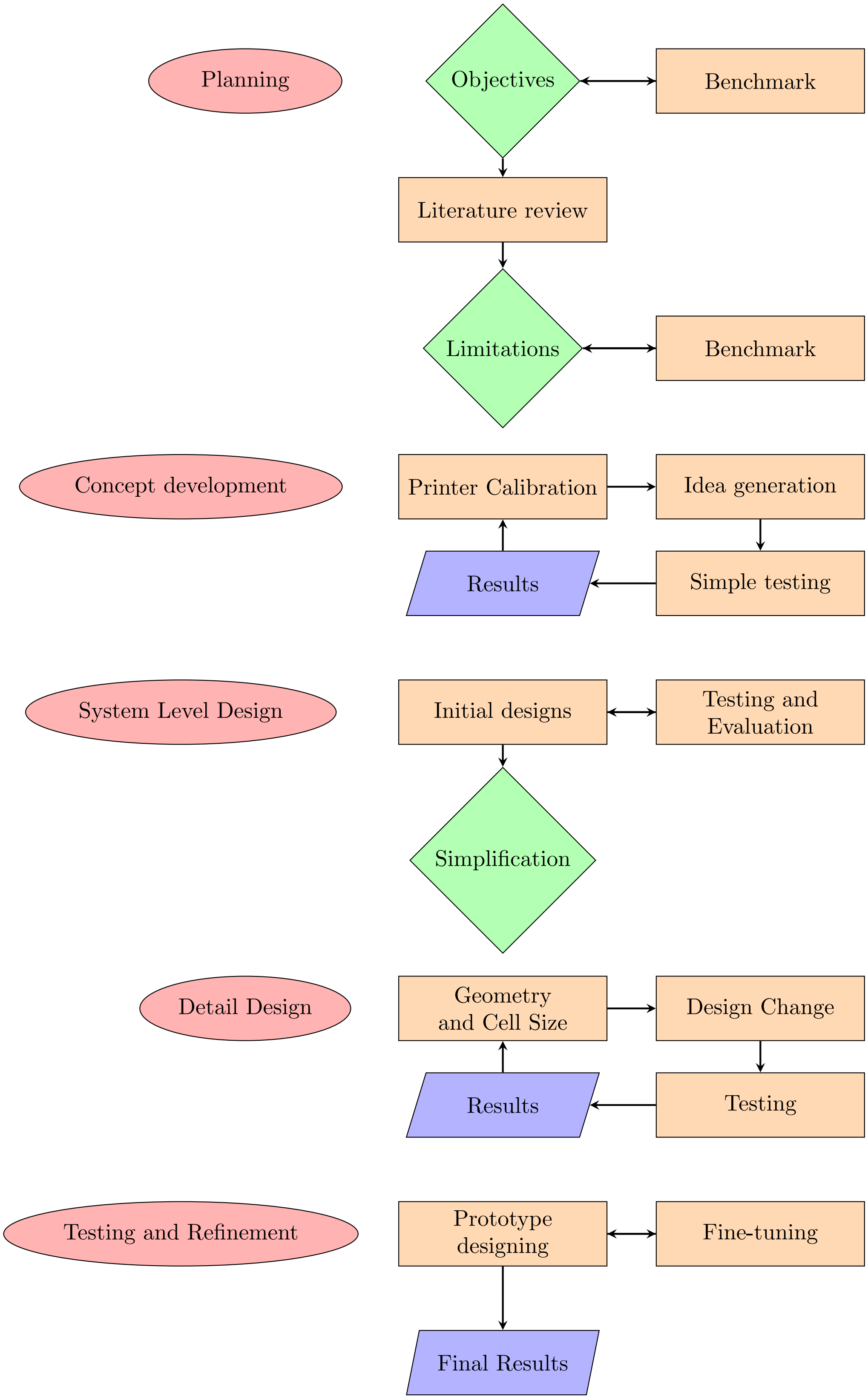
During the detail design phase the product should be described at a more granular level by defining exact dimensions, selecting materials, specifying tolerances and developing necessary documentation. The previously broad exploration of concepts and system level design should move towards a more precise design that can be refined and optimized to meet set requirements.

Based on important decisions on limitations, structural design and parameters from previous phases, a more systematic design and testing process could be initiated. Specific design parameters was tested systematically with precise compression tests and the results was used for optimizing the design. Iteratively the results could become better and better by fine tuning the design and parameters consequently gathering enough results.

2.3.5 Testing and Refinement

The testing and refinement phase is described as the phase where prototypes are created, evaluated and developed to meet the product requirements. It is important in this phase to validate the product using the customer needs as well as technical specifications. Prototyping and refinement is done repeatedly to optimize the design to a reliable and manufacturable product.

In the master thesis this phase was performed to test the final results in the context of an end consumer product produced in LSAM. The previous results needed some fine tuning as well as alteration to fit the prototype. Another iterative process of designing and fine tuning was performed to achieve a prototype that could represent the feasibility of the results.


Planning
Objectives
Benchmark
Literature review
Limitations
Benchmark
Concept development
Printer Calibration
Idea generation
Results
Simple testing
System Level Design
Initial designs
Testing and Evaluation
Simplification
Detail Design
Geometry and Cell Size
Design Change
Results
Testing
Testing and Refinement
Prototype designing
Fine-tuning
Final Results

2.4 Printer settings

For FFF desktop printers there is a lot responsibility for the operator to achieve prints with good quality. The number of parameters and settings that affects the end result are vast and is individual for each material and printer. This becomes of greater importance when trying more complicated geometries for example lattice structures therefore a method for finding the best printer settings for the material and the printer is required for sufficient results.

For this a plug-in called *Calibration shapes* is used in the slicer program *Ultimaker Cura*. In the plug in certain step files can be used to test the most important printer settings, finding suitable values. There are many shapes that can be used for different settings but the main ones used is the following:

- TempTower
- Retract Tower
- FlowTower
- Bridge Test
- Overhang Test

The main shape used is a so called temperature tower, as can be seen in figure 3, to test which temperature is most suitable. The settings of temperature will change for different sections of the tower to indicate which temperatures gives the desired results. The range of the material is between 190 - 230 C.

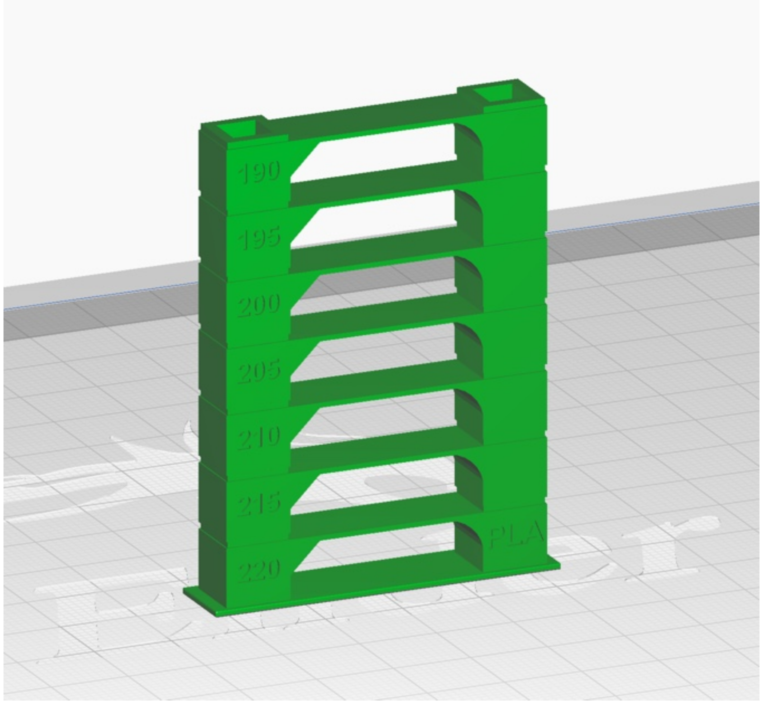


Figure 3: Temptower in Ultimaker Cura

Another important setting is the retraction speed which is a function to reduce stringing and undesirable extra material. When the printer needs to go to a new point there is a risk that undesired molten filament is extruded when changing positions and this often leads to stringing. Stringing is thin strings that are created when the undesired molten filament gets dragged between the old position and the new one. This phenomena is more frequent when using flexible materials with higher elasticity which is a big drawback of using flexible materials.

An iterative trial and error method was used to find suitable values to the parameters seen in table 1. Each parameter from the list below was tested printing with calibration shapes or other relevant shapes. In an iterative manner one parameter at a time was tested by printing structures where only changes was made to that parameter. The result was assessed on visual properties like overall quality and stringing. The starting value of each parameter would be chosen to make sure that better results was achieved by increasing the value. Once good results was achieved a few more tests would be done to ensure the tipping point had been reached. In this manner an estimated optimal value for each parameter was discovered, however the dependency of parameters meant some of the trials had to be done once again because new values to other parameters changed the results.

- Speed
- Temp
- Retraction
- Flow percentage
- Quality
- Fan
- Bed temperature
- Z-offset
- Geometry
- Wall thickness

Working systematically in this manner with an ever growing excel list better and better results was achieved and finally a set of printer settings was established seen in table 1. The most important parameters and their optimal values was chosen and for the remainder of the project these settings was never changed but for a few exceptions.

Table 1: Printer setting parameters and values used.

Parameter	Value	Unit
Layer Height	0.2	mm
Line Width	0.4	mm
Wall Thickness	0.8	mm
Print Temperature	195	°C
Build Plate Temperature	30	°C
Flow	125	%
Print Speed	25	mm/s
Retraction Distance	1	mm
Retractions Speed	5	mm/s

3 Background

Reviewing and explaining the literature areas covered in this thesis to present a better understanding of the technology and the processes.

3.1 Material Extrusion

Simply explained material extrusion means that melted material is extruded from a nozzle in patterns for several layers. The material is solidified when cooled and because of the molten state it is connected to the previous layer. A structure is built by adding the material layer by layer in certain patterns for each layer for the entire height of the desired geometry. Each layer can be seen as a thin slice of the geometry and by adding all slices upon each other a desired shape is created. A depiction of the technology can be seen in figure 4 where each layer can be seen as well as the pattern for each layer.[6] [7]

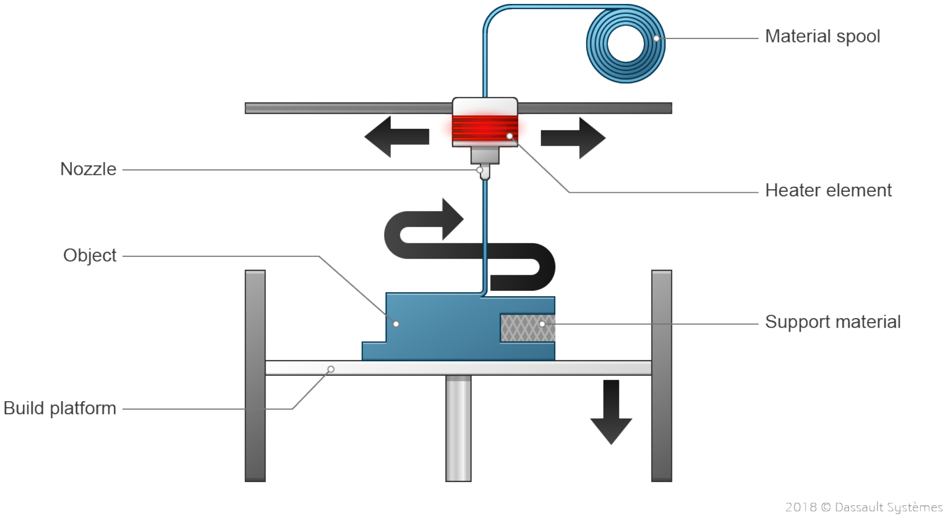


Figure 4: Practical depiction of material extrusion creating a shape by adding material layer upon layer.[8]

In this project Material Extrusion is used because it is the cheapest and most available production method also it is the most common method used in LSAM.[9] Material extrusion is the cheapest AM method and therefore it is the most feasible for furniture production. However flexible structures printed with material extrusion needs to be examined because material extrusion is a technology with some drawbacks. Support material is needed for overhangs, prints have anisotropic behaviour and prints can have uneven surfaces.

3.1.1 Anisotropy

Anisotropy is a definition of materials with different mechanical properties in different directions and it affects all AM technologies in varying degree. The effect is the greatest for material extrusion because the bonding is only depending on the connection because of the molten state between layers. One can view it as the fibers of wood, strongest when a load is applied perpendicular to the fibers but weakest when applied in parallel with the fibers. In figure 5 this is presented with a 3d printed part where the print layers can be seen and the anisotropic behaviour visualised. This is because the bond between the layers is weaker than the material itself.[6]

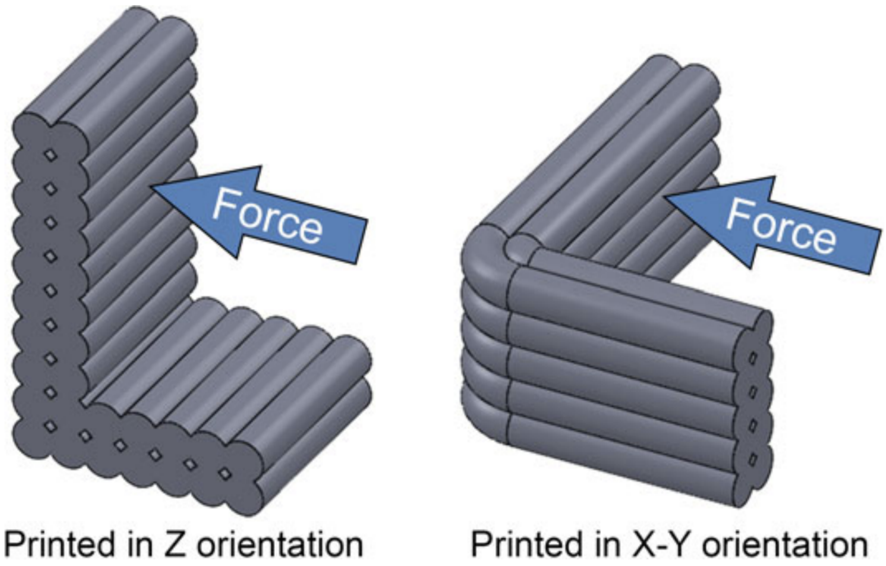


Figure 5: The anisotropic behaviour of Material extrusion. [6]

The anisotropic behaviour of material extrusion parts is of great deal when designing a part as well as printing it. Different print orientations and design parameters greatly affects the part's mechanical properties as seen in figure 6. The print orientations can be chosen to achieve desired properties in certain load cases. For the project only compression forces in one direction will be tested and therefore breakage due to anisotropy could be avoided if the print orientation is chosen correctly. [10]

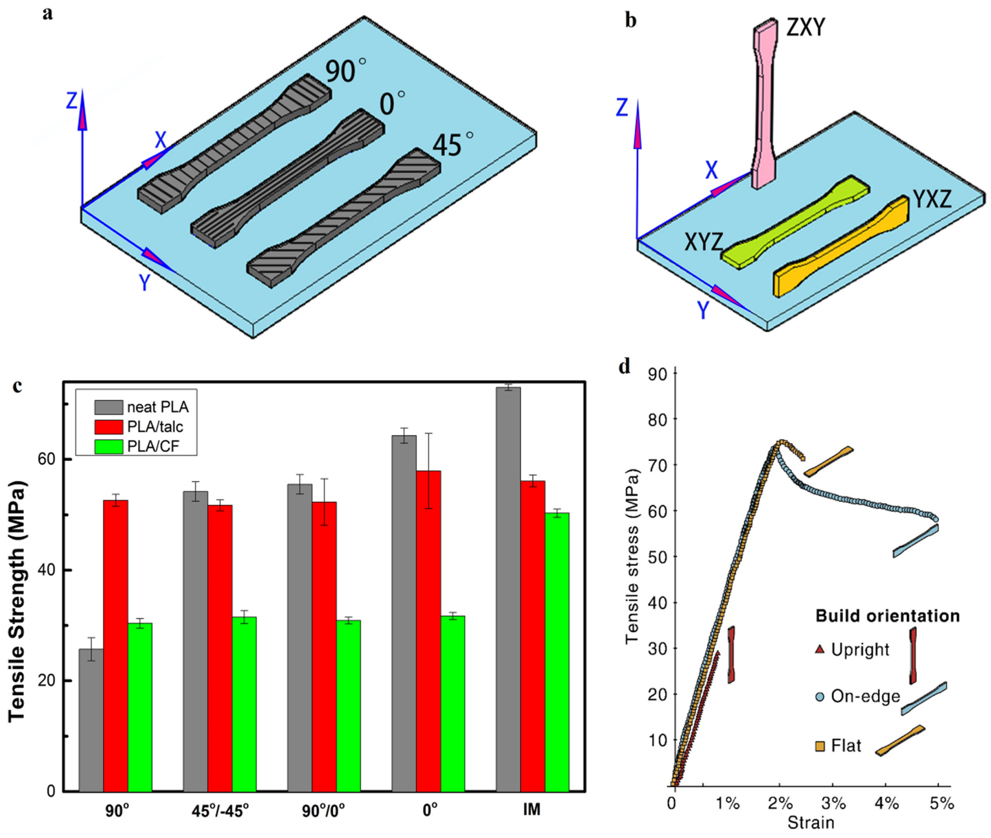


Figure 6: Mechanical properties due to different print orientations. [11]

3.1.2 Support Material

For most polymer-based AM technologies support material is needed for overhangs because in these areas the material needs support before it has solidified. Usually support material is removed manually after prints have been finished which makes it expensive. For lattice structures, support material is highly undesirable because it is extremely difficult or impossible to remove because of the complicated geometry. For earlier work in the STEPS project a powder based SLS printer have been used which eliminates the need for support material. therefore many of the previously designed structures can not be printed using a FFF printer. However design parameters can be taken into consideration and successful designs can be altered to be printable without support material. The number one parameter that can be altered to achieve this is the vertical angle. As long as structures only contains vertical angles less than 45 degrees no support material is needed.

Short distances of horizontal overhangs could avoid support material if the distance is short enough. Depending on material, temperature and filament thickness. This is called bridging and can be quite effective for small prints if the settings for cooling is correct.[6]

Using Meshmixer, a mesh editing software, there is a program that helps with choosing print orientation to avoid certain overhang angles. This could be used to avoid support material altogether and will be examined to see if it is helpful. Ideamaker is a good program to use afterwards to help choosing a flat surface which is suitable to start the print on.[12]

Another useful method similar to bridging is sacrificial bridging. If holes are present when bridging is attempted the bridge simply will not work since it is interrupted and the holes will be printed in thin air. Instead one can put a sacrificial one layer thick lid on the holes so that the holes have some support to start the print on.

3.1.3 Stair-step and accuracy

A distinctive trait of material extrusion is that the smallest possible feature is determined by the nozzle size. No feature can be smaller than the diameter of the nozzle size and therefore material extrusion printers generally have quite poor surface quality and accuracy. The nozzle diameter also determines the amount of material that can be extruded for each second. therefore the print speed and accuracy have a linear relationship and leads to trade-off decisions. This presents a challenge for LSAM since a lot of material needs to be extruded to keep the printing times relatively low but sacrificing surface quality and accuracy is not desired. Generally this leads to wall thicknesses and feature sizes to be close in size to the nozzle diameter.

When printing using material extrusion a phenomenon called stair-stepping is usually occurring in slants and angled surfaces as seen in figure 7. This is because the extruded material is placed in horizontal patterns and small joints are created between layers. This is especially visible when printing wall thicknesses and features that are small in size relative to the nozzle diameter. For the project flexible lattice structures is the main focus with complicated geometries and therefore the stair-stepping effect needs to be taken into account for the finer details.

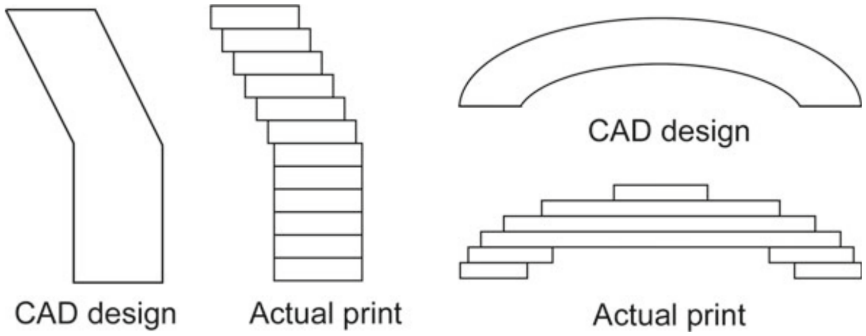


Figure 7: Stair stepping effect of material extrusion. [6]

3.2 Material

Polymers are generally divided into two categories, thermoplastics and thermosets. Thermoplastics can be repeatedly melted and reshaped which makes it fairly reusable and recyclable. Thermosets on the other hand, cure into a permanent structure which makes remelting impossible.[13] The properties of thermosets are superior to thermoplastics when it comes to thermal resistance, mechanical strength and chemical durability which makes it a desired material when such properties are needed.[14] To recycle or reuse thermosets the options are few, consequently it most often ends up in landfills or in the form of carbon emissions due to incineration.[15] Moreover thermosets that are used in furniture applications such as polyurethane are fossil based and needs toxic chemicals in production. [16]

Since FFF printing relies on melting the material before extruding it, thermosets are not available. In other AM methods such as Stereolithiography (SLA) and digital light processing(DLP) curable thermoset resins with flexible properties are available, however these are generally fossil based, expensive and difficult to recycle.[17]

The existing flexible materials for FFF usually extends to two different materials, TPU(Thermoplastic polyurethane) and PLA (Polylactic acid). Because TPU is fossil based PLA was a suitable choice for the master thesis since it can be bio sourced from cornstarch or sugarcane. However the properties of normal PLA can be brittle and not so flexible, therefore additives are usually added to achieve such properties.[18] The material used for this thesis was *Gearlab PLA Flex* (GLB255001) with such additives. However how these additives affect the biodegradability of this specific material is uncertain but for the extent of this thesis this topic is not researched further. Research shows that there are evidence for flexible and biodegradable materials for additive manufacturing however these materials are not as available and therefor the Gearlabs material was chosen.[19]

3.3 Stiffness and Flexibility

The mathematical definition of flexibility of an object is usually referred to its opposite, stiffness. The stiffness of an object or material is defined as "the ability of a system to resist deformation when subjected to a load". therefore the lower the stiffness the higher the flexibility. Calculating the stiffness of a system one can use *Hooke's law* where P equals the force, δ equals the elongation and K is the spring constant or stiffness constant.

$$P = K\delta$$

As long as the system returns to its original length the relationship between load and elongation can be seen as linear according to figure 8. To make sure the structures are not plastically deformed they are measured before and after testing to be able to use the linear relationship of *Hooke's law.* [20].

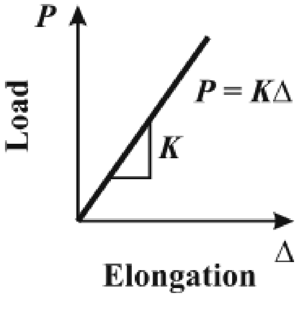


Figure 8: Linear relationship of Load and Elongation.

3.4 Literature Review

The area of theory and research for the project is most commonly referred to as *deployable structures* which is defined as structures with the capacity to transform and adapt its geometry to configurations.[21] In this thesis deployable structures in the form of compliant flexible structures are investigated. Compliant meaning elastic deformation is spread through the material instead of relying on specific hinges.[22] In recent years research on flexible structures has grown towards advanced technologies such as medical applications, aerospace and temporary architecture.[23]

Since flexible structures often involves complicated geometries as seen in figure 9, additive manufacturing has had growing influence in the area. However the most often the studies are focused towards advanced AM Methods such as SLS or multi material printing. Using these methods more complex geometries can be achieved since they are not limited to anisotropy or support material to the same degree as FFF. [24] In the available literature there are several examples of printed structures that have been tested for mechanical properties such as energy absorption and stiffness. [25] However these are less feasible to end consumer products since they use expensive equipment that would not be well suited in production. Therefor this master thesis can provide the area with data and results using technology more suited to production of end consumer applications, more specifically LSAM of furniture.

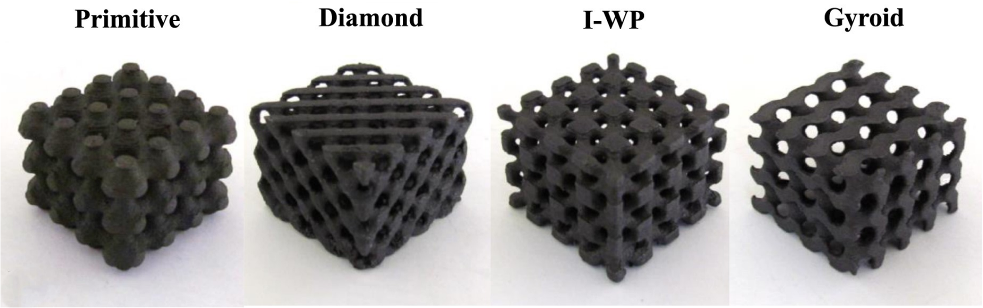


Figure 9: Four different examples of 3D printed flexible structures.[26]

In the available literature there is a lot of research done through FEM simulations and theoretical models. However the use of iterative physical testing is more limited and challenges connected to printability and precision from FFF printing can be a contribution to the literature through the results of this report.[27]

For studies using FFF there are examples of flexible lattices in TPU that can mimic the foam like properties of polyurethane foams. Specifically a gyroid-based triply periodic minimal surface meaning a continuously curved structure that is repeatable in three dimensions. Adjusting density and wall thickness these lattice structures can be optimized to respond similarly to compressions tests as PU-foams. When tested these gyroids showed comparable cushioning performance to furniture applications. However the material used in this example was a highly flexible TPU meaning results using a more sustainable material is still relevant. The printer used for the experiment needed modifications to be able to print with a such flexible material still showing complexity while printing in flexible materials.[28]

The contribution of this master thesis should not be exaggerated since the results are limited by the use of one single material, one printer type, and relatively simple testing conditions. This means that the findings cannot be generalized to all bio-based materials or all AM processes. What the thesis does provide is an indication of what is possible with accessible technology today.

4 Idea Specification

Before generating ideas, some specifications needed to be set up to define what the ideas should fulfill. The main goal of the structures is to replace polyurethane and therefor the general properties of polyurethane used in furniture applications are specified in the bullet list below. The stiffness of polyurethane which is the method used in this thesis to measure flexibility has been established in the objectives section. Another property that is needed for polyurethane in cushioning is elasticity, the ability to deform under load but to return to the original shape when the load is removed. The level of elasticity is dependent on the amount of load applied and therefor 100% elasticity is not aimed for but the structures should be able to return to a shape that is very close to the original in a reasonable load case. A reasonable load case can be defined using a study for a seat-cushion, where data shows average pressures of around 6.5 kPa and local peaks of around 25 kPa.[29] For the test structures surface area of 30x30 mm this corresponds to 4-18 N loads to cover average and peak loads.

Furthermore the structures need to be tested in compression tests, therefor they need to be printable and testable. To define what is printable each design needs to be able to finish without manual help and only one failured print per design. More fails than that would be considered as a design that needs changing or is not feasible. If a print needs changing of print settings the threshold is less than three parameter changes for one iteration, but if it needs changes for more iterations it is a concept that is not viable. Considering layer adhesion or disconnected faces the threshold is decided at less than or equal to two occasions per print. If the gap is more than 3 mm this is considered a failed print and the design would not be approved. To be testable the criteria is quite similar, no new disconnection or gaps should be evident after testing. The design needs two flat surfaces on opposite sides where the load can be applied from the compression test equipment.

The following specifications were defined as base for the idea generation.

- Properties of polyurethane
    - Stiffness between 2-5 N/mm for 30mm cubes.
    - Elasticity: No plastic deformation in reasonable load cases.
- Printable using FFF
    - No manual intervention during printing
    - Less or equal to one failed print per design
    - Less or equal to three parameter changes for one iteration only
    - Less than or equal to two disconnected faces or failed layer adhesions with gaps less than 3 mm wide
- Testable
    - No new disconnected faces or visible breakage after a reasonable load case
    - Two flat surfaces on opposite sides, flat enough for even load distribution

5 Idea Generation

For the project a lot of inspiration could be taken from the previously mentioned study by F. Sinclair but from other sources as well presented in this section. The biggest limitation in the project compared to many other similar works is the simple AM method used, FFF. Many of the tested ideas are adaptations from previous ideas to work with a FFF printer without support material.

5.1 Z-Direction extrusion

The conventional way of FFF printing is based on printing in layers and only moving in the Z-direction once one layer is finished. However rewriting the G-code one can manipulate the printing pattern to extrude in different directions as seen in figure 10. This could eliminate problems regarding stair-stepping, support material and anisotropy as well as creating more geometrically complex structures. Using a plug in for Grasshopper 3D called Silkworm one can change the G-Code in a more effective manner.

However more research about the method suggests it is not a feasible method for a 3-axis FFF printer using a flexible material without support material. The biggest problem would be collisions of the printer head and the printed parts because of travel path of the nozzle. Even with a 5-axis system this can be problematic and one needs to optimize the travel path to avoid collisions.[30] If the problems regarding collisions would be solved one would still have to overcome more obstacles regarding cooling time for solidification and how to print without support material.

Figure 10: Three different slicings depending on print direction.[30]

5.2 Springs

Investigating flexible structures and flexible solutions springs are a natural place to start. Defined as "a flexible device used to exert force or torque and store energy" there is a lot that can be learned from the different designs of springs. Usually the different types of springs are defined by the direction of the force it is dampening and for this project the compressive type of springs are investigated. The most common spring is the helical compression spring seen in figure 11 but other spring designs such as leaf springs and belleville springs as seen in figures 12 and 13 are also of interest.[31]

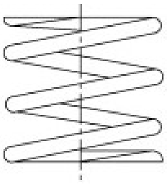


Figure 11: Helical coil spring.[32]

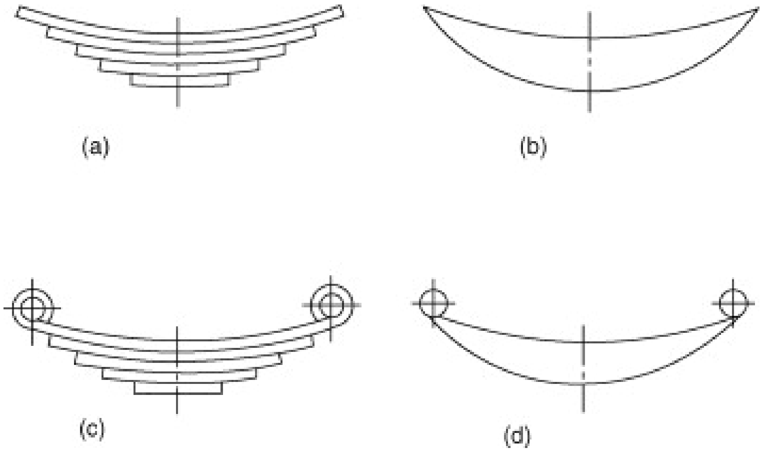


Figure 12: a) semi elliptic leaf spring, b) simplified representation of a semi elliptic leaf spring, c) semi elliptic leaf spring with fixing eye, d) simplified representation of a semi elliptic leaf spring with fixing eye.[32]

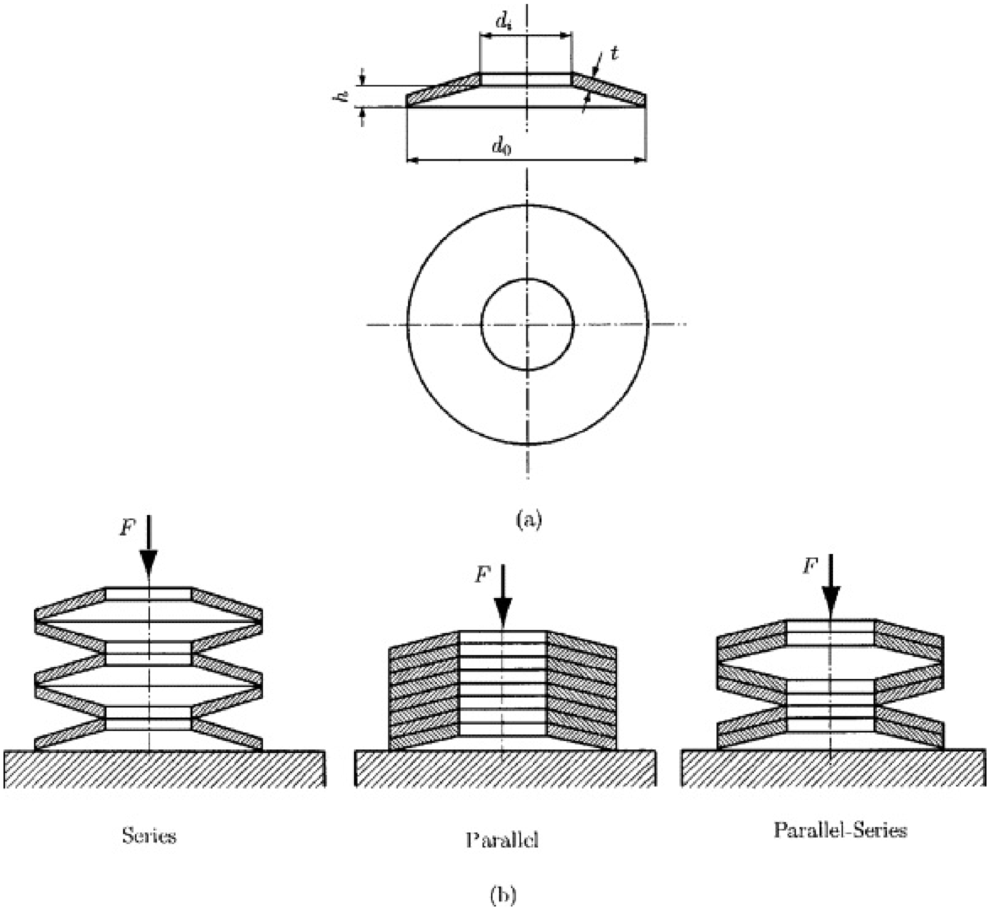


Figure 13: a) Belleville spring, b) Belleville springs stacked in different formations.[33]

5.3 Existing structures

By searching for inspiration from similar projects within STEPS, structures that have already been designed as seen in figure 1 will be altered to suit FFF printing. From previous projects the structures chosen for this thesis seen in figure 14 was the structures that showed the most promise in flexibility. The main AM process used in STEPS has been SLS which is much more suitable for creating complex geometries because it does not need support material.[4][34] The main alteration needed are to change angles of walls to be under 45°which usually is the lowest angle possible with FFF printing. Other simplifications are also needed to achieve feasible designs.[6]

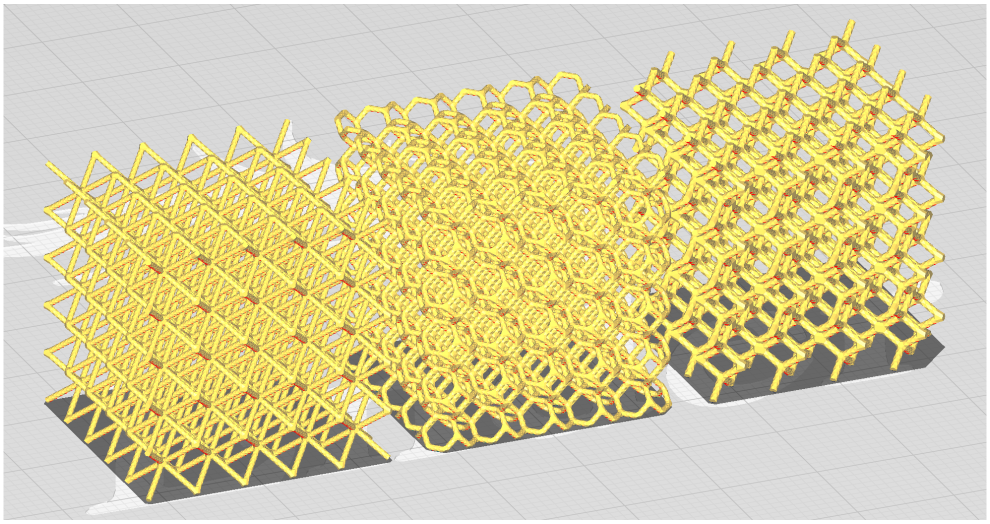
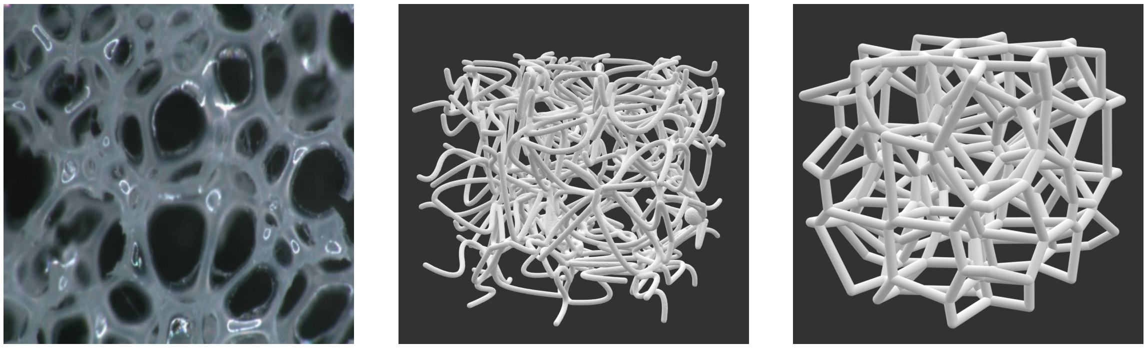


Figure 14: Structures used from previous projects, from the left, X-cell, Vintiles and Diamond.

5.4 Polyurethane

Since replacing polyurethane foam is the main goal of the project inspiration can be found by investigating this material closer. Looking closely to the crystalline structure of polyurethane foams one can find solutions to mimic the structure as seen in figure 15 (a).[35] Achieving structures similar to foams using FFF one can test a method of random extrusion above the base plate of the 3D printer letting the material form itself in random structures. Another way of achieving foam like structures is modeling it using the Grasshopper software with tools such as the Voronoi diagrams.[36] In figure 15 (b) and (c) there are two examples of designed structrures trying to mimic the crystalline structure of polyurethane.



(a)

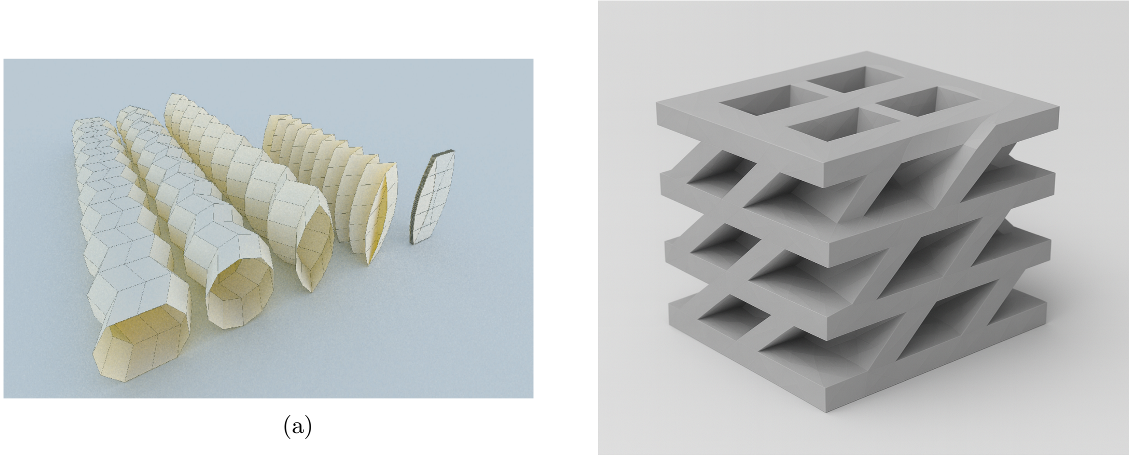
(b)

(c)

Figure 15: (a) Microscopic image of polyurethane foam. [36] (b) Voronoi diagram with a more random structure (c) Voronoi structure with closed cells.

5.5 Origami deployable structures

Origami as the art of folding a 2D structure to create a 3D structure seems like a suitable place to find inspiration for ideas. The deployable and dynamic nature of origami can be used for finding patterns or structures which can enable flexibility as seen in figure 16 (a). [21] Many geometries or patterns can be learned from origami but it is also possible to learn about the actual movement of parts within the structures once compression is applied. [37] A design idea was generated using origami as inspiration as seen in figure 16 (b).


(a)

(b)

Figure 16: (a)Examples of deployable structures.[21] (b) Design idea of an origami inspired flexible structure

6 Idea testing and evaluation

Many of the ideas that are tested and evaluated are inspired from previous studies and experiments in the area of lattice structures and flexible structures. However many of those structures might be functional in theory or numerically but creating such structures that work practically one needs to take more factors in to account. Using the idea specifications defined in section 4 the designs are evaluated and tested on those criteria. The first critera that is tested is printability and the designs can be quickly evaluated against this critera since visible breakage or print failure can be seen already during the printing process. If the breakage is smaller and more difficult to evaluate a caliper is used to measure the size of disconnected faces or gaps.

6.1 Initial Designs

During the initial testing period it quickly became evident that the limitations of using a flexible material with a FFF printer was greater than expected. Due to the high flexibility of the material, bending of the struts occurred between layers therefore lattice structures were difficult to achieve. This leads to unsuccessful prints because the printhead misses the previous layer and extrudes with none to minimal support as seen in figure 18. It is possible that this could be fixed with a less flexible material or other printer settings but this path was not pursued since it was assumed that it would give inadequate results or simply take too much time. Almost all designs generated at this point with geometries that were complicated, like the examples in figure 17, did not pass the printability specification from section 4. From this point the project took a path towards much more simple designs and new decisions regarding the concept generation needed to be made.

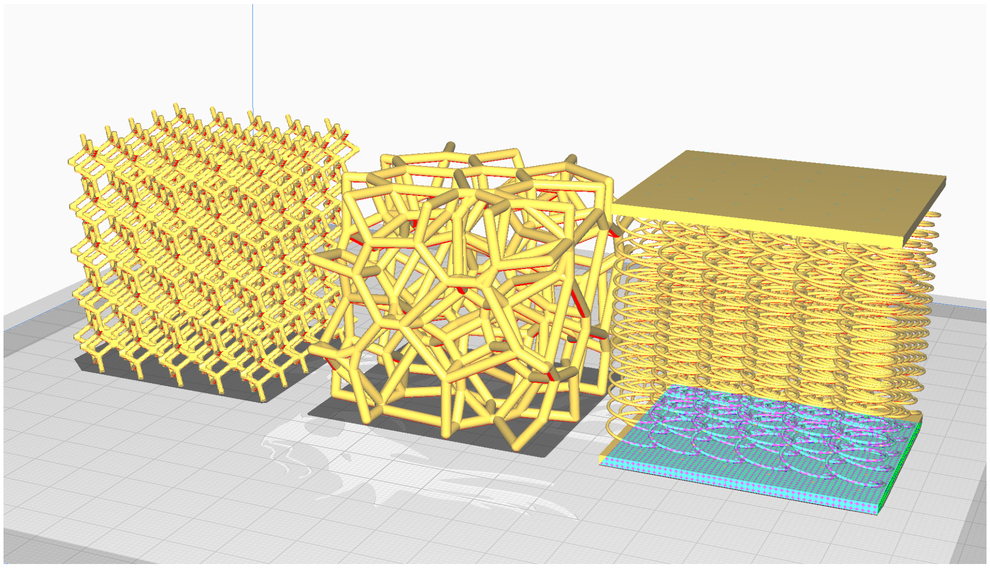


Figure 17: Examples of initial designs which were not feasible.

Figure 18: Failed print due to flexing struts.

6.2 Simplification

The first simplification that needed to be established was that the structures needed continuous walls in the Z-direction to enable successful prints. This limitation quickly made it easier to get successful prints with good results. However this means the structures loses flexibility in one direction which could lessen the amount of possible applications.

6.3 Geometry and Cell Size

To standardize the project a cube size of 30x30 mm was chosen as the standard size of the structures. Once the Z-direction was limited to walls the designs of the structures was actually a 2D pattern which limited the complexity of the designs. A process of finding suitable geometries was initiated with a collection of geometries that was chosen for further testing in figure 19. Listed below is the four patterns and the motive for further testing.

- The hexagonal pattern was inspired from various origami deployable structures that have similar patterns.
- The ellipse pattern derived from trying out different circular patterns, because the ellipse has a lower radius in a certain direction it seemed interesting to test if that could give it a good flexibility.
- The diamond pattern was mainly inspired from watching spring designs. Looking at a helical coil spring in profile it actually forms half a diamond pattern.
- Because a diamond pattern should be tested a quadratic one was also developed to test if the angle of the walls in the direction of compression could affect the flexibility. This angle can be seen in figure 19.

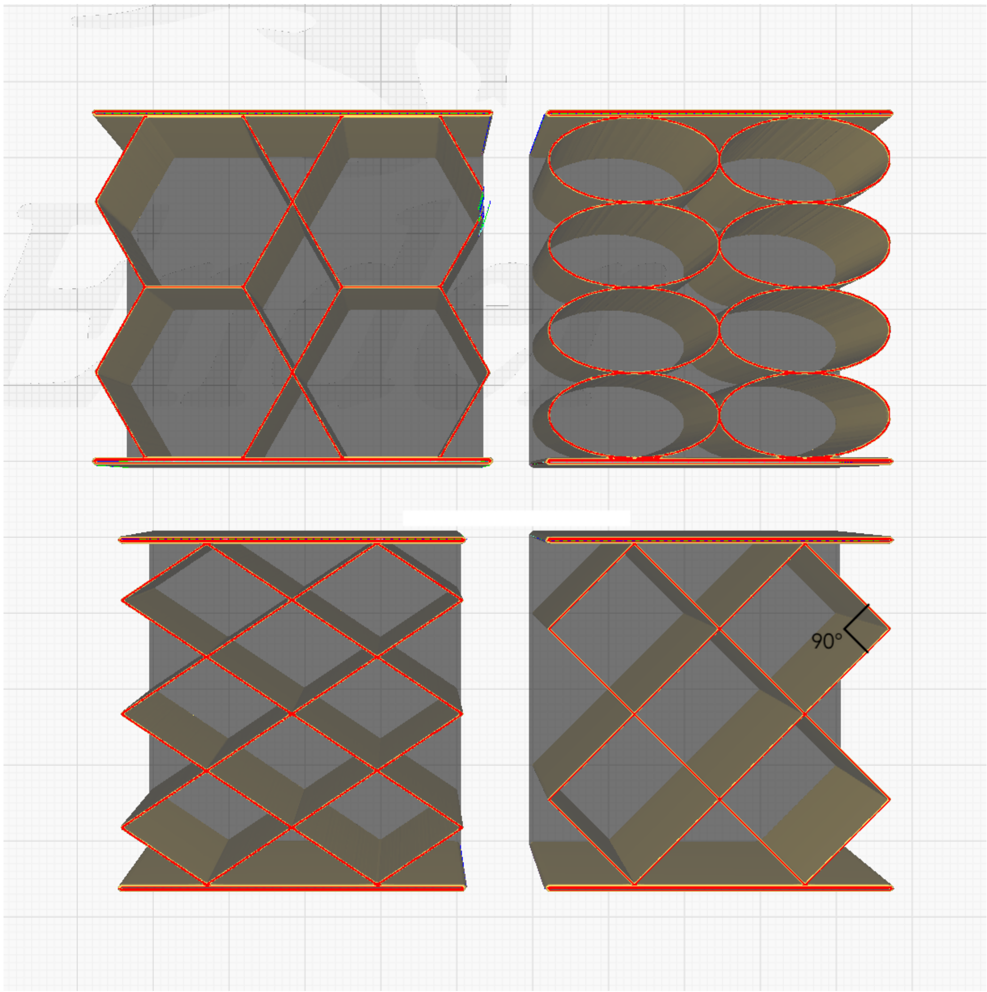


Figure 19: Four main patterns that formed the base of the collection of geometries.

6.4 Testing

An iterative design and testing method was initiated with several rounds of results and exclusion. The structures are named firstly according to the pattern and secondly according to the number of cells in the vertical direction and horizontals directions. For example Dia2-3 is the name of the structure in the bottom left corner in figure 19 above.

6.4.1 First round

For the first round of testing, four patterns with different cell numbers was designed for each geometry as seen in figure 20. For each pattern a minimum of two different cell numbers was designed. Using the digital measurement equipment explained in the methodology section compression tests were conducted and the results are gathered in table 2.

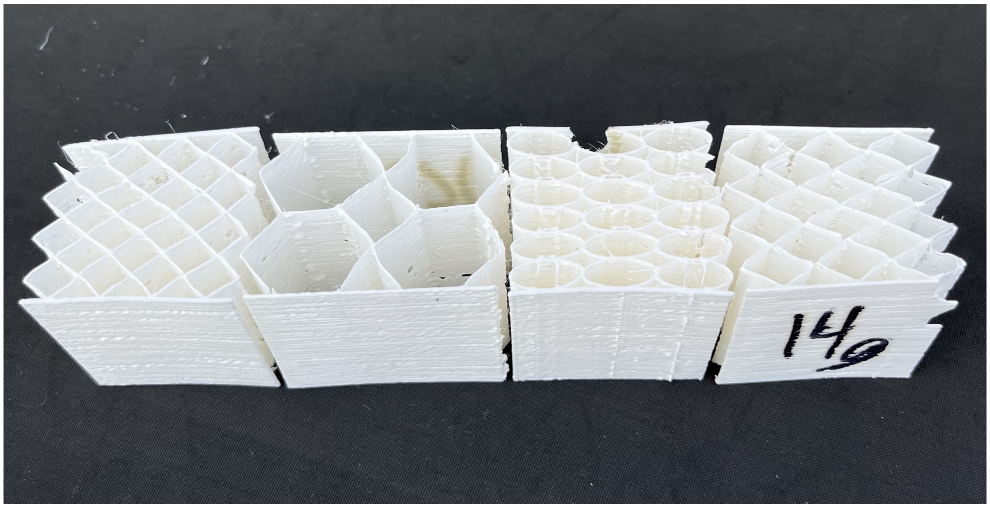


Figure 20: Examples of structures tested in the first round, from the left; Rec4, Hex2, Ellipse3-6 and Dia3-4

Based on the results from the first round of testing, the hexagonal and rectangular geometries showed similar results of higher stiffness than the diagonal and ellipsical patterns. However the hexagonal pattern was excluded from the process because the compression was uneven and it showed more signs of breakage under compression.

6.4.2 Second Round

For the three remaining geometries the number of cells was increased by one cell to investigate further. As seen in table 2 the stiffness at the same load case showed the highest stiffness for the rectangular pattern. However the deformation for the ellipsical pattern was uneven which is why another ellipse pattern Ellipse 5-10 was designed, printed and tested to see if that was the case for greater cell numbers and a bigger load. As seen in figure 21 the deformation was still uneven which is why the ellipsical pattern was excluded from the third round of testing.

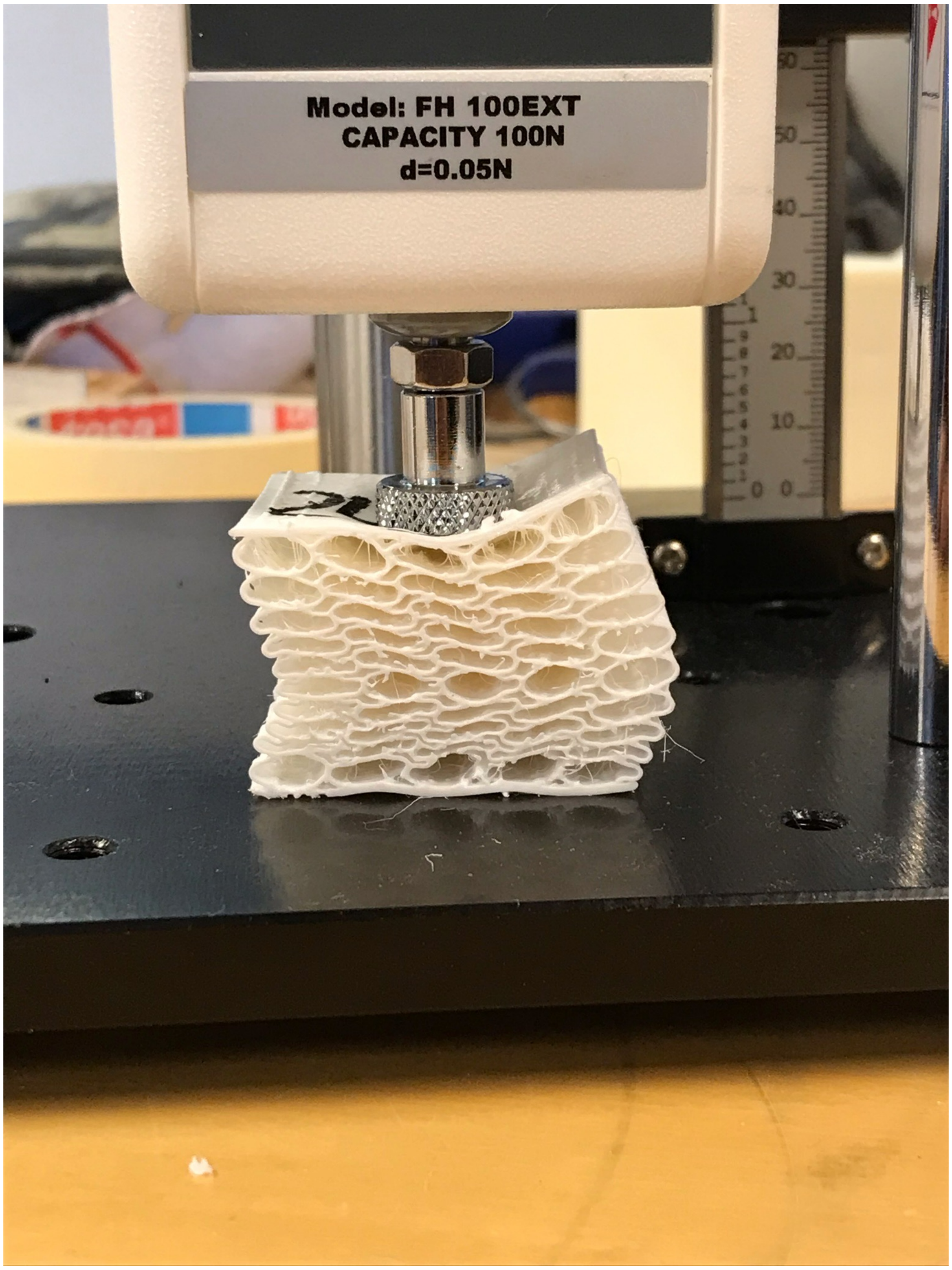


Figure 21: The deformation of the structure skewing to the right in the image

6.4.3 Third Round

The third round of testing was focused on increasing the number of cells to investigate the effect of number of cells on the flexibility. For the diagonal structure the number of cells was increased in two ways. Firstly in both the horizontal and vertical directions and secondly only in the vertical direction. By only increasing cell numbers in the vertical direction, the angle of the walls as seen for the rectangular pattern in figure 19 could be decreased and tested if it affected the flexibility.

6.4.4 Fourth Round

A fourth round of testing was performed strictly focused on the wall thickness of the patterns. The patterns *Rec 1* and *Dia 1-2* was chosen for this experiment starting with a wall thickness of 1mm. It was quickly concluded that the stiffness was greatly affected and a fifth round of testing was planned to gather more results.

6.4.5 Fifth Round

A fifth round of testing was performed with a reduced number of cells and three different wall thicknesses 1mm, 2mm and 3mm per pattern. Another design was implemented to test if a lower stiffness can be achieved even though a higher wall thickness is used. A single leaf spring design was created as can be seen in figure 22.

Figure 22: A print of the spring design.

Table 2: Structures in every round of testing.

Structure	Load (N)	Elongation (mm)	Stiffness (δ)	Thickness	Mass (g)
Round 1					
Rec2	1	-12.34	-0.081	0.4	9
Rec4	4	-5.76	-0.694	0.4	13
Hex2	2	-11.56	-0.173	0.4	10
Hex3	4	-7.3	-0.548	0.4	13
Hex4	4	-3.36	-1.190	0.4	16
Ellipse2-4	1	-13.44	-0.074	0.4	12
Ellipse3-6	4	-5.72	-0.699	0.4	16
Dia2-3	1	-8.5	-0.118	0.4	11
Dia3-4	4	-10.4	-0.385	0.4	14
Round 2					
Rec6	15	-7.45	-2.013	0.4	19
Ellipse4-8	15	-10.5	-1.429	0.4	20
Ellipse5-10	30	-5.1	-5.882	0.4	24
Dia4-6	15	-16.95	-0.885	0.4	17
Round 3					
Rec8	30	-8.18	-3.667	0.4	22
Rec10	30	-3.28	-9.146	0.4	27
Dia6-8	30	-10.41	-2.882	0.4	23
Dia2-6	1	-7.08	-0.141	0.4	16
Dia2-8	2	-15.18	-0.132	0.4	18
Round 4					
Dia2-3	30	-4.56	-6.579	1	36
Rec2	30	-5.33	-5.629	1	30
Round 5					
RecGap	7.5	-17.68	-0.424	1	20
Rec1	7.5	-12.52	-0.599	1	19
Rec1	50	-12.23	-4.088	2	38
Rec1	50	-2.35	-21.277	3	59
Spring	1	-14.87	-0.067	1	17
Spring	7.5	-12.43	-0.603	2	34
Spring	30	-15.65	-1.917	3	52
Dia1-2	15	-20.08	-0.747	1	26
Dia1-2	50	-9.05	-5.525	2	50
Dia1-2	50	-2.17	-23.041	3	75

6.5 Fine Tuning

During the designing process some problems arouse with the prints that needed solving. For some of the prints simple changes to the printer settings was adequate to solve those problems. When slicing parts for 3D printing the slicing software *Ultimaker Cura* will make simplifications to the geometry to create reasonable print paths and layers. In that simplification, thinner walls and complicated joints can disappear or change shape as can be seen in figure 23. In the design process it is necessary to make robust designs to avoid such issues with designing methods like overlapping volumes. Using overlapping volumes one can create extra thick walls especially around joints to avoid slicing and printing issues in these areas. However issues are still probable to arise and using settings for mesh fixes like *Union overlapping volumes* and *Keep disconnected faces* the remaining problems could be solved.

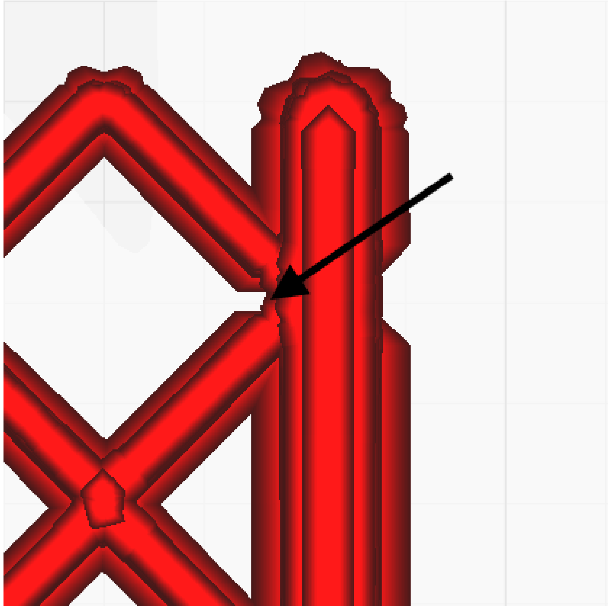


Figure 23: Disconnected face.

7 Results

The most simple way of analyzing the results from table 2 is showing the dependency of mass on the stiffness, the most reasonable assumption would be that the stiffness increases with mass. This can be a first good indication of how the design affect the stiffness and what parameters can be changed to achieve satisfying results on the stiffness.

As seen in figure 24 the trend is that the stiffness increases with mass however the dependency is not linear. Looking at the two red dots which represents *Dia 1-2* and *Rec 10* it is clear that other factors greatly affects the result.

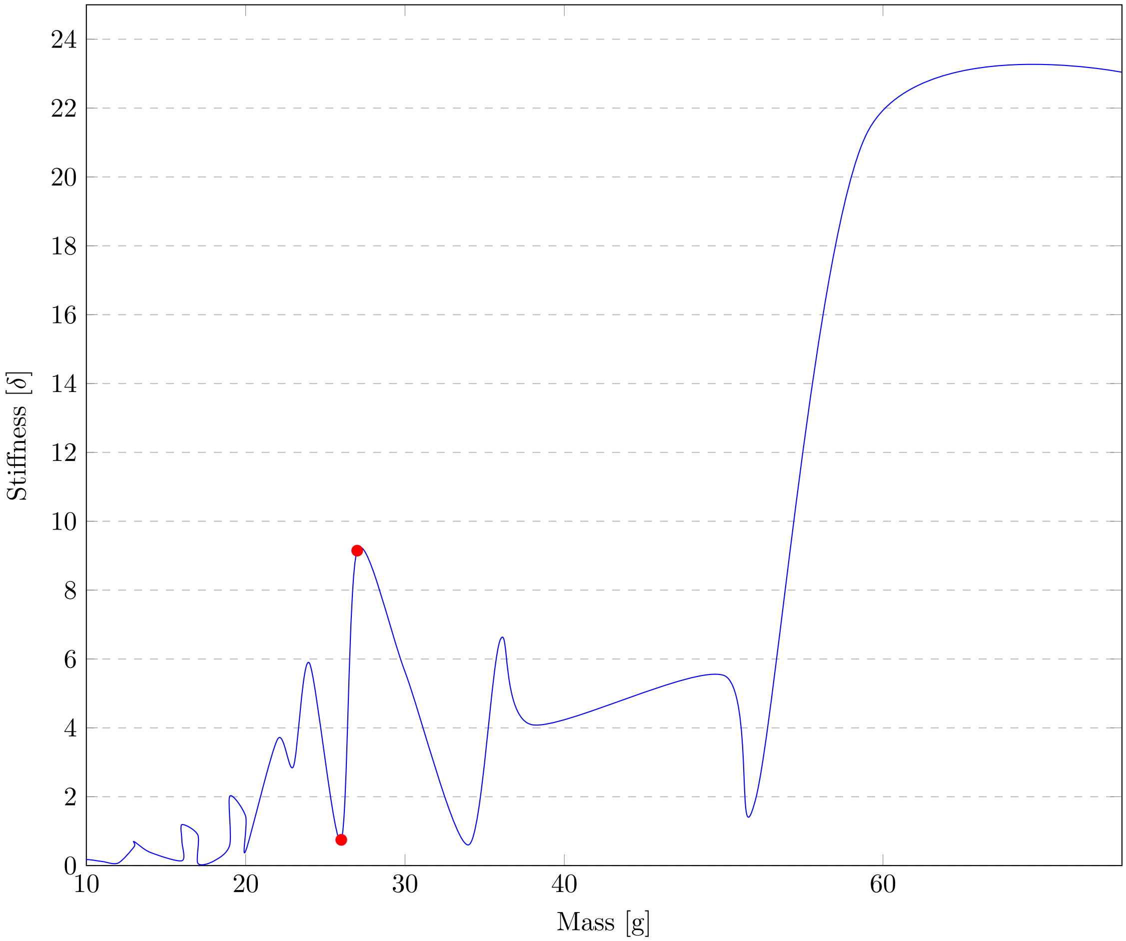


Figure 24: Stiffness dependence of Mass

To further investigate how the different parameters affect the stiffness, more graphs are presented below.

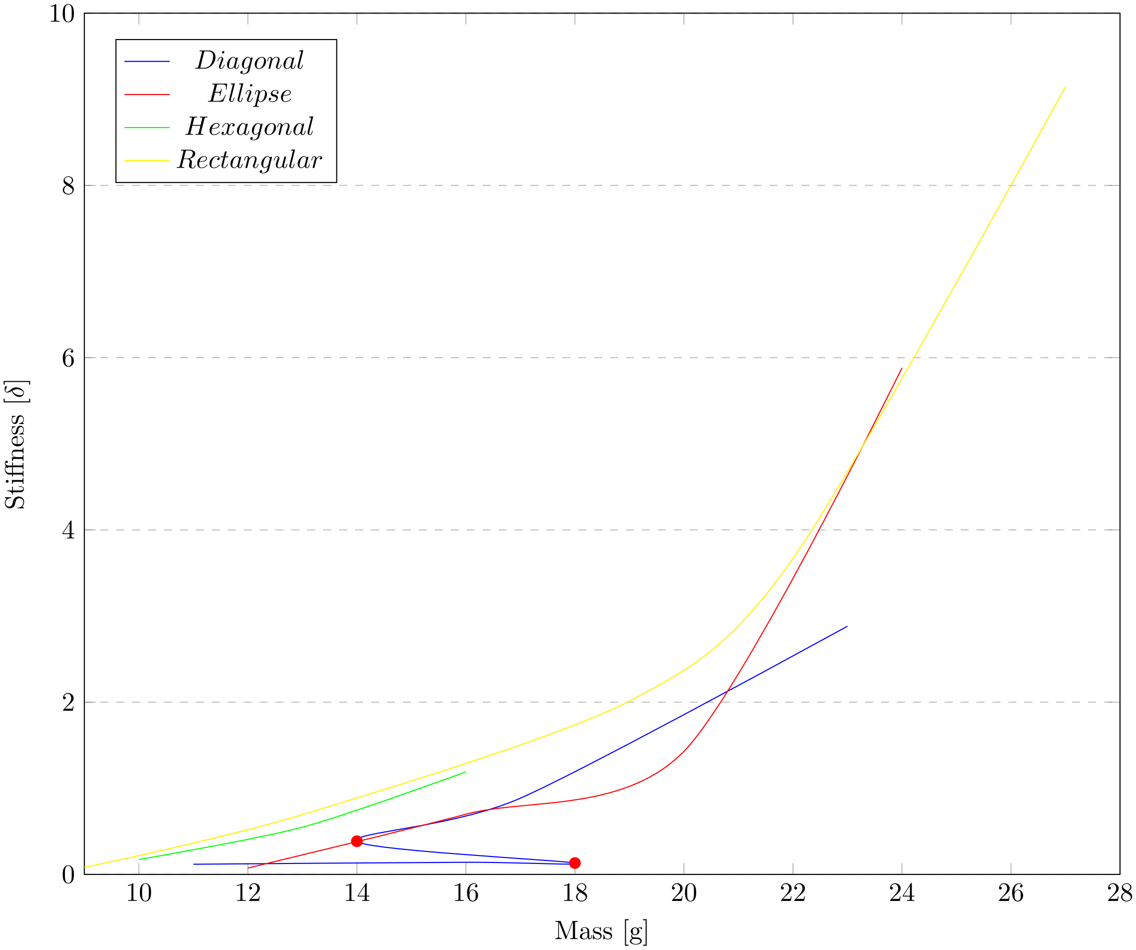


Figure 25: Stiffness dependency on Mass for different patterns

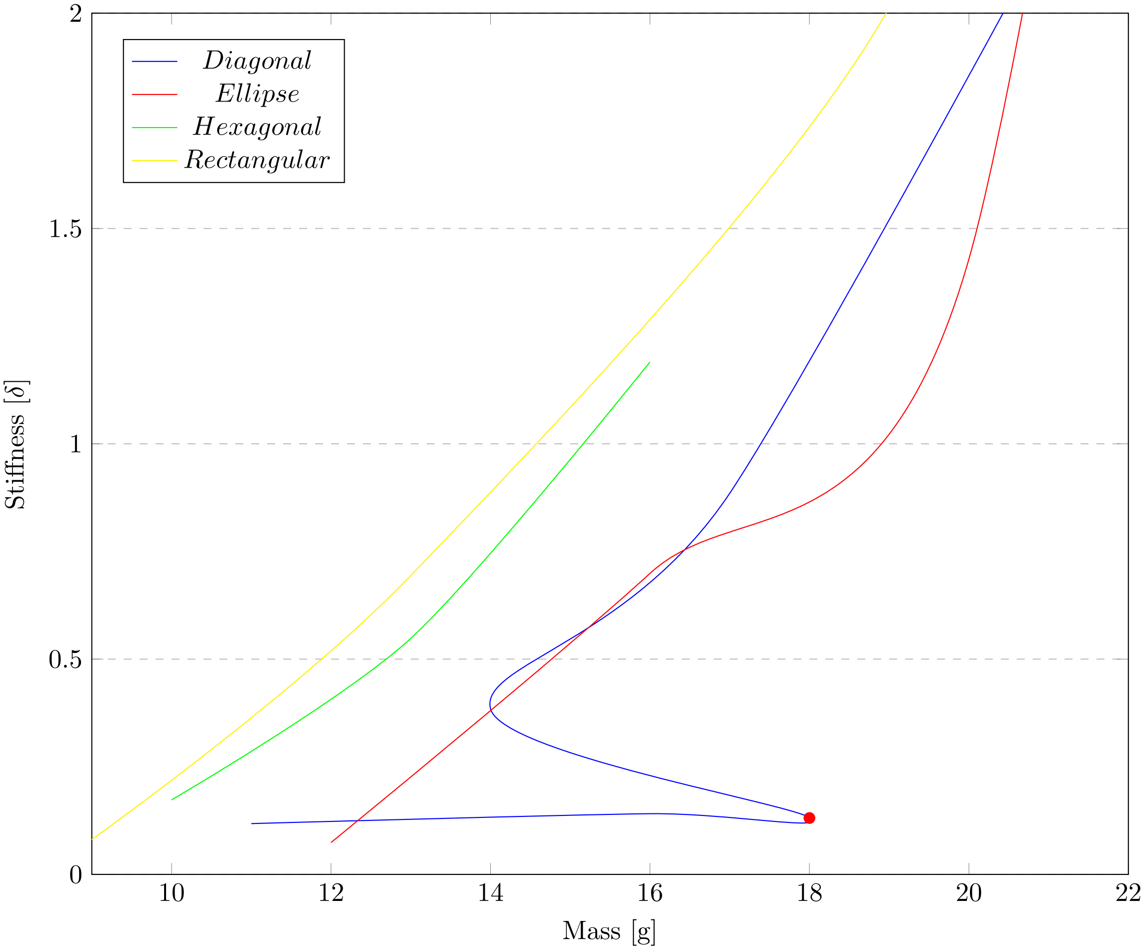


Figure 26: Zoom in for Stiffness values between 0 and 2

Two points of interest in figure 25 are presented for the diagonal structure where a big change in stiffness can be seen depending on cell number and the relationship between vertical and horizontal cell numbers. For the two patterns that are symmetrical in both the vertical and horizontal direction, *Hexagonal* and *Rectangular*, the cell numbers are the same in both directions. But for the *Diagonal* and *Ellipse* patterns this relationship can be compared. In figure 26 the red point showing *Dia 2-8* where a reduction in stiffness is achieved even though the mass is higher suggests that the cell number relationship in vertical and horizontal directions is worth investigating further.

To investigate the feasibility of manufacturing flexible structures with LSAM, patterns with varying wall thickness was also tested. The wall thickness in LSAM is the biggest difference between desktop printers and LSAM printers. This is mainly to save time and to be able to print faster. The wall thickness in LSAM is usually between 0.5-4 mm which is why wall thicknesses of similar sizes were tested.[9] In figure 27 below the results are shown.

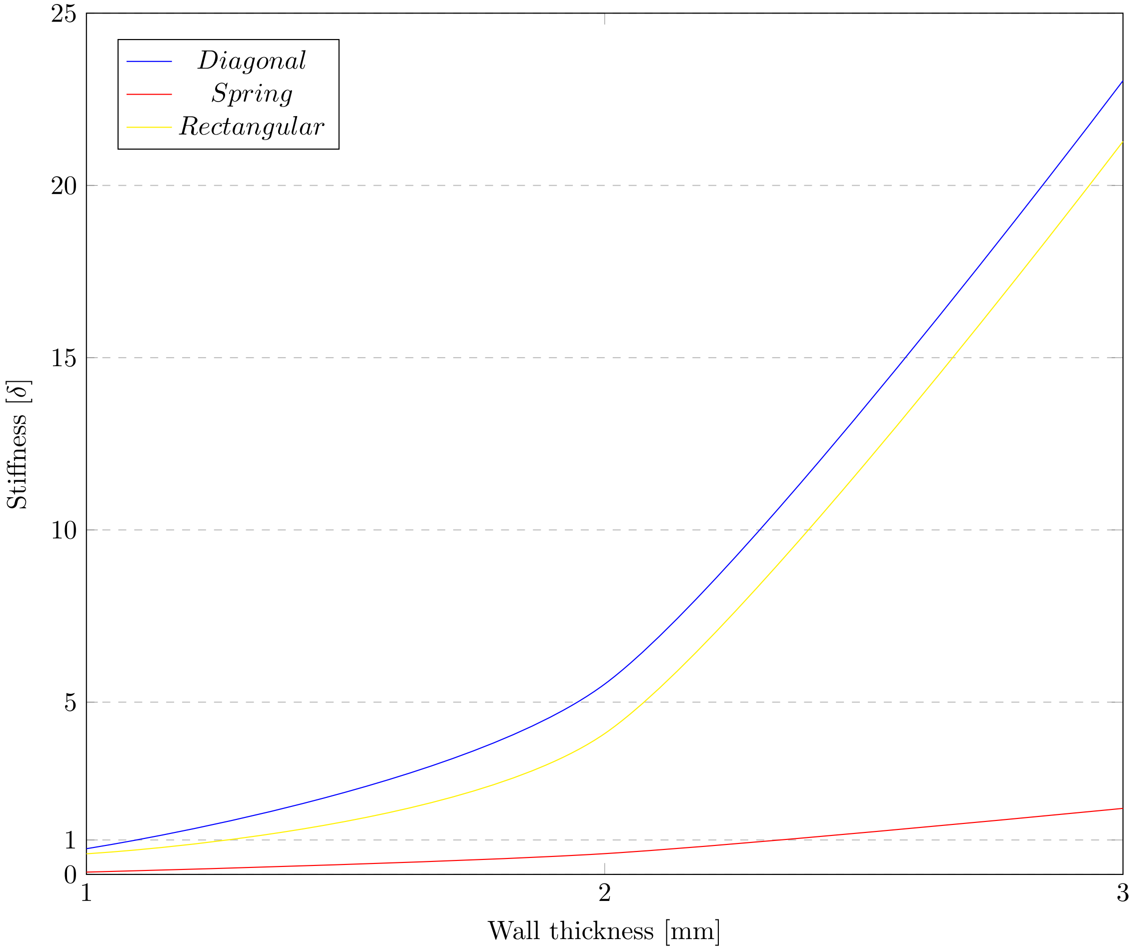


Figure 27: Stiffness dependency on wall thickness.

7.1 Prototype

For a wall thickness of 3 mm the only pattern with a stiffness lower than the specified limit of 2-5 N/mm was the spring design. Therefore a simple cushion is designed with the spring structure to test the viability of the results for furniture applications. The cushion is printed using the same printer as the structures which has a limited build volume which affects the design. To solve this problem the cushion is designed to be quite small and it is divided into two parts as seen in figure 28.

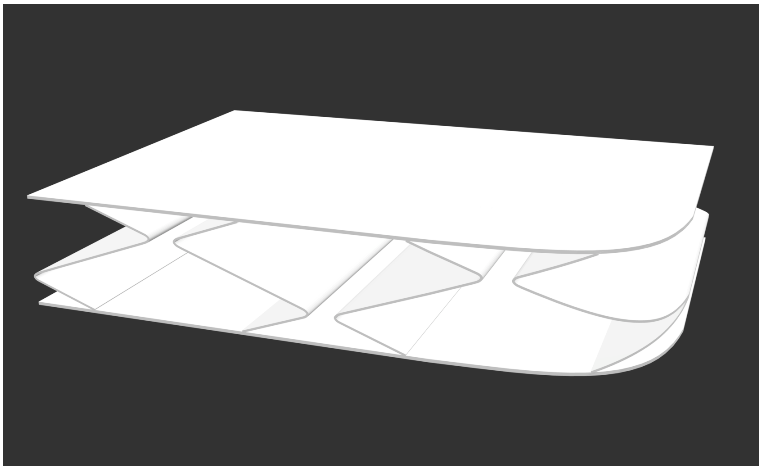


Figure 28: STL File of the prototype showing the spring design in repeated pattern.

The two parts are then fused together using a technique called Wet-Layup where a reinforcement material like fiberglass is fused together with a liquid resin consequently creating a bond in a fibre reinforced composite material as seen in figure 29.[38] The finished prototype can be seen in figure 29 below. Because of issues with availability, the prototype is printed in another material called *Colorfabb PLA/PHA*. This material has an elongation at break at 6.1% compared to the 350% of the *Gearlab PLA Flex (GLB255001)*.[39][40] Such a big difference in flexibility of the material has big effects on the results on flexibility of the structure, however the prototype shows descent results in flexibility thanks to the spring design.

Figure 29: A printed prototype of a seat-cushion fused together in fiberglass.

The viability of the cushion is tested using the specification from section 4, however the specifications of the prototype is slightly changed. The former reasonable load case is now replaced with a reasonable load case of an actual human sitting on the cushion as seen in figure 30. Therefore to be testable the cushion must be big enough for one person to sit on it. There was no equipment available to test the stiffness of the prototype and therefore the viability of the stiffness is only estimated.

Figure 30: The seat cushion tested by a human on a stool.

The stiffness is estimated to be of a reasonable level since it gives a good cushion or dampening feel without any signs of visible breakage. However the design only solves the flexibility in one direction and the feel and softness is a big difference on the prototype compared to the feel of the structures. This results in a cushion that is more similar to the suspension of a car seat rather than the cushion of a sofa that is more soft. To achieve more comfortable results, more research is needed towards the use of different materials and how to combine that with the design. A study could investigate how the flexibility of the material affects the flexibility of the structure and study the dependency between material and design. That dependency can then be used to optimize the choice of material together with the choice of design to achieve satisfying results.

8 Discussion

The project's focus was to find new solutions to mimic the properties of polyurethane foam by developing flexible structures using additive manufacturing. By finding new ways to achieve a flexible material one can greatly improve the environmental effects that fossil based solutions has. Using a FFF printer with a bio-based material new structures was designed and tested to evaluate the mechanical properties and discuss the possibility to replace polyurethane.

8.1 Printer settings

Using a flexible material for the study it quickly became evident that one of the big challenges for the project was to achieve sufficient print results for a wide range of structures. Because the material is flexible and deforms easily between print layers, many of the previous thoughts and ideas would become obsolete and a new thought process was initiated. Even if the end goal was flexible structures, using a flexible material meant a considerable amount of time needed to be spent understanding and altering the print settings.

A big issue for the print quality was stringing which is more frequent when using flexible materials because of the elasticity of the material. Thin strings will be dragged from the latest point of extrusion to the next point and decrease the overall print quality as well as introduce an unpleasant visible feature to the structures. Even though the visible properties of the structures are not focused on in this study it still gives a negative attitude towards the result. The thin strings can increase the overall mass of the structures, increase the amount of material in undesirable locations as well as intervene with print paths and layers of the print. It could be advantageous to the results of this project to further investigate stringing because it is a very frequent phenomenon when printing in flexible materials. However this study did not focus or evaluate the effects of stringing on the mechanical properties and therefore it was concluded that it would be best to optimize the print settings to avoid it.

To find well adjusted printer settings many parameters needed calibration using different tools like the tower tests which give results for different increments in the same prints ultimately reducing the number of iterations. However many of the parameters are dependant of each other meaning changing one parameter is often not enough. This was the reason of a time consuming iterative process that consumed a lot of the time for the project just to find printer settings that was suitable for the chosen material. During the process each iteration meant using the calibration shapes and evaluating the results which sometimes was more or less a visible check. A more sophisticated approach with scientific testing in each iteration could have given even better print results but could however have taken even more time. This is an area that also could have been investigated even more but for the scope of this study limitations and simplifications had to be done. This is one of the big drawbacks using cheaper technology like a desktop FFF printer but is probably necessary if one wants to apply the solution to a profitable system or process.

8.2 Design Limitations

Beyond finding suitable printer settings other simplifications had to be made to achieve feasible results because of the limited technology of a FFF desktop printer. The biggest decision that was made was to limit the structures to a two dimension pattern instead, resulting in continuous walls in the z-direction. This was a major breakthrough in getting better results however it greatly limited the scope to structures with rigid properties in one direction. It could be a crucial drawback with the structures to the possible areas of implementation.

The testing of the finished structures was only done in one direction which meant that the rigidity of a certain dimension did not affect the results but still it needs to be taken into account when discussing possible applications. For upholstery purposes like chair cushions the direction of the force usually is limited to one direction and therefore it could still be viable but for other applications like pillows one could imagine that the rigidity in one direction can be undesirable. If the design limitation of continuous walls was to be overcome by better designs or better AM technology one could achieve results with flexibility in three directions but it needs further investigation.

8.3 Geometry and Patterns

In the study an increased density or wall thickness was chosen in highly deformed areas to reduce failures and increase print quality. The main idea behind this design decision is to evenly spread loads and increase the durability of the structures. For spring designing the load distribution is a key factor for good results and it is also where this inspiration comes from. Comparing a spring design in profile and the diagonal structures one can see big similarities which could suggest why that design had the most easily controlled and favorable results.

For the diagonal structures it became evident that the resulting stiffness quite easily can be controlled to optimize for the desired parameters as well as being the pattern with the most uniform deformation. For example one can decrease the angle for the diagonal shape and therefore making it easier to deform to optimize lower stiffness for less material. In a similar matter one can optimize for lower stiffness with a pre-decided wall thickness similar to a real case of LSAM. This result can be seen in figure 27 where the stiffness for the spring shape, which is a variation of the diagonal pattern, is substantially lower than that of the diagonal or rectangular shapes. It is also possible to achieve a desired stiffness by controlling the cell number or the wall thickness which can be desired for furniture designs like beds where the stiffness could be optimized for the weight of the person sleeping in it.

8.4 Sources of error

To understand and evaluate the results of a study it is important to discuss possible sources of error and how they can impact the results. For this study the main sources of error can be limited to testing equipment and conditions as well as linear assumptions.

For testing the stiffness of the different structures a digital load and distance measuring tool was used. The equipment should be quite accurate in its measurement because it is digital and the loads as well. However it was needed to adjust the load depending on the stiffness of the structure to get reasonable results. For instance a load that was to big would press the structure close to maximal compression where there was no space between struts and the linear relationship could not be assumed. Similarly a load that was too small would give such a low elongation that it was not easy measurable. therefore the load was adjusted to get a reasonable amount of elongation.

Whether the change in load would dispute the validity of the test is difficult to know but it could be a source of error. Similarly the higher loads increases the risk of plastic deformation where the linear relationship of Hooke´s law is no longer valid. To increase the certainty of avoiding plastic deformation the structures was measured before and after the load testing however the plastic deformation can be so small that is difficult to measure even though a digital tool was used. If testing would be done many times a higher level of certainty of a linear relationship could be achieved but the limitation of time made such extensive testing unreasonable. Furthermore the plastic deformation could occur inside the structure in certain areas where the load can be higher. This deformation is not measured and for the study it was not possible to take such deformations in to account and can therefore be a source of error.

Another factor to take in to account is the environment when printing as well as testing. Temperature and humidity can affect the material during printing and testing. For the study there was no controlled environment during printing or testing which means that the humidity and temperature could be different for different structures and therefore affect the results.

The load case of the study is also very simple and is not enough to validate the plausibility of implementing it in real product applications. It does give a good indication of the flexibility and whether implementation could be possible but more factors needs testing to get a better validation. Testing of fatigue as well as testing with load in a more realistic manner could get better results towards real case validation.

8.5 Applications

The main reason for using FFF for the study was to test producing flexible structures using a relatively cheap technology in the AM sector that also exists for LSAM and could therefore enable economically viable products. However compared to injection moulding or plastic extrusion it is still expensive with a low capacity. The main advantage of AM for creating flexible structures is to create complicated geometries, however in the case of FFF printing with a flexible material without support material it proved to be difficult. For the study the resulting structures is quite simple geometrically and therefore it can be discussed whether AM should be the designated manufacturing method. Because the resulting structures have simple geometries it could actually be viable to produce it with injection moulding or extrusion therefore reducing costs and production times dramatically. If this would be possible the solutions could compete with the cheap price of polyurethane but using a much more environmentally friendly material, however it would need further research to determine if those production methods are viable options.

9 Conclusion

This study aimed to replace fossil based polymers such as polyurethane using a bio based polymer printing flexible structures using FFF. The end use products was focused towards furniture industry but a broader application case was also discussed. Adjusting existing results within the STEPS project as well as generating new ideas finalized in a number of structures that was viable to print using a desktop FFF printer. These structures was tested using a simple method to evaluate their flexibility or rather their stiffness to determine how the design can affect the flexibility. The result shows that the design or pattern of the structure can affect the flexibility however it is important to also evaluate how the choice of material can influence the results. For this study only one material was tested that showed promise and many of the structures have a subjective foam feel. Testing more materials might show that the most important factor is the choice of material and therefore the design might not be used to optimize flexibility but to optimize other parameters such as mass or use of material.

Most importantly this study proved that foam like structures can be achieved with FFF printing in environmentally sustainable materials. The level of flexibility or foam like properties can however be questioned based on the application that one would want to implement for. If it can be implemented to any kind of industry it also need to be economically viable which another choice of manufacturing method might enable.

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