UiT The Arctic University of Norway

Faculty of Science and Technology

Study of 3D printed polymer structures and geometries

The impact of raster angle configurations on mechanical properties

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Abstract

3D-printing of polymers come in a large variety of methods and materials, each configuration with its own strengths and weaknesses. To compute and estimate mechanical properties of 3D-printed parts, good knowledge to the geometry of the internal structures is important to obtain. This will vary between different printers and slicers. As 3D-printed parts are anisotropic, it is often challenging to estimate their mechanical properties. To achieve a deeper understanding of this matter, an empiric approach of printing and testing specimens with different internal structures, will be one objective of this thesis. The results will be compared to both traditional calculation of mechanical strength in isotropic materials, as well as to results from a state-of-the-art study carried out in this thesis.

Acknowledgement

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I also want to send my gratitude to researcher Morten Monland Olavsbråten for assistance with laboratory testing.

This has been an educational journey.

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1 Introduction

Additive Manufacturing is the umbrella term, covering a variety of manufacturing methods. The most common method in this field of production is known as 3D printing. Printing physical three-dimensional models, layer by layer, adding material using both different techniques and materials. As 3D-printing becomes increasingly utilized as a manufacturing method, the need of verification of the mechanical properties of 3D-printed products increases.

Most products will have to go through different mechanical tests to verify the mechanical properties. A test of significant importance is a tensile test, where a specimen of a given material is exposed to a tensile force until failure. The two main objectives in this thesis will be to design and manufacture a tensile test grip-fixture using 3D printing. Secondly to perform tensile tests of 3D printed specimens with different internal structures.

1.1 Background

At the Faculty of Engineering Science and Technology in the University of Tromsø, there is a long and proud history of educating engineers within several fields of technology. Along with a rich environment for Research and Development there is constantly a need to be updated and capable of performing education and research within the different fields of engineering.

Material technology plays a key role in engineering, and the faculty provides good facilities for both manufacturing and testing of components and parts in a range of materials. Additive Manufacturing have become increasingly integrated in the everyday routines for students producing prototypes, as well as researchers' performing development and testing.

The faculty has a range of facilities for material testing, equipment mainly intended for metals or ceramics, which in some cases can be inconvenient for testing polymers and weaker materials. Polymers play a significant role in 3D printing, and as the use of 3D printers increase, a need of knowledge about the mechanical properties of printed parts increases.

1.1.1 Fused Filament Fabrication (FFF)

In this project some key factors in 3D printing with polymers is studied. The printing method used is called Fused Filament Fabrication (FFF). [1] A thermoplastic filament heats up to its melting temperature range and extrudes through a nozzle onto a building platform, building a three-dimensional model layer by layer. [1]

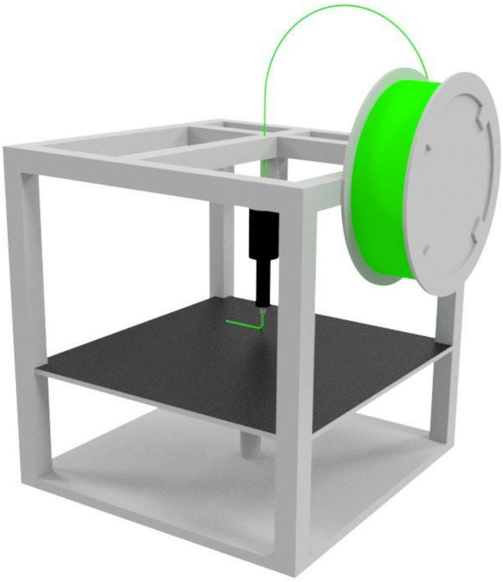

Figure 1, Illustration of an FFF-3D-printer

Before the printing can start, the digital geometry of a CAD-model is sliced in a 3D-slicer software. The software creates a file for the 3D-printer, with all specifications necessary for the printer to build the three-dimensional geometry layer by layer. A 3D-slicer-software has normally numbers of adjustable parameters, which by a great deal affect the way the model is printed and consequently the mechanical properties of the finished part. [2]

In the 3D-slicer software, a 3D-model typically consists of four sections, (figure 2), but a model can be printed with only some of the sections, i.e., wall and infill without roof and floor, as shown in figure 3.

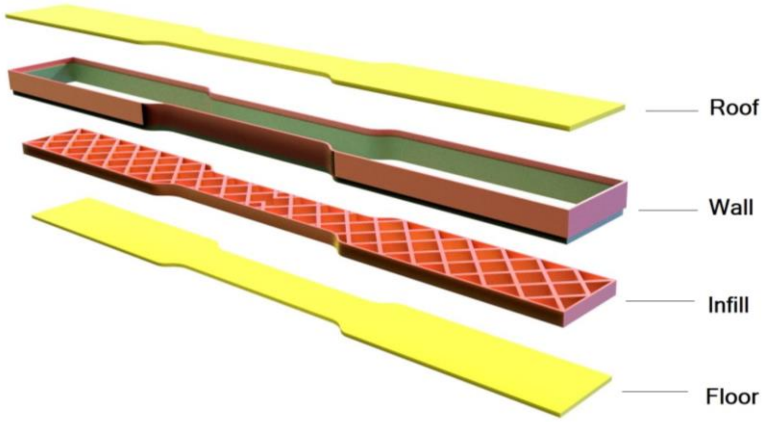

Figure 2, The sections of an FFF-printed model

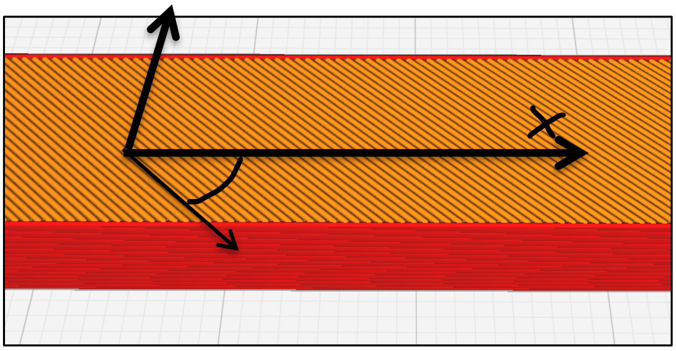

Figure 3, Model with only wall and infill and a 45° raster angle

1.1.2 Raster Angles

The infill section of the print, normally obtain the largest volume of the printed geometry. The infill can be printed with a partial percentage of material, to save time, weight, and material. In this project all printing will be done with 100 % infill. This is due to the focus solely on the raster angles effect on the mechanical properties.

With a linear infill pattern, the lines of material, can be driven in a specific angle to the x-axis, as seen in figure 3. The raster angles of interest in this project is illustrated in figure 4-7.

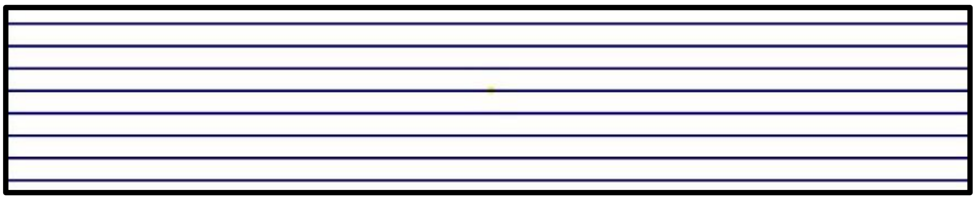

Figure 4, Raster angle = 0°

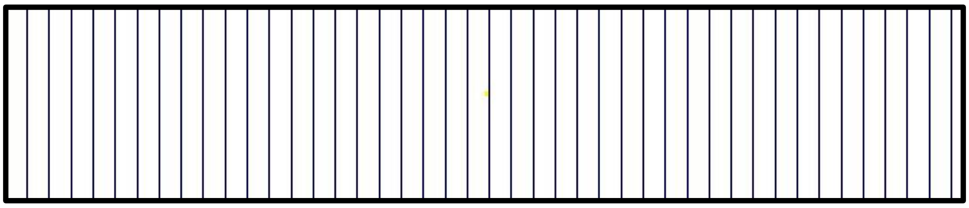

Figure 5, Raster angle = 90°

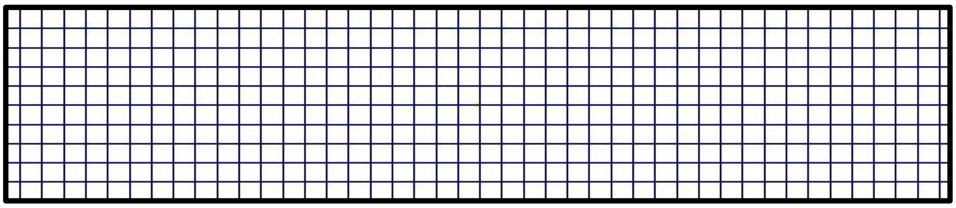

Figure 6, Raster angles = 0° and 90°

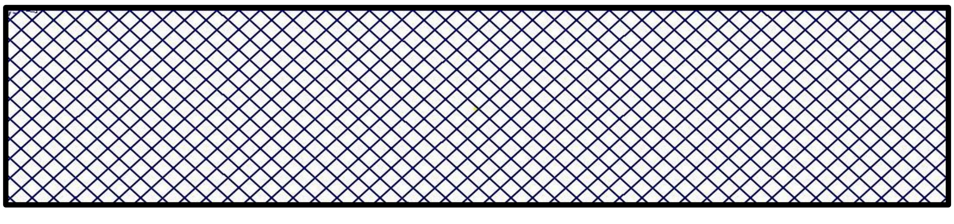

Figure 7, Raster angles = -45° and +45°

1.1.3 Tensile testing

The conventional method for tensile stress testing of materials, uses a uniaxial tensile testing machine. [3] A material specimen is attached to two grips that interactively increases distance, applying tension to the specimen with a constant speed until failure.

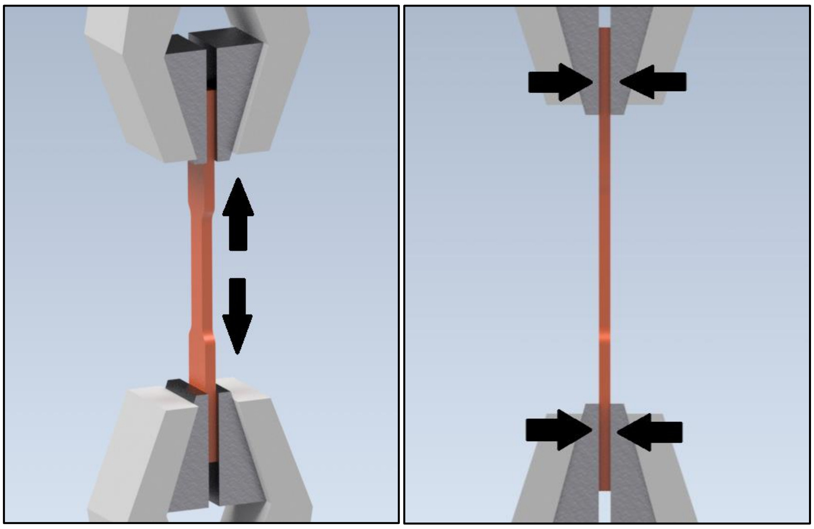

Figure 8, Typical grip configuration

1.1.4 Alternative tensile testing rig

A problem with conventional grips is the horizontal pressure it provides, increasing the risk of deformation to the ends of the specimen when testing partial infilled 3D printed polymer parts.

In this project an alternative tensile test rig will be developed using a digital force gauge and 3D printed grip-fixtures, attached to, and driven by a hydraulic jack.

Figure 9, Illustration of existing elephant jack

2 Preliminary Works

2.1 Limitations

The project is limited to the development of a method for tensile testing of polymer specimens, including the design and manufacturing of the grip-fixture needed for fixing the specimen in place during testing. Some relevant tensile testing of 3D-printed specimens will be performed and compared to results found in two recent articles in the projects state-of-the-art study.

2.1.1 Design

The design process in this thesis will focus on the design of the grip-fixture, intended for fixing the test-specimen in each end. The grip-fixtures will be manufactured in a 3D printer.

The design of the tensile test specimen is given in the standard; ASTM-D638, however the ends of the specimen will be redesigned to fit the grip-fixtures.

2.1.2 Testing

The test specimens will be tested for tensile stress at break for four different raster angle configurations. The four configurations are; (0°), (90°), (0°/90°) and (-45°/+45°). The material used for the test specimen is Polylactic Acid, PLA. [4]

2.1.3 Comparison

The results will be evaluated and compared with results and findings in the state-of-the-art investigation. A comparison will also be done to an analytic mathematical model for a theoretical homogeneous and isotropic case i.e.: a casted PLA [4] specimen.

2.2 State-of-the-art investigation

The state-of-the-art investigation in this project has focused on recent knowledge in the field of mechanical properties and internal structures for FFF-printed polymers. The investigation is performed using Google Scholar. The search for relevant literature was limited to recent articles and papers containing tensile stress testing and effects of different raster angle configurations. As mentioned in 2.1.2, the test of interest, is tensile testing of PLA with four specific raster angle configurations.

Presented below is a relevant selection of results from two scientific publications accessed through Google Scholar using the search phrase: "*tensile test raster angle orientation.*" All the results collected in this investigation are results from tensile strength comparison among FFF-printed PLA specimens with different raster angles. The results will be compared to the results in this project.

2.2.1 Results from recent relevant publications

Tensile testing of FFF-printed PLA specimens:				
Article 1:	B. Arifvianto, Y. Wirawan, U. Salim, S. Suyitno and M. Mahardika, "Effects of extruder temperatures and raster orientations on mechanical properties of the FFF-processed polylactic-acid (PLA) material," *Rapid Prototyping Journal,* vol. 27, no. 10, pp. 1761-1775, 2021. [5]			
Year:	2021			
3D-printer:	Delta Anycubic			
Layer thickness [mm]:	0.2			
Infill [%]:	100			
Infill pattern:	Linear			
Relevant results from this article:				
Raster angles [°]:	0	90	0/90	-45/+45
Tensile strength [MPa]:	45*	35*	34*	38*
*Approximate values				

Table 1, Results of article 1. [5]

Tensile testing of FFF-printed PLA specimens:				
Article 2:	M. M. Hanon, R. Marczis and L. Zsidai, "Influence of the 3D Printing Process Settings on Tensile Strength of PLA and HT-PLA," *Period. Polytech. Mech. Eng., no. , Jan. 2021,* vol. 65, no. 1, pp. 38-46, 2021. [6]			
Year:	2021			
3D-printer:	Bq Witbox 2			
Layer thickness [mm]:	0.2			
Infill [%]:	100			
Infill pattern:	Straight (linear)			
Relevant results from this article:				
Raster angles [°]:	0	90	0/90	-45/+45
Tensile strength [MPa]:	48.7	48.9	54.9	56.5

Table 2, Results from article 2. [6]

2.3 Requirements

- The standard used for tensile stress test is ASTM D638
- The material used for specimen is Polylactic acid (PLA) [4]
- The software used for design is Autodesk Inventor
- The 3D-slicer used for specimens is Ulimaker Cura
- The 3D-slicer used for grip-fixtures is Markforged Eiger
- The 3D-printer used for specimens is Ultimaker 2E+
- The 3D-printer used for grip-fixtures is Markforged Mark Two
- The force gauge used in tensile test-rig is Kern FH 5K

2.4 Objectives of the project

The project objective is to develop an alternative method for tensile testing of 3D-printed polymer specimens, to design and manufacture grip-fixtures for a tensile test-rig, using 3D-printing, and finally collecting results from testing different raster angles impact on the tensile strength of 3D-printed PLA-specimens.

A personal objective is to achieve a deeper understanding and knowledge of this field of technology, as well as getting more familiar with the scientific processes and methods used in research on a higher level.

3 Design process

The development of an alternative method for tensile testing of 3D-printed polymers will utilize existing equipment in the laboratory facilities at the faculty. The idea is to use a hydraulic elephant jack as the source of force, a digital power gauge, and grip-fixtures to fix the test-specimen during tensile testing. In this design process the focus will be on the grip-fixtures needed for the tensile test rig.

The design process used in this project is a well-known process in the field of engineering design. The literature used as a guide, is the book; “Engineering Design

Methods”, by Professor Nigel Cross. [7] His method is based on an eight steps process as seen in figure 8.

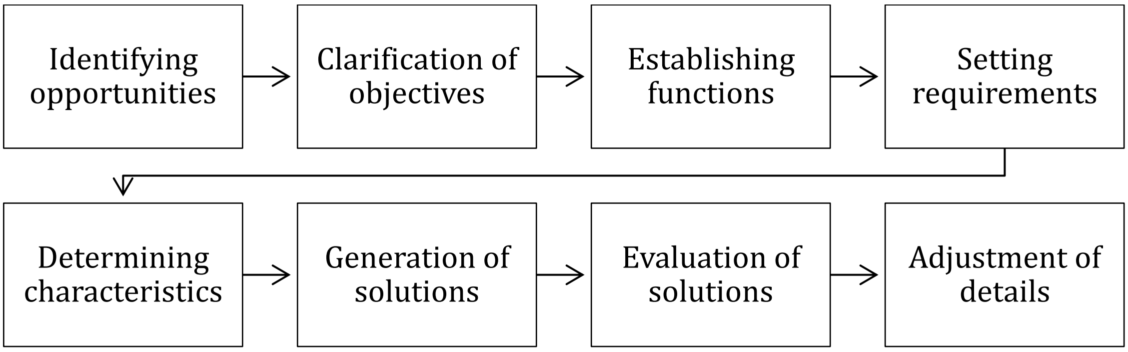

Figure 10, The eight steps of the design process

3.1 Identifying opportunities

In the initial part of the design process, an overview of the problem and the limitations is important to achieve. A deeper understanding of the methods used to solve the problem is necessary. [7] Tensile testing conventionally is done, using machines with grips, holding the specimen in please using a pressure force. The grips relative motion has only one degree of freedom, the Z-axis. By utilizing the existing hydraulic jack, one question is on how to deal with the jacks natural working motion and if it can be combined with a need of a linear motion.

Function:
• Work in a linear motion. • Lock specimen ends without crushing the specimen. • Be combined with existing jack.
Physical strength:
• Withstand the force necessary to perform tensile tests on specimen, including a safety factor. • Withstand repeated use without any significant failure or deformation.
Material:
• A 3D printable polymer material.
Production:
• 3D-printing.
Maintenance:
• Few parts. • Easy to replace parts.

Table 3, Mapping table.

3.2 Clarification of objectives

The objectives of the product are already explained previously in this chapter and are overall goals important to keep in mind during the design process.

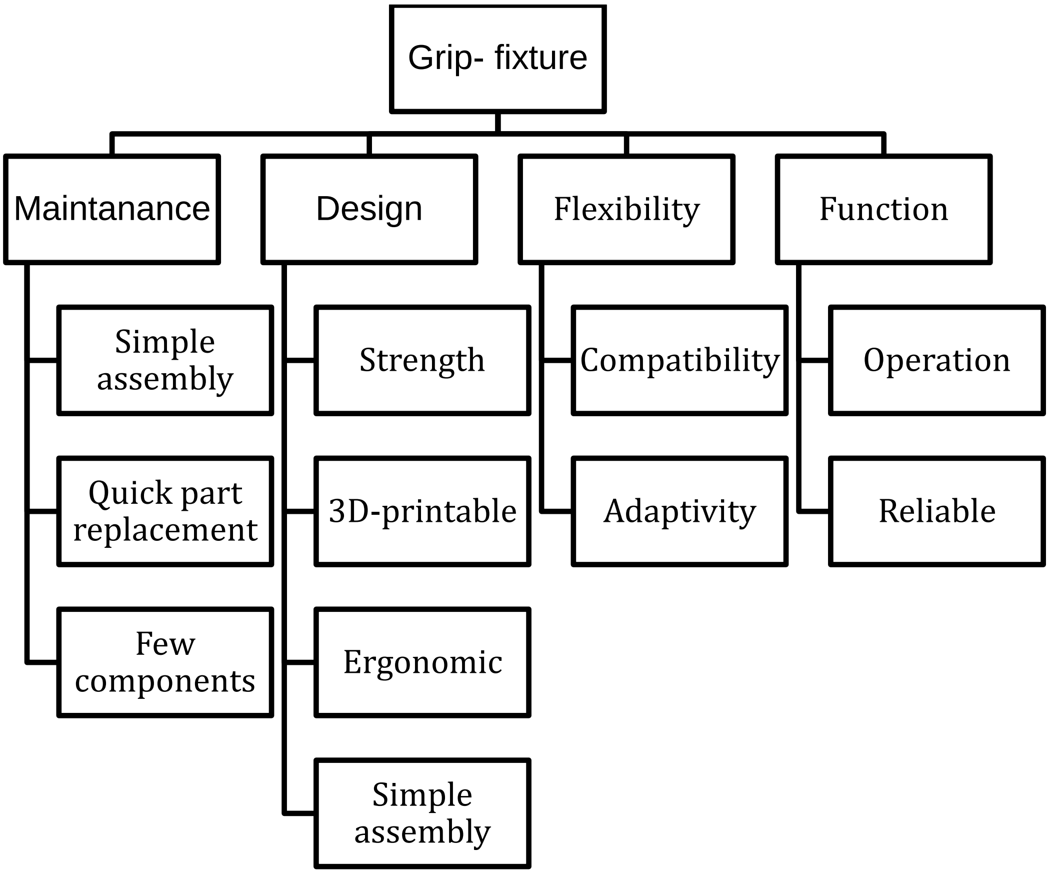

Figure 11, Objective tree for grip-fixture [7]

3.3 Establishing functions

Now it is time to establish the functions of the product. At this point a technique called "the black box" is used to process the needs into workable solutions.

Figure 12, Illustration of the Black Box [7]

MAIN FUNCTIONS	
Input:	Output:
Fixate partial and fully infilled 3D-printed specimen.	Conical or T-shaped geometry of specimen-end cavity
Integrated as a link in a flexible tension rig configuration. (Rope, cable, chain, etc.)	In-line/ collinear configuration. (Specimens and tools natural axis.)
SUB-FUNCTIONS	
Functions	Parts involved
Tension transfer	All
Maintenance	All
Connection to shackle	One end of grip

Table 4, Main and sub-functions [7]

3.4 Setting requirements

In step two and three of the design project, the overall objectives for the grip-fixture are clarified. Now it’s time to transform the objectives to specifications that will be locked in the rest of the design process.

Specification #:	The specifications of the grip-fixture:
1	It must be 3D-printable
2	Compatible with the jack/force gauge
3	Withstand tensile force necessary, multiplied with a safety factor of 3
4	One centered pin-connection for linkage to jack/force gauge
5	Holding the specimen through the testing, with out deformation to the specimen-ends.
6	Trouble-free operation

3.5 Determining characteristics

To determine the characteristics of the design, a Quality Function deployment Analysis (QFDA) is used [7]. The QFDA will analyze the possible solutions for different functions established in the previous steps of the design process.

Grading				
1	2	3	4	5
Very good	Good	Moderate	Weak	Insufficient

Quality Function Deployment Analysis				
Fixture mechanism:	Time used to swap specimens	Complexity	Reliability	Sum:
Conical connection	1	1	4	6
Bolted connection	3	2	2	7
Pressure connection	2	2	3	7
Combination of all	3	3	1	7

Table 5, Quality Function Deployment Analysis - Mechanism

Quality Function Deployment Analysis				
Material:	Geometric accuracy	Strength	Cost	Sum:
Onyx	1	3	2	6
Onyx with CCF	1	1	3	5
Nylon	1	3	2	6

Table 6, Quality Function Deployment Analysis - Materia

3.6 Generation of solutions

In step six in the design process, different concepts will be designed for evaluation. These concepts are based on the guiding from the previous steps in the process. Based on the Quality Function Deployment Analysis in last step, the mechanism with the highest score, (lowest number), is the conical connection. The material with the highest score is Onyx combined with continuous carbon fiber reinforcement. (CFF)

3.6.1 Concept 1

Grip-fixture with conical connection:

Figure 13, Grip-fixture with conical connection

Concept 1 has a simple conical connection to the specimens ends. However, this is only holding the conical sides of the specimen increasing the risk of bending motions, due to the high transversal forces occurring in the ends of the specimen.

3.6.2 Concept 2

Grip-fixture with a combination of conical, bolted and pressure connection:

Figure 14, Grip-fixture with conical, bolted and pressure connection

Concept 2 has been designed with a combination of the previous mentioned connection solutions. This will provide pressure on all sides of the specimens' end, combined with one single bolted connection through a hole in the center of the end. This solution will provide the safest and reliable connection, and simultaneously distribute forces on all sides of the specimen.

3.7 Evaluation of solutions

After evaluation of the two concepts, the choice of concept 2 is the best option in order to solve the intended tasks. A stress analysis is performed with the finite element method in Autodesk Inventor. (Figure 15)

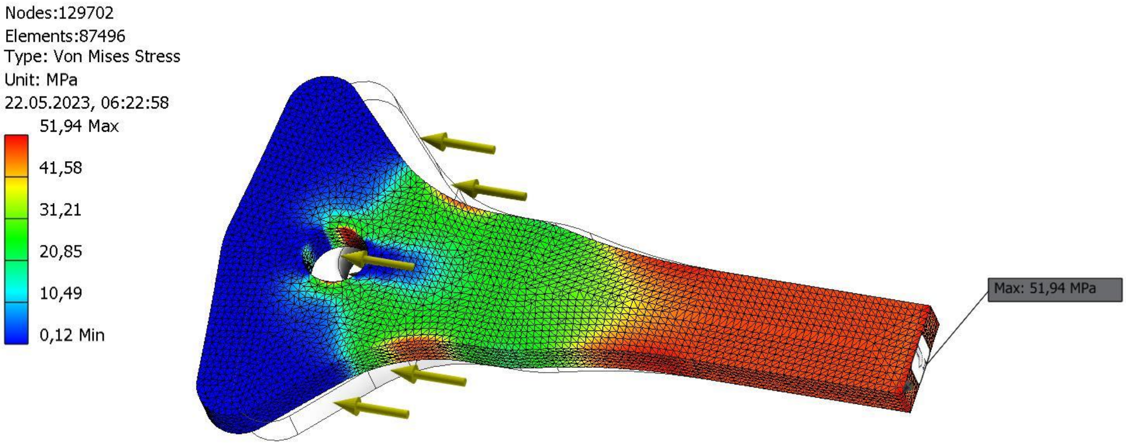

Figure 15, Stress analysis from Autodesk Inventor

3.8 Adjustment of details

The last step in the design process is to adjust details of the chosen concept. It is printed in a Markforged Mark Two 3D-printer with continuous carbon fiber (CCF) reinforcement.

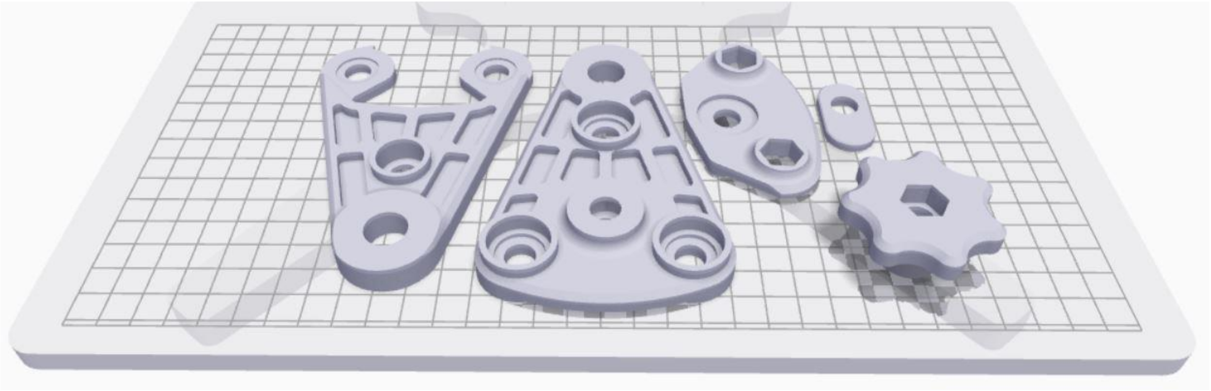

Figure 16, Virtual build tray on Markforged Mark two

The CCF were placed in the xy-plane to achieve a high strength in the intended tension-direction. (See figure 17)

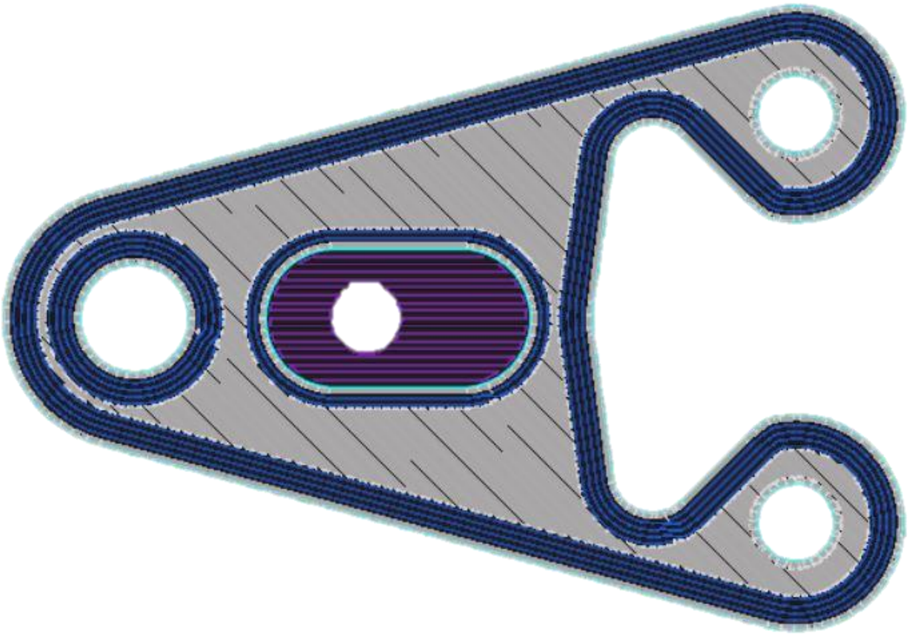

Figure 17, Horizontal section with CCF locations

4 Calculations

In these initial tensile tests performed in this project, the data collected is only the force applied during the test. To find the approximative maximum stress in the specimen, the maximum force from the data is divided on the cross-sectional area of the specimen. However, the cross-sectional area changes slightly under tension, but is negligible for this stage of the development of a test-rig.

The elongation of the specimen during the test is not measured, but an extensometer will be integrated to the system as part of future improvements. The hydraulic of the jack is manually actuated and the speed of the test is not constant. That will also be part of future improvements. (See chapter 8)

Figure 18, Specimen

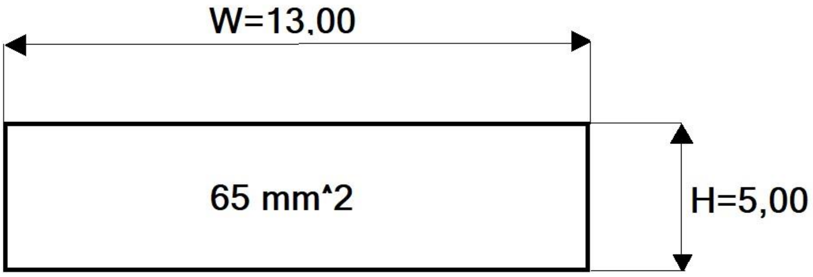

Figure 19, Cross-section of specimen [mm]

Typical maximum yield stress of PLA is in the range 50-70 MPa.

For plain tensile stress in a homogenous isotropic case, i.e.: casted PLA, of the specimen used in this project, we set the maximum stress = 70 MPa

$$\sigma = \frac{F}{A} \quad \longrightarrow \quad F = \sigma * A = 70 * 65 = 4550\ N$$

This is for comparison to the forces and stresses measured in the testing of the 3D-printed specimens.

5 Testing

All tensile tests performed in this project was done according to the following set up: The hydraulic jack was used as the source of force. The grip-fixture in the lower end was attached to a lifting strap by a steel shackle-connection. The strap was fixated to the lower structure of the jack. The upper grip-fixture was connected to the jacks lifting boom by the force gauge and steel shackles. (Figure 14)

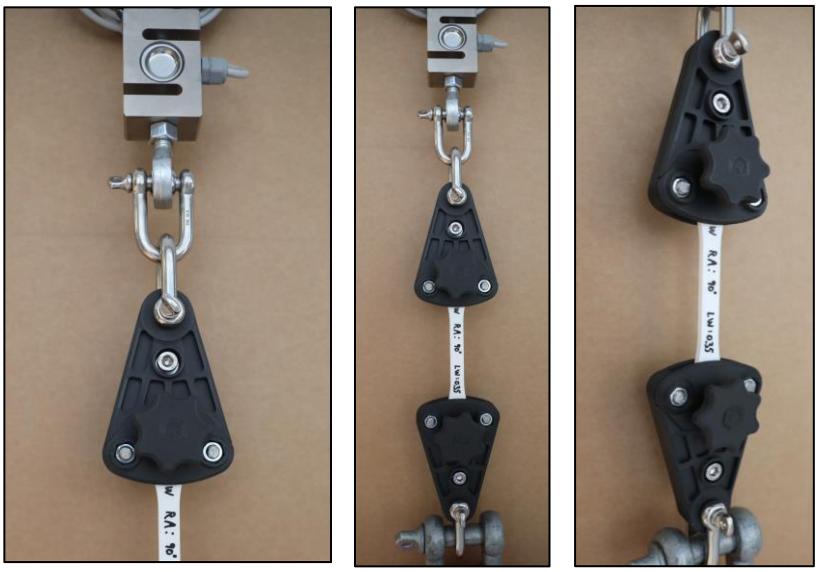

Figure 20, Tensile testing assembly

The tensile testing was done with a total of three batches of specimen. All batches consisted of four specimens, each batch with equal specifications regarding raster angle configurations; specimen 1 = (0°), specimen 2 = (90°), specimen 3 = (0°/ 90°) and specimen 4 = (- 45°/ +45°).

The difference in specifications between the three batches, was all regarded to *raster line width* and *material flow*.

5.1 Tensile test batch 1

Tensile testing of FFF-printed PLA specimens				
Batch 1				
3D-printer:	Ultimaker 2 E +			
Layer thickness [mm]:	0.1			
Infill [%]:	100			
Infill pattern:	Straight (linear)			
Raster line width [mm]:	0.4			
Material flow [%]:	95			
Specimen:	1	2	3	4
Raster angles [°]:	0	90	0/90	-45/+45
Max. force [N]:	700	200	1800	1600
Max. Tensile stress [MPa]:	10.8	3.1	27.7	24.6

Table 7, Test data, batch 1

Figure 21, Specimen, batch 1

5.2 Tensile test batch 2

Tensile testing of FFF-printed PLA specimens				
Batch 2				
3D-printer:	Ultimaker 2 E +			
Layer thickness [mm]:	0.1			
Infill [%]:	100			
Infill pattern:	Straight (linear)			
Raster line width [mm]:	0.35			
Material flow [%]:	110			
Specimen:	1	2	3	4
Raster angles [°]:	0	90	0/90	-45/+45
Max. force [N]:	4100	2050	3200	3400
Max. Tensile stress [MPa]:	63.1	31.5	49.2	52.3

Table 8, Test data, batch 2

Figure 22, Specimen, batch 2

5.3 Tensile test batch 3

Tensile testing of FFF-printed PLA specimens				
Batch 3				
3D-printer:	Ultimaker 2 E +			
Layer thickness [mm]:	0.1			
Infill [%]:	100			
Infill pattern:	Straight (linear)			
Raster line width [mm]:	0.35			
Material flow [%]:	105			
Specimen:	1	2	3	4
Raster angles [°]:	0	90	0/90	-45/+45
Max. force [N]:	1500	1100	2550	2300
Max. Tensile stress [MPa]:	23.1	16.9	39.2	35.4

Table 9, Test data, batch 3

Figure 23, Specimen, batch 3

6 Results

The testing of the specimens has shown significant deviation in results, both compared between the three batches and compared to the results from the state-of-the-art study (Ch. 2.2.1). The maximum stress is achieved in batch 2. The only variation in settings between batch 2 and 3 is a decrease in material flow, from 110%-105%. The significant improvement from batch one is due to both a slight overlap between the raster lines, and to an increase in material flow. These two parameters, *line width* and *material flow*, has here showed to be crucial regarding the mechanical properties of FFF-printed parts.

The tensile test-rig has worked as intended and has proven to be a useful tensile test set up. There are improvements that can be done in order to compete with the accuracy of a conventional tensile testing machine. (Ch. 8)

7 Conclusion

This project has given valuable knowledge and experience in an important area of engineering design. 3D-printing of polymers has grown from being a rapid prototyping technology, to also be a manufacturing method for good reasons. The 3D-printers and the materials accessible today can compete with conventional manufacturing techniques of short-series productions and complex designs. The necessity of studying the material complex of 3D-printed parts is therefore very important.

8 Future work

The tensile test-rig should be further developed with an extensometer compatible with the force gauge’s software, to measure the elongation of the specimen during testing. The hydraulic jack could preferably be driven by a hydraulic pump, fixing a constant speed regardless of the pressure/force. Other grip-fixtures could be produced to test bending stress etc.

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Appendix A

Specimen Building Log:

			UM printer A:		UM printer B:			
	Material:	L. height [mm]:	Specimen 1:	Specimen 2:	Specimen 3:	Specimen 4:	Date:	Comment:
			Raster Angles [°]:					
Batch 1	UM Tough PLA	0.1	0	90	0/90	-45/+45	25.04.23	*
Batch 2	UM Tough PLA	0.1	0/90	-45/+45	0	90	28.04.23	**
Batch 3	UM Tough PLA	0.1	0/90	-45/+45	0	90	05.05.23	***

* Poor bonding between raster lines on 0 and 90.

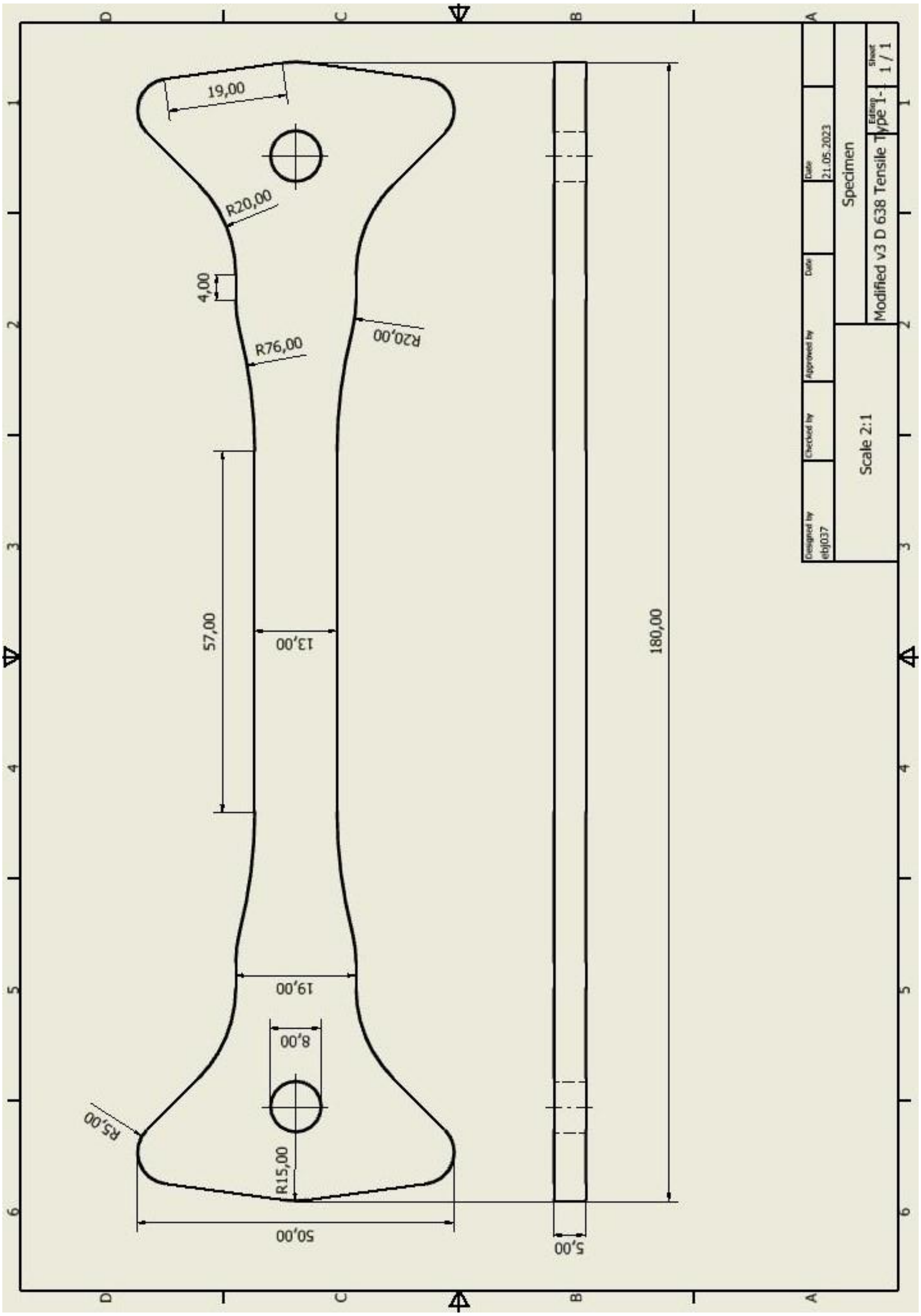
** Increased infill flow from 95-110 %, as well as reducing all line width from 0.4 -0.35 mm.

*** Decreased infill flow from 110-105 %

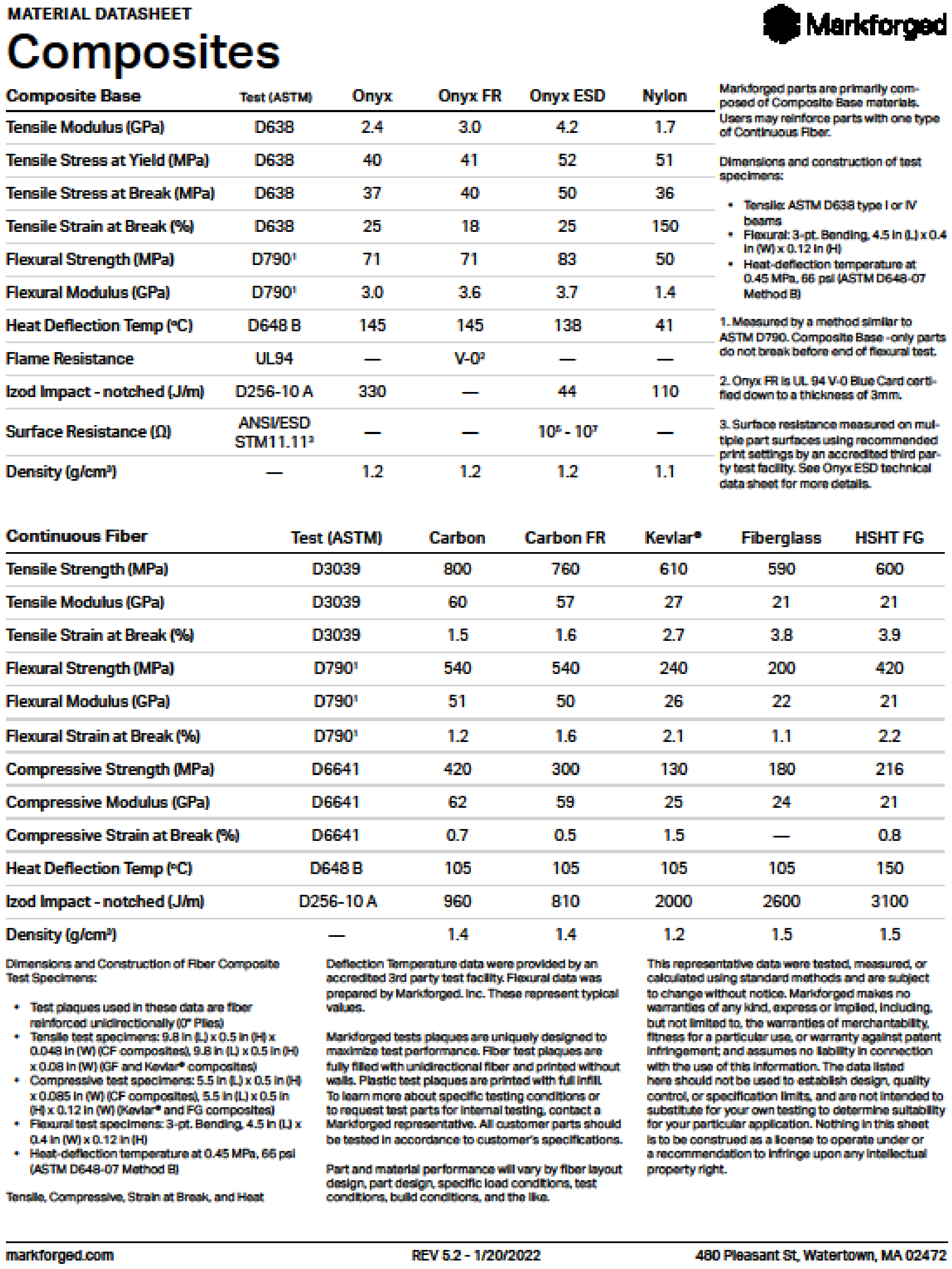
Appendix B

Tensile test form				
Guided standard:	ASTM D638			
Specimen:	Modified v3 D638 tensile type 1 (Appendix C)			
Grip-fixtures:	3D printed CFRP			
Force gauge:	Kern FH-M 5K			
Batch:				
3D-printer:				
Layer thickness [mm]:				
Infill [%]:				
Infill pattern:				
Raster line width [mm]:				
Material flow [%]:				
Specimen:	1	2	3	4
Raster angles [°]:				
Max. force [N]:				
Max. Tensile stress [MPa]:				

Appendix C


19,00
R20,00
4,00
R76,00
R20,00
57,00
13,00
180,00
19,00
8,00
R5,00
R15,00
50,00
5,00
Designed by
ebj037
Checked by
Approved by
Date
Date
21.05.2023
Scale 2:1
Specimen
Modified v3 D 638 Tensile Type 1-
Edition
1
Sheet
1 / 1
A
B
C
D
1
2
3
4
5
6

Appendix D



MATERIAL DATASHEET

Composites

Composite Base	Test (ASTM)	Onyx	Onyx FR	Onyx ESD	Nylon
Tensile Modulus (GPa)	D638	2.4	3.0	4.2	1.7
Tensile Stress at Yield (MPa)	D638	40	41	52	51
Tensile Stress at Break (MPa)	D638	37	40	50	36
Tensile Strain at Break (%)	D638	25	18	25	150
Flexural Strength (MPa)	D790[1]	71	71	83	50
Flexural Modulus (GPa)	D790[1]	3.0	3.6	3.7	1.4
Heat Deflection Temp (°C)	D648 B	145	145	138	41
Flame Resistance	UL94	—	V-0[2]	—	—
Izod Impact - notched (J/m)	D256-10 A	330	—	44	110
Surface Resistance (Ω)	ANSI/ESD STM11.11[3]	—	—	10^5 - 10^7	—
Density (g/cm^3)	—	1.2	1.2	1.2	1.1

Markforged parts are primarily composed of Composite Base materials. Users may reinforce parts with one type of Continuous Fiber.

Dimensions and construction of test specimens:

- Tensile: ASTM D638 type I or IV beams
- Flexural: 3-pt. Bending, 4.5 in (L) x 0.4 in (W) x 0.12 in (H)
- Heat-deflection temperature at 0.45 MPa, 66 psi (ASTM D648-07 Method B)

[1] Measured by a method similar to ASTM D790. Composite Base -only parts do not break before end of flexural test.

[2] Onyx FR is UL 94 V-0 Blue Card certified down to a thickness of 3mm.

[3] Surface resistance measured on multiple part surfaces using recommended print settings by an accredited third party test facility. See Onyx ESD technical data sheet for more details.

Continuous Fiber	Test (ASTM)	Carbon	Carbon FR	Kevlar®	Fiberglass	HSHT FG
Tensile Strength (MPa)	D3039	800	760	610	590	600
Tensile Modulus (GPa)	D3039	60	57	27	21	21
Tensile Strain at Break (%)	D3039	1.5	1.6	2.7	3.8	3.9
Flexural Strength (MPa)	D790[1]	540	540	240	200	420
Flexural Modulus (GPa)	D790[1]	51	50	26	22	21
Flexural Strain at Break (%)	D790[1]	1.2	1.6	2.1	1.1	2.2
Compressive Strength (MPa)	D6641	420	300	130	180	216
Compressive Modulus (GPa)	D6641	62	59	25	24	21
Compressive Strain at Break (%)	D6641	0.7	0.5	1.5	—	0.8
Heat Deflection Temp (°C)	D648 B	105	105	105	105	150
Izod Impact - notched (J/m)	D256-10 A	960	810	2000	2600	3100
Density (g/cm^3)	—	1.4	1.4	1.2	1.5	1.5

Dimensions and Construction of Fiber Composite Test Specimens:

- Test plaques used in these data are fiber reinforced unidirectionally (0° Plies)
- Tensile test specimens: 9.8 in (L) x 0.5 in (H) x 0.048 in (W) (CF composites), 9.8 in (L) x 0.5 in (H) x 0.08 in (W) (GF and Kevlar® composites)
- Compressive test specimens: 5.5 in (L) x 0.5 in (H) x 0.085 in (W) (CF composites), 5.5 in (L) x 0.5 in (H) x 0.12 in (W) (Kevlar® and FG composites)
- Flexural test specimens: 3-pt. Bending, 4.5 in (L) x 0.4 in (W) x 0.12 in (H)
- Heat-deflection temperature at 0.45 MPa, 66 psi (ASTM D648-07 Method B)

Tensile, Compressive, Strain at Break, and Heat Deflection Temperature data were provided by an accredited 3rd party test facility. Flexural data was prepared by Markforged. Inc. These represent typical values.

Markforged tests plaques are uniquely designed to maximize test performance. Fiber test plaques are fully filled with unidirectional fiber and printed without walls. Plastic test plaques are printed with full infill. To learn more about specific testing conditions or to request test parts for internal testing, contact a Markforged representative. All customer parts should be tested in accordance to customer's specifications.

Part and material performance will vary by fiber layout design, part design, specific load conditions, test conditions, build conditions, and the like.