Experimental and FE Analysis of
3Dprinted fiber reinforced honeycomb
structured composite materials

Giarmas Evangelos

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Student Name: Evangelos Giarmas
SID: 1106150011
Supervisor: Dr. Dimitrios Tzetzis

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Abstract

The present dissertation thesis is one of the first worldwide efforts to study the behavior of 3d printed fiber reinforced honeycomb structures. The 3d printer that has been used for the experiments is “Markforged Mark Two”. Markforged printers are unique in their ability to lay continuous strands of fibers (carbon, glass and kevlar) inside 3D printed parts to achieve strengths comparable to metals. The novelty in this research is the fact that the fiber reinforcement will be inserted in the total body of the honeycomb structure, despite the existent papers that try to add reinforcements in specific parts of specimens.

Another important effort that has been made in this dissertation thesis, is to simulate 3d printed materials in Finite Element Analysis software. The ANSYS Workbench has been selected for this purpose. 3d printed technology is really new and CAE software programs are not really appropriate to study these materials yet. However, ANSYS tries to overcome these problems with the announcement of 3DSIM which is a software that will be able to simulate 3d printed structures. ANSYS hopes that by combining its flagship software with exaSIM (additive manufacturing simulation workflow), and FLEX (helps to develop 3D printing operations and best practices based on one’s materials and equipment selections), it will be able to help users reduce the risks, trial and error of implementing a 3D printing workflow. It also hopes to speed up the installation and optimization of 3D printing equipment [1],[2]. In addition the proper and more accurate simulation of 3d printed structures will be possible.

Finally, another new approach that has been studied in this thesis, is to make high resistant honeycomb structures that will be able to be sandwiched between other more flexible materials. This new approach may have great impact in several aerospace applications, where lightweight and less stiff honeycomb structures are being sandwiched by carbon fiber panels in order to acquire the proper mechanical properties until now. The new proposal, that will be presented in this research, will make possible the elimination of the use of fibers (carbon, glass or Kevlar), by adding them in special selected parts of the honeycomb structure and remove them from the bottom and top panels.

Evangelos Giarmas

13/3/2018
Preface

The purpose of this dissertation is to study how the 3d printed fiber reinforced honeycomb structures behave under certain loads. Some important factors will be studied for the first time globally. First of all, the honeycomb structure will be 3d printed and reinforced (fiber) by the printer. In addition, a methodology that will allow to simulate 3d printed fiber reinforced structures in ANSYS will be proposed. Finally, the honeycomb structure that can be produced with the selected methodology may be able to replace the way that Carbon Fiber Technology works until now.

Due to all the above reasons, the research on the selected scientific field was really difficult. There are no many similar publications, so too much investigation should have been done. However, hopefully this dissertation will give some new tools to the scientific community in order to go even further the research that has been recently started in these fields.

Finally, it should be emphasized that the experimental tests have been made in the 3d Lab of International Hellenic University with the invaluable help of the lab’s engineer Manolis Tzimitzimis. The supervisor of this dissertation was Dr. Tzetis who inspired this effort from the beginning and without his help the final result will not be so interesting.
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1. **Introduction**

The great interest that has recently been shown in 3D printing technologies inspired the creation of this dissertation thesis. Additive Manufacturing is widely used for the fabrication of polymer components ranging from prototypes to final products. Various Additive Manufacturing techniques for polymer manufacture have been developed, including; Stereolithography (SLA) applied using photopolymer liquids, Selective Laser Sintering (SLS) involves the use of polymer powders, while Fused Deposition Modelling (FDM) uses polymer filaments. The latter is the most widely utilized system for polymer AM manufacture due to its relative low cost, low material wastage and ease of use. However, the biggest roadblock for 3D printing technology has been materials. Many of the most common materials limit 3D printing to prototyping and modeling, without being able to produce usable products, as they are weak and brittle. As the technology has advanced, so have its materials. Today 3D printing materials are able to be used in many demanding applications. Stiff composites, Nylons and even metal materials are entering affordable price ranges for all kind of customers. In addition, proper use and education around those materials is necessary, as stronger materials are available.

Until now, thermoplastics are the most frequently utilized materials for FDM due to their low cost and low melting temperatures. The most common include Polylactic acid (PLA), Acrylonitrile butadiene styrene (ABS) and Polyamide (PA or Nylon). One of the basic drawbacks of FDM technique is the formation of porous inner structures in the fabricated component which leads to poor mechanical properties. These limitations have hampered the wider adoption of 3D printed components for use as final products, leaving prototyping as the primary application. To overcome all the above problems, Markforged has brought strong 3D printing down to an affordable level by creating Continuous Fiber Fabrication (CFF) 3D printing machines that lay continuous composite fibers like fiberglass, Kevlar, and carbon fiber inside 3D printed plastics to improve their strength properties. The model “Markforged Mark Two” at the IHU’s 3d lab has been used for the aims of this thesis. The idea of studying the fiber reinforced honeycomb structures showed up after concerning the many uses and the important properties that they have. Honeycomb structures found widespread applications in various fields, including architecture, mechanical and chemical engineering, transportation, nanofabrication and biomedicine. A major challenge in this field is to understand the unique properties of honeycomb structures, which depended on
their structures, scales and the materials used [5]. The shape of honeycomb structures can vary but the most common feature in them is a lattice of hollow, thin-walled cells which are often hexagonal and columnar. During the design process, honeycomb structures allow the minimization of materials and bring savings on both weight and cost [6]. One of the novelties that this research will try to bring is to overcome the main idea in which the fabrication of honeycomb structures based on. Honeycomb structures are widely used in sandwich structures. These consist of two thin, stiff and strong face sheets separated by a lightweight honeycomb core. The core material keeps the face sheets in their relative positions in the sandwich with little increase in weight, to increase bending and buckling resistance [6]. The reverse in this typical design will be proposed by this research, as the creation of a stiff honeycomb core will give the opportunity to use lightweight and less strong face sheets. Furthermore, having in mind that many of the face sheets are now carbon fiber panels, the cost reduction will be significant, as with the use of fewer fibers inside the honeycomb structures the performances of these two alternatives may be similar.

Finally, a finite element analysis of these 3d printed fiber reinforced honeycomb structures will be studied for first worldwide time in this thesis. An innovative way to simulate 3-point bending tests for these complex structures in ANSYS Workbench will be proposed and the results will be presented in detail. Finite Element Analysis is a very strong tool for the engineers all over the world. However, due to the fact that 3d printing is a new technology, the existent FEA software are not able to simulate 3d printed materials properly as this production technique may lead to the formation of porous inner areas in the component.

All the above has been studied for the aims of this thesis. 3 point bending tests in the laboratory of the International Hellenic University has been made in order to study experimentally the desired proposals.
2. **Literature Review**

The research that has been made, will be divided in 3 different parts for the aims of this dissertation. As a result, literature review that concerns the honeycomb structures, the 3d printing technology with continuous fiber reinforcements and Finite Element Analysis of 3d printed materials will be presented separately.

2.1 **Honeycomb Structures**

2.1.1 **Introduction to Honeycomb Structures**

Honeycomb with hexagonal cells has the most common structure amongst cellular materials and can be easily fabricated by using different technologies and materials. However, to meet the specific needs for many applications, hexagonal honeycomb structures had evolved into many new ones in the industrial environment, leading to rapidly increasing diversity from traditional engineering to micro- and nano-fabrication. In Figure 2 the different types of honeycomb structures are presented [5].

The shape of honeycomb structures can vary widely but a lattice of hollow is the common feature in them. Honeycomb structures allow the minimization of materials and as a result savings on both weight and cost during the design process. Furthermore, honeycomb structures have relatively high compression and shear properties [7]. Generally, the internal angles of honeycombs are different and honeycomb structures do not have equal length cell walls as well. In addition, the thickness of the cell walls may not be the same. A typical honeycomb cell is shown below in figure 1 [8].

![FIGURE 1: Unit cell of an undeformed honeycomb](image-url)
Honeycomb structures are usually built of sheets or plates that form the edges of unit cells, with their diameters ranging from micrometers to millimeters. Most honeycombs are closed cell structures. In order to create a honeycomb structure, these unit cells are usually repeated in two dimensions. Another important characteristic of honeycomb structures is the relative density, which is the ratio between the density of the cellular structure and that of the solid. This factor is vital in order to describe the properties of honeycombs [5].

**FIGURE 2**: Periodic honeycombs with various cell shapes. (A-a) Regular hexagonal cell; (A-b) square cell; (A-c) triangular cell; (A-d) columnar cell; (B-a) OX cell; (B-b) rectangular cell; (B-c) reentrant hexagonal cell; (B-d) asymmetrical honeycomb; (C-a) square supercell constructed from mix of squares and triangles; (C-b) Kagome cell; (D-a) flex-core cell; (D-b) double-flex cell; (D-c) reinforced hexagonal cell; (E-a) truncated-square cell; (E-b) trichiral cell; (E-c) tetrachiral cell and (E-d) hexachiral cell. K and M denote two arbitrary vector axes in space [5].

### 2.1.2 Hierarchical Structures

The concept of structural hierarchy in materials developed simultaneously in several scientific fields such as polymer science, structural biology and fractural science for ceramic or organic aggregates. This is represented when the structures themselves contain structural elements. The hierarchical honeycomb structures are known to be large contributors in identifying the bulk mechanical properties. Very high damage tolerances
from impact loading have been recorded due to many natural hierarchical materials. The enhancement of the mechanical behavior of the structures, without compromising the elastic properties of the material, is the main objective of introducing hierarchy to honeycomb structures. Hierarchical structures are obtained by adding material, where it is most needed to reinforce areas of high stress [8].

The way that cells are organized or stacked together in a hierarchical structure plays a huge role in identifying the mechanical properties of it. Research has shown that enhanced mechanical behavior and superior elastic properties have been resulted with the use of hierarchical cell organization of sandwich panels, with cores made of composite lattice structures or foams. It has also been proven that better performing structures, that are lighter as well, have been resulted from increasing the levels of hierarchy in honeycomb structures. Specifically, by repeating the process of replacing the vertices with even smaller hexagons, even higher order hierarchical honeycombs can be achieved. Figure 3 shows the evolution of a first and second order hierarchical honeycomb [9].

![Evolution of a regular hexagonal honeycomb and its corresponding cell into first and second orders of hierarchy](image)

The structural organization of the first and second hierarchical order is defined by the geometrical parameters γ1 and γ2 that shown in figure 3. These parameters define the ratio of the smaller hexagonal edge length, to the original hexagon’s edge length. It easily noticed that for the first order hierarchical honeycomb, the edge length is b. For second order hierarchy, c is the edge length. It is important to have in mind that the original hexagon’s cell length is a. The range of values for the 1st order hierarchy is 0 ≤ b ≤ a/2, and thus 0 ≤ γ1
≤ 0.5. The regular honeycomb structure is attained by setting γ1 equal to zero. In a second order hierarchical honeycomb, there are two limitations: 0 ≤ c ≤ b and c ≤ a/2-b. In normalized form, the geometrical constraints are 0 ≤ γ 2 ≤ γ 1 if γ 1 ≤ 0.25 and 0 ≤ γ 2 ≤ (0.5 − γ 1) if 0.25 ≤ γ 1 ≤ 0.5.[8] From simple geometrical analysis, the equation to find the relative density (ρ*/ρs) of the first and second order hierarchical honeycomb are the following:

First order hierarchy

\[ \frac{\rho*}{\rho_s} = \left( \frac{t}{a} \right) \left[ \frac{(1 + \sin \theta)}{3 \sin \theta \cos \theta} \right] \left( 1 + 2 \gamma_1 \right) \]

Second order hierarchy

\[ \frac{\rho*}{\rho_s} = \left( \frac{t}{a} \right) \left[ \frac{(1 + \sin \theta)}{3 \sin \theta \cos \theta} \right] \left( 1 + 2 \gamma_1 + 6 \gamma_2 \right) \]

In regular hexagonal hierarchical cellular structures with θ = 30, the relative density relations are simplified below:

Regular 1st order hierarchy

\[ \frac{\rho*}{\rho_s} = \left( \frac{2}{\sqrt{3}} \right) \left( \frac{t}{a} \right) \left( 1 + 2 \gamma_1 \right) \]

Regular 2nd order hierarchy

\[ \frac{\rho*}{\rho_s} = \left( \frac{2}{\sqrt{3}} \right) \left( \frac{t}{a} \right) \left( 1 + 2 \gamma_1 + 6 \gamma_2 \right) \]

It is easily understood that structures with improved mechanical behavior can be built by introducing hierarchy to different types of cellular structures. Taylor and Smith explored the effects of hierarchy on the in-plane elastic properties of honeycombs. The introduction of a square or triangle geometry into the super and sub-structure cells of the honeycomb investigated in that research. In addition, the effect of negative Poisson’s ratio materials with hierarchical honeycombs have been studied. Taylor and Smith have shown, through finite element analysis, that it is possible to improve (by up to 175% compared to a similar density first order hierarchy) the in-plane modulus, by functionally grading such hierarchies. In addition, they have proved that with negative Poisson ratio materials, the density modulus can be increased importantly [10].

In another research, a novel class of sandwich composite structures with 3D-printed core materials and Carbon Fiber Reinforced Polymer (CFRP) face sheets have been manufactured. Truss, conventional honeycomb, and re-entrant honeycomb (Figure 4) are designed as the core material topologies. Under uniaxial compression, the truss and conventional honeycomb structures provide a non-auxetic behavior while the re-entrant
honeycomb structure provides an auxetic behavior as expected. The evaluated Poisson’s ratio for each structure consists well with the theoretical prediction. Three-point bending tests are conducted and the flexural stiffness, flexural strength, and energy absorption are evaluated on these sandwich composite structures. The experimental and numerical results show a very good agreement in terms of the deformation pattern, flexural stiffness, and flexural strength. Under bending, the re-entrant honeycomb sandwich structures show an interesting global failure mode because of the relatively homogeneous stress distribution. Furthermore, the energy absorption capacity is significantly increased due to the fact the re-entrant honeycomb sandwich structures exhibit sequential snap-through instabilities. In contrast, the truss and conventional honeycomb sandwich structures show catastrophic failure earlier due to the localized stress concentration [11].

Hedayati and Sadighi tried to obtain analytical relationships for the mechanical properties (yield stress, Poisson's ratio, elastic modulus) of octagonal honeycomb structures. Both the Euler-Bernoulli and Timoshenko beam theories were considered for acquiring the analytical relationships. Two Finite Element models were also built, one consisting of only 1/4 of a unit cell and the other consisting of a large set of unit cells. The simulation results that came out from these two models were very close and the difference between them was less than 4% for elastic modulus. For relative densities smaller than 25%, the comparison of the

FIGURE 4: Design of unit cell of the truss, conventional honeycomb, and re-entrant honeycomb structure. Here, L is the length of the inclined cell walls of truss structures; t is the thickness of the cell walls; and θ is the angle between the inclined cell walls. The shapes of regular and re-entrant honeycomb structures are described as the length of the vertical cell walls, H; the length of the inclined cell walls, L; the thickness of the cell walls, t, and the angle between the vertical and inclined cell walls, θ [11]
Euler-Bernoulli and Timoshenko analytical results in one hand and the numerical results in the other hand, showed that the analytical Timoshenko results and the FE models were close to each other in terms of all the properties of yield stress, Poisson's ratio and elastic modulus. Furthermore, the results of the two finite element models and the Timoshenko analytical solution showed good correlation with the experimental results as well. Finally, the elastic properties of the octagonal honeycomb structure were compared to those of having mixed, square, triangular and hexagonal unit cell types. The octagonal honeycomb showed elastic modulus and yield stress values close to those of hexagonal honeycomb and lower than the other mentioned structures [12].

The effects of the core material thickness and density on the material properties of composite sandwich honeycomb structures were studied in a research by Jianfeng Wang and Chengyang Shi. The material bending strength and stiffness were analyzed by three-point bending tests. The conclusions are presented below:

- The material strength could be improved by increasing the density or thickness, while optimum middle density or thickness values maximized the bending stiffness. In addition, the stiffness changed to a higher degree with a change in density or thickness than the strength.

- Improvements in the interfacial properties between the panel board and core material may increase the panel peeling force. Such improvements could be an increase in the connection area or cohesive material quality, or addition of another fiber. The ultimate tension depended on the sandwich structure strength after stripping of the panel board[13].

### 2.2 3d Printing technology with Continuous Fiber Reinforcements

Continuous carbon fiber reinforced composite structures are widely used in astronautics and aeronautics because of their enhanced mechanical behavior. However, the high manufacturing cost of these materials may be deterrent for the use of these technologies in the automotive and consumer product industries. New low-cost production methods may enhance the possibility of using these materials in more and more applications. 3d printing technology has made great improvements and the manufacturing of metallic and ceramic materials, flexible films and biological materials is now possible. Furthermore, fiber-reinforced composites manufactured using 3D printing techniques have been started [14].
Karsli and Aytac investigated the effects of fiber length and content on the morphological, thermal and mechanical properties of Carbon Fiber reinforced Polyamide Type6 composites. Fiber length at the studied range had no effect on the hardness, modulus and tensile strength values, but by increasing it, the strain at break points of composites increased as well [15].

A new 3D printer that reinforces 3D printed parts with continuous fibers (Carbon Fiber, Glass Fiber or Kevlar Fiber filaments) has become commercially available. It is the printer that will also be used for the aims of this dissertation thesis. This new 3D printer, MarkOne by MarkForged, builds functional 3D printed parts which are stronger than conventional FDM printed parts. The MarkOne 3D printer reinforces FDM printed parts by inserting concentric fibers that follow the geometry of the component. Another reinforcement option is an Isotropic Fiber fill pattern that creates a unidirectional ‘sheet’ of fiber on each layer, by placing all fibers parallel to each other in a certain angular orientation selected by the user. Generally, the objective of these new FDM printing methods is to increase the strength of 3D printed parts so that they can be used for functional products rather than prototype ones [16].

In a research from Garrett and Benjamin, the tensile properties of fiber reinforced 3D printed parts tested. Tensile tests were carried out on four combinations of samples that were built using the MarkOne 3D printer. In addition, an increase in the volume of fiber reinforcement brings an increase in ultimate strength and stiffness of the test samples, as testing outputs have shown [16].

Zhanghao Hou and Xiaoyong Tian, in another study, proposed cross lap and panel-core lap designs to fabricate the Continuous Fiber Reinforced Composite Lightweight Structures (CFRCLs). Most important specifications for CFRCLs were density and fiber content. Factors, that have been chosen in order to be investigated, were the influence of the process parameters in the 3D printing process on the fiber content and the performance of the printed CFRCLs. The optimization of the structure parameters and process resulted to a maximum compression strength of 17.17 MPa for the 3D printed Continuous Fiber Reinforced Composite Lightweight Structures, with a fiber content of 11.5% vol. This innovative process had great potential in fabricating CFRCLs with complex shapes, high mechanical properties, and multifunctional benefits [17].
In another research the idea of designing the nozzle in a way to uniformly mix the carbon fiber and PLA resin has been studied. Figure 5 presents that nozzle. Due to the weak bonding behavior between carbon fiber and PLA resin, the preprocessing of carbon fibers was essential in order to achieve better interfacial strength. The experiments indicated that the modified carbon fiber reinforced composites had 164% and 13.8% higher flexural strength and tensile strengths (respectively), than the original carbon fiber reinforced samples. In addition, the modified carbon fiber reinforced samples presented higher storage modulus than the PLA and original fiber reinforced samples, for about 166% and 351%, respectively. Furthermore, the results from Scanning Electron Microscope (SEM) indicated better fiber matrix bonding behavior of the carbon fiber preprocessed printing technology. This rapid prototyping technology, for the continuous carbon fiber composite, seems to Introduce important advantages to manufacture complex and high performance’s composite parts[18].

![Figure 5: Extrusion device for printing continuous carbon fiber reinforced PLA.](image)

The carbon fiber and Polyamide Type 12(PA12) composite filaments (printable for FDM) were fabricated and the carbon fibers were dispersed homogenously in polyamide’s matrix, in a research that supported by the National Natural Science Foundation of China. It was found that the crystallization maximum temperature and the degradation temperature increased 3.46 °C and 7.50 °C respectively, after importing 10 wt% carbon fiber. Comparison between pure PA12 parts, fabricated by FDM, and those with 10 wt% of carbon fibers to the PA12 matrix, brought out an observable increase in tensile strength, modulus values and flexural strength, without sacrificing the impact property. The excellent properties of the parts fabricated by FDM with fiber reinforcements can provide the expansion of this technology in even more industrial applications [19].
Petrone and Sao compared two different specimens in order to study how the different reinforcement affects the energy absorption. The first one existed of Polyethylene honeycombs reinforced with continuous-unidirectional fibers and the second one with short-random fibers. The presence of face sheets and the influence of core height were investigated for each specimen. The cores made from continuous fiber reinforced composites, presented a large elastic region and increased peak loads, showing better behavior to impact loading compared to that of short fiber reinforced. The presence of face sheets enhanced the energy absorption in the panels, due to the fact that energy was dissipated during bending and stretching the face sheets. However, this phenomenon seemed to reduce at larger core heights. That finding has also been supported by statistical analysis based on the Taguchi method that presents an important antagonistic interaction between the existence of face sheets and the core height. The interactions between material type and presence of face sheets or core height were not important, suggesting that they may be negligible. Finally, for high strain rate applications and for large deflections, thermoplastic honeycomb cores reinforced with continuous fibers present higher peak force transmission [20].

Another work studied experimentally, and with the aid of Scanning Electron Microscopy (SEM), micrography of materials produced by 3D printing based on Fused Filament Fabrication (FFF). Two printing materials were investigated. PLA and PLA reinforced with short Carbon Fibers (length about 60 mm in a weight fraction of 15%). The specimens were printed with material deposition specially oriented (at 0+, 90+ or ±45+), with standard microstructure and same build parameters. The outcomes for the stiffness concluded that the short carbon fibers increased at about 220% the tensile modulus E1 (respective to the printing direction) of the reinforced PLA (in comparison to the tensile modulus of the simple PLA). The tensile modulus E2 (transverse to the printing direction) and the shear modulus G12 (respective to the plane of printing) were also increased due to the fibers at 125% and 116% respectively [21].

A study from Xinhua Yao and Congcong Luan proposed a method to insert continuous carbon fibers into 3D printed parts. Based on the uniaxial tension and 3-point bending tests, the mechanical strength of a 3d printed structure significantly improved by over 70% in tensile strength and 18.7% in bending strength with the use of 3d printed continuous carbon fibers in them. In addition, reduction in weight and print time for 26.01% and 11.41% respectively were achieved, without decreasing the tensile strength [22].
The use of Additive manufacturing in Injection Molding inserts, proved to be an environmentally friendly, fast and cheap method for flexible rapid prototyping and pilot production, as Thomas Hofstatter and David B Pedersen presented. Fiber-Reinforced Polymers (FRP) in Additive Manufacturing technology helped to improve lifetime significantly and reduce crack propagation velocity to a great grade. Short carbon fibers presented an important effect on Young’s modulus, but a decreasing one on tensile strength and break strength, allowing to efficiently use the material in low-strength systems where low deformation is needed during specific loads. Despite the average increase of Young’s modulus, it was found that the fiber matrix interface requires enhancement in order to eliminate failures in the part \[23\].

2.3 Finite Element Analysis (FEA) of 3d printed materials
A paper from Yi-Tang Kao and Ying Zhang, described the bending behaviors of bi-material structure (BMS) by using both experimental and FEA methods. Bi-material Structure contains a 3D printed brittle plaster scaffold structure filled with silicone elastomer. The plaster phase gives the strength and the stiffness during bending, as the elastomer ameliorates the toughness. Both experimental and FEA results noticed that the plaster phase did not break suddenly because of the progressive development of microcracks (due to the contraction force provided by the silicone filler). The bending behaviors of BMS were successfully modeled using a FEA method. The FEA model was built using ABAQUS (Version 6.14-2). The used FEA method enabled the analysis with uniform and coarse mesh in the part to simulate the effect of microcracks inside the material. The outcomes compared with other common FEA methods in crack modeling. Although the FEA successfully simulates the behaviors of BMS during bending, it is not yet a predictive model that can be used for performance prediction or design optimization, as not only some numerical limitations, but material variations from 3D printing, can cause errors as well. Some of them are the following: i) the brittle cracking model does not include compression damage and more complex loading conditions can lead to inaccurate results from FEA and ii) no failure definition exists for the hyperelastic model and that can lead to a tougher and stronger structure than an actual one \[24\].

An important effort in the direction to create a software, that will be able to simulate 3d printed materials, has been made from 3D Matter, which is a unique firm that has been
trying to fill in the knowledge gaps associated with 3D printing. During this research, many 3D printing filaments analyzed in order to determine which materials overcame the rest. 3D Matter has ventured into the world of software design by releasing OptiMatter, that is a software that allows users to compare various printing parameters and materials, by analyzing the mechanical properties of the 3D-printed results. A static linear FEA on a model of a stool, that would be manufactured in polylactic acid (PLA), has been built. The aim of that test was to compare injection molded PLA to 3D-printed one. Although 3D Matter has not yet tested the results that experimentally, it has performed empirical analysis of smaller 3D printed structures that confirm a close enough correlation between FEA predictions and the actual displacement of a part under certain loads. Figure 6 represents the results of a FEA that has been made in 3d Matter [25].

Robert Sayre in his research found out that 3d printed materials tend to exhibit properties of the laminate as a whole, rather than exhibiting failure in a single lamina when performing uniaxial pull or compression test, as long as they are modeled in FEA software using a lamina configuration. ABAQUS software has been used for that FEA. All the test samples, tensile, compression, and bending had higher stresses than their respective isotropic counterparts for a specific load. Furthermore, composite parts yielded at a lower load than their respective isotropic samples. FEA users should think about the failure criterion for 3D printed laminates, as important difference from that for an isotropic elastic-plastic material will be present. That happens due to the fact that perfect bonding between 3D printed layers cannot be achieved, so the modifications to the material properties seem to be necessary in order to mimic the behavior of 3D printed structures [26].
A study from López and Chiné tried to evaluate the elastic properties of 3D printed carbon fiber pylon under compression stress and compare them with experimental data, in order to estimate its properties and allow the use of Finite Element Analysis tools. The 3D printed samples were fabricated by a continuous fiber fabrication (CFF) process. The principal elastic modulus $E_z$ and $E_y$ were obtained by making experiments with ASTM D695 standard. The software COMSOL Multiphysics 5.2a, using the Solid Mechanics module, has been used in order to accomplish the FEA. The CAD model has been created in SolidWorks and then imported to COMSOL. Two different CAD models are designed: the first one was a solid orthotropic material, while the second one was a laminated specimen. Appropriate boundary conditions were set in order to simulate the experimental condition. The results from the FEA of the 3D printed reinforced material gave a relative error of 16.4%. However, several factors affected the mechanical behavior of the reinforced polymer. Some of them were the width, the distance between extruded filaments, the layer thickness and the filament pattern. Therefore, taking into consideration all the above complexity of that material, the error that has been came out was acceptable. Further simulations for a prototype pylon have been also developed, showing that the prototype exceed the yield point at 42.03 MPa. As a result, redesigning or a topology optimization of the part should be done. To sum up, the simulation of fiber reinforced materials is a challenging task. The isotropic model presented a lower error, however the orthotropic model was a more suitable method for studying the mechanical performance of reinforced materials [27].

Another important difficulty in the process of simulating a 3d printed materials in a FEA software is the determination of the factors that may affect the tensile strength of the printed structures. Parameters as the orientation angle, type of material and infill rate were selected by Heechang Kim and Eunju Park in order to estimate which parameters had effects on the mechanical properties of the specimens. The optical microscope was used to test any effects on the extruded filament. Several outcomes were drawn from the analysis. The best mechanical properties found from materials in the x-direction, with fill rates of 100% (using PLA), and it was also possible to print products with improved mechanical properties using these factors. The 3D printer used in that research was capable of printing products using multiple materials. Considering the fact that PLA and ABS are the most common filaments, experiments in order to verify the difference in tensile strength, regarding the proportion of these materials, have been contacted. However, the results from the analysis of variance (ANOVA) showed the inadequate extruding of FDM as 3D
printing method. The problem was that overlaps and voids may occur in the boundary between two 3d printed materials. In order to solve the mentioned problems, the researchers changed the structural design by adding horizontal layers and vertical lines. However, simply adding additional vertical lines to the product may still be ineffective, since overlapping and voids may exist between the materials. Nevertheless, an additional horizontal layer improved the mechanical behavior of the part [28].
3. **Methodology**

The methodology that has been followed in order to make the research on 3d printed fiber reinforced honeycomb structures will be presented in this chapter. The design principals that have been used in order to create the honeycomb structure, that has been finally tested, will be explained as well. Markforged Mark Two was the 3d printer that used for the aims of this dissertation thesis. The 3-point bending tests have been made at IHU’s laboratory. The testing machine that has been used is Testometric’s model M500-50AT. Finally, ANSYS Workbench has been used for the Finite Element Analysis.

3.1 **Brief Presentation of Markforged Mark Two**

As it is has already mentioned, Markforged has made it possible to create functional and strong 3d printed structures with the aid of fiber reinforcement. Fiberglass, Kevlar, and carbon fiber are commercially available until now. Figure 7 presents the model Mark Two that is available at IHU’s 3d lab.

![Markforged Mark Two 3d Printer](image)

**FIGURE 7: Markforged Mark Two 3d Printer**

The printer has two print nozzles. One that lays down a plastic filament, just like other compatible FDM printers. This plastic forms the outer shell of the part as well as the internal matrix of the structure. The second print nozzle lays down a continuous strand of a composite fiber on every layer with Markforged Continuous Fiber Fabrication process. The
strength and toughness of Markforged Continuous Fibers, in comparison to metals, is presented in Figure 8 [3]. The Full technical specification can be found in the table 1.

![FIGURE 8: The strength and toughness of Markforged continuous fibers in comparison to metals](image)

<table>
<thead>
<tr>
<th>Table 1: Mark Two specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Printing Technology</strong></td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
</tr>
<tr>
<td><strong>Weight</strong></td>
</tr>
<tr>
<td><strong>Build Volume (x,y,z)</strong></td>
</tr>
<tr>
<td><strong>Material Compatibility</strong></td>
</tr>
<tr>
<td><strong>Highest Layer Resolution</strong></td>
</tr>
<tr>
<td><strong>Extruders</strong></td>
</tr>
<tr>
<td><strong>Filaments Size</strong></td>
</tr>
</tbody>
</table>

### 3.1.1 Fiber Fill

Two fill strategies are available in Markforged printers. Isotropic Fiber or Concentric Fiber. The first one is the Concentric Fill, that simply traces a specific number of shells within the walls of the designed part. This fiber fill choice prevents bending around the Z axis and essentially reinforces the walls of the part, preventing the walls from deforming. The second reinforcement option is the Isotropic Fiber fill pattern. This pattern effectively creates a unidirectional ‘sheet’ of fiber on each applied layer by routing all fibers parallel to
each other in a single angular orientation, with 180 degree turns when the path reaches the edge of the part. The Isotropic Fiber fill pattern reinforces bending in the XY plane because any bending forces applied in that plane will generate a tensile load on at least some of the fibers, which are strongest in tension. Figures 9 and 10 show how these two techniques can be applied in the final structures [4].

![FIGURE 9: Concentric Fiber Reinforcement](image)

![FIGURE 10: Isotropic Fill Reinforcement](image)

One important thing that should be noticed is that isotropic fiber, by default, puts 2 concentric rings of fiber around the outside of the part. This choice ensures a smoothly reinforced external surface as the outermost fibers are parallel and continuous to the edge of the part.

One other important detail, that has been taken into account during the design of the honeycomb structure that has been used for analysis, is the minimum thickness of the printed fiber. This thickness is 0,1 mm for fiberglass and 0,125 mm for the carbon fiber [4].

### 3.1.2 Fiber Routing Techniques

The Basic Fiber Routing techniques are the following:

- **Single Sandwich Panel**: A sandwich panel is a common composite layup technique in order to obtain torsion resistance around the surface that the composite sheet creates. A sandwich panel is the composite equivalent of an I-beam, with a stiff, strong material making up the top and bottom of a part. Markforged printers have
the ability to create a lightweight honeycomb structure between the layers in the top and bottom. Most of the researchers until now use this technique and concentric reinforcement in order to make their testS. Figure 11 represents some samples [3].

![Image](image_url)

**FIGURE 11: Concentric ring reinforcement of test specimens fabricated with Single Sandwich Panel Technique**

- **Fiber Perimeter:** Fiber Perimeter will make the created part stronger around the Z axis, while sandwich paneling increases strength around the XY plane. Concentric Fill reinforces the walls of a structure, so creating a fiber perimeter within the final part will make it more resistant to bending.

- **Shelling:** This option is preferable when it is not easily understood the loads that a part will face. With a sandwich panel on the top and bottom of the part and shells of fiber in between, the flexural strength of the created structure will be improved on every axis [4].

### 3.2 Brief Presentation of Testometric M500-50AT

The experimental part of the research has been done in the IHU’s lab. The specimens, that have been constructed, tested with 3 point bending flexural tests in order to estimate the displacement and the yield point of 3d printed fiber reinforced materials. The machine that has been use was Testometric M500-50AT. Figure 12 presents the machine.
Some of the key features that these machines have are the following:

- Self diagnostics software with on screen notification icons. Remote control of machines is also available.
- Digital display of force, displacement, cell capacity, speed, position, mode, units etc
- Real time graphic display with multiple axis selection, autoscaling
- High resolution auto ranging load cells with accuracies better than +/-0.5% down to 1/1000th of the load cell capacity
- 50kN machine capacity
- Speed Range from 0.001 mm/min to 1000mm/min (steps of 0.001mm/min) [29]

The complete technical specifications can be found in the table below.
### M500-50 AT specifications [29]

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine Capacity</td>
<td>50kN</td>
</tr>
<tr>
<td>Accuracy</td>
<td>+/- 0.5% of reading down to 1/1000th of load cell capacity</td>
</tr>
<tr>
<td>Vertical space</td>
<td>1180mm</td>
</tr>
<tr>
<td>Crosshead travel/resolution</td>
<td>980mm by 0.001mm</td>
</tr>
<tr>
<td>Throat</td>
<td>420mm</td>
</tr>
<tr>
<td>Frame stiffness</td>
<td>200kN/mm</td>
</tr>
<tr>
<td>Speed range</td>
<td>0.001mm to 1000mm</td>
</tr>
<tr>
<td>Speed accuracy</td>
<td>+/- 0.1% under stable conditions</td>
</tr>
<tr>
<td>Crosshead guidance</td>
<td>Linear slides integral within column</td>
</tr>
<tr>
<td>Max force at full speed</td>
<td>50kN</td>
</tr>
<tr>
<td>Max speed at full load</td>
<td>600mm/min</td>
</tr>
<tr>
<td>Data sampling rate</td>
<td>Maximum 12kHz with up to 200Hz data frames</td>
</tr>
<tr>
<td>Overall dimensions W x D x H</td>
<td>762mm x 505mm x 1585mm</td>
</tr>
<tr>
<td>Weight</td>
<td>245kg</td>
</tr>
<tr>
<td>Electrical Supply</td>
<td>Universal input</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-10°C to +40°C</td>
</tr>
<tr>
<td>Operating humidity</td>
<td>+10 to +90% non-condensing</td>
</tr>
<tr>
<td>Number of Columns</td>
<td>2</td>
</tr>
<tr>
<td>Power</td>
<td>1kW</td>
</tr>
</tbody>
</table>

### 3.3 Specimen Choice

One of the most important problems that this research has faced, was the proper choice of the specimen that will be tested in 3-point bending. Until now, most of the researchers have tested specimens according to commercial ASTM tests for plastics. These are the following:

- ASTM D790: Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials for commercial materials [28]

By using the above standards, the honeycomb structures could be built by the 3d printer and the choice of adding continuous Kevlar, Carbon or Glass fibers could have been done. However, these specimens would have been built as sandwich panels with concentric reinforcement in the top and bottom of the structure as figure 11 shows above. The main
idea in these structures is to have a lightweight honeycomb core with reinforced face sheets. Too much research has been made in this field, so the decision to study something new has been taken. In this research, the possibility to create a strong fiber reinforced honeycomb core will be studied. The main aim of this study is to make the fundamental steps towards the opportunities that 3d printing technology has born.

Due to all the above reasons, the shape and the size of the created specimen will be affected in a great grade from the Markforged capabilities. Following the guidelines of figure1, the decision to have an angle $\theta=30^\circ$ has been taken. Furthermore, according to Wang and Liu, $h$ and $l$ considered equals in length ($l=h=20\text{mm}$) [30]. In addition, it should be taken into account that the minimum thickness of the 3d printed continuous fiber is 0,1 mm for fiberglass and 0,125 mm for carbon fiber. A very important study of the printing results that Markforged can give according to the width of a designed feature has been made. The feature that is very important for the aims of the present study is the thickness of the honeycomb’s walls. The decision to choose concentric reinforcement has been made as well. Furthermore, at least two concentric fiberglass rings around each honeycomb should have been built. This choice helped to avoid problems that only one concentric fiberglass ring may have caused. Taking into account all the above details and by studying how the printer operates, the decision to create honeycombs with wall thickness at 6,5mm ($t$ from figure 1) has been made. Figure 13 presents the designed honeycomb structure that will be tested experimentally and with FEA.

![FIGURE 13: Technical Drawing of the designed Honeycomb structure as specimen](image)
It is very important to emphasize at this point, that as soon as these technologies advance, many new capabilities will be born. It is very possible to have the option to create thinner honeycomb reinforced walls in the future and much more smaller specimens as well. This is a research that has been made with the first worldwide 3d printer that is able to lay continuous fibers. Figure 14 shows the above honeycomb structure, represented in markforged online software (eiger). The concentric fiberglass walls are easily observed. In addition, it should be noticed that the height of the studied honeycomb structure was 5mm.

One also very important detail is the fact that the studied honeycomb structure is only a part of a bigger one. However, important restrictions both in the time needed in order to print a very big structure and in the computing power that will be necessary in order to make the FEA, drove us in the study of a part of the structure that presented above. Figure 15 shows the possible extended honeycomb structure.
3.4 Experimental 3-point bending tests and Finite Element Analysis

The most important part of this dissertation thesis was to design and implement the strategy that will be followed in order to reach to the desired results. As it has already been understandable from the literature review, despite the fact that research has been done in the field of honeycomb structures, the simulation of 3d printed fiber reinforced structures is something that few researchers have tried. So, the challenge was great.

3.4.1 Validation of the FEA model

First of all, experimental 3-point bending tests have been made in the lab of IHU. The aim of these tests was to ensure that the designed honeycomb structure will be able to give information about the behavior of 3d printed materials during bending. As soon as these tests seemed to give important details such as the yield point of the material and the deflection of the structure, the try to build the same model in solidworks and then inserted it to ANSYS Workbench has been made.

The main aim of this process was to ensure that the designed model will be available to give results near the experimental ones. It was expected that differences will be found, as 3d printed materials cannot be easily simulated to ANSYS, but once there would be found some kind of correlation between the experimental and FEA results, the success will be great.

The first material that has been used in the 3d printed honeycomb structure was PLA. That was not a random choice. PLA is a very popular material in 3d printing technology, so much more information will be found about it. In the optimistic scenario that the created FEA model was valid, the decision to print a fiberglass reinforced honeycomb structures would have been made.

That would be the most challenging part of this study. There is no other similar worldwide try until now, so the model that will be created in solidworks and then tested in ANSYS will be the first proposed model in order to test fiber reinforced structures in ANSYS Workbench. Most of the existing FEA models, that study carbon fiber or fiberglass structures, are designed with top and bottom fiber sheets that can be modeled in ANSYS Composite Prepost. However, the use of continuous 3d printed fibers inside a structure is something that has not been studied yet.
3.4.2 FEA model for future use

Finally, after all these tests and simulations the try to propose a methodology in order to study 3d printed fiber reinforced honeycomb structures will be proposed. Hopefully, the proposed solution will enable the future users to spend less time in 3d printing tests and experiments, by saving important resources and time. Nowadays, too much time (according to the printed structure) is needed and some of these materials are really expensive, so it is not affordable for many users and labs to make many experimental tests. With the use of the presented methodology many problems may be faced efficiently.

3.5 New honeycomb Structure Design and Philosophy

Finally, as it is has already mentioned, the designed honeycomb structure has some innovative design aspects that may be used in many applications, instead of the typical ones that many aerospace and automotive industries use. Some thoughts and proposals, about how these fiber reinforced honeycomb structures may be used in industrial application, should be presented in the end of the dissertation thesis.
4. Experimental and FEA Results of 3-point Bending Tests

This chapter presents the experiments that have been made in the lab and the Finite Element Analysis Model that proposed in order to simulate the 3-point bending tests in Ansys Workbench. In addition, the validation method, that has been used, was one of the most important steps of this dissertation thesis, because it was the only way to test the fundamental parts of the FEA model. PLA has been used as 3d printed material for that stage, as PLA is highly used all over the world and much information is available about it.

4.1 1st 3-point bending test of the Honeycomb structure made by PLA

The first honeycomb structure printed and 3-point bending test made in the lab of IHU. Figure 16 represents the honeycomb structure placed on Testometric M500-50AT.

![Honeycomb Structure at 3-point bending Test](image)

**FIGURE 16: PLA Honeycomb Structure at 3-point bending Test**

The two most important values, that has been measured, were the Ultimate Strength and the Yield Strength. Ultimate strength is the capacity of a material or structure to withstand
and Yield strength is defined as the yield stress, which is actually the stress level at which a material can withstand the stress before it is deformed permanently.

The maximum force (ultimate) that recorder during that test was 392,2 Nt at a deflection of 9,497 mm. The yield point found at 285,5 Nt with a deflection of 5,1mm. It is crucial to emphasize that after that point, the plastic deformation of the material started until the fracture at 45,145 mm of displacement. All these details are presented graphically in Figure 17. All the above information found after taking into consideration that the initial slope is where stress is directly proportional to strain. So careful calculations, on the results taken from the experiments, made in order to find the yield point at figure 17. It is very important to emphasize at this point, that the Force – Deflection diagrams have been selected in order to study both the experimental and FEA results, as these diagrams can also be built after the simulation at ANSYS. By this way, the comparison between the experimental and FEA results has been feasible. The conversion of these graphs to stress-strain ones would not have been able to help in this study, as force and deflection are two parameters that can be easily taken out from ANSYS.

![Force-Deflection Diagram of 3-point Bending Test (PLA Honeycomb Structure)](image)

**FIGURE 17: Force-Deflection Diagram of 3-point Bending Test (PLA Honeycomb Structure)**

**4.2 Validation of the FEA Model in ANSYS Workbench**

First of all, the 3-point bending experiment designed in Solidworks. Figure 18 shows that model. After that, the CAD model inserted in the CAE software (ANSYS Workbench). The Static Structural Analysis System has been chosen then for the FEA.
4.2.1 Preparing the FEA Model

After having chosen Static Structural as the Analysis System, setting the simulation parameters correctly was a crucial step in order to get correct solutions from the simulation.

Material Properties

Despite the fact that much information is available for PLA, as it is the most common 3d printed material, properties such as the density of the material that has been used for the aims of that research studied in detail. It is important to emphasize that due to the imperfections that 3d printed technology may cause to the 3d printed structure (gaps in the main body of the build item), the theoretical density that many manufacturers give is not right. This phenomenon may cause important problems for the current research, as high precision details should be available in order to build a reliable FEA model.

The method that has been used in order to find the accurate density of the material that has been used at IHU’s lab was the following:

- Print the structure
- Find the accurate volume of it from the Solidworks Model
- Weighting the 3d printed structure (get the mass)
- Divide the mass with volume and get the density

Following the above steps, the density of the 3d printed PLA found 1110 kg/m$^3$
In table 3, the most important materials properties that has been used are presented [31].

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's Modulus</td>
<td>MPa</td>
<td>3500</td>
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<tr>
<td>Shear Modulus</td>
<td>MPa</td>
<td>1287</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td></td>
<td>0.36</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>MPa</td>
<td>70</td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td>MPa</td>
<td>73</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>MPa</td>
<td>80</td>
</tr>
<tr>
<td>Flexural Strength (Ultimate)</td>
<td>MPa</td>
<td>4000</td>
</tr>
</tbody>
</table>

Finally, one of the most important details that should be noticed at this point, was the use of Multilinear Isotropic Hardening in order to obtain more precisely the plastic deformation that the honeycomb structure faced. The important property of Multilinear Isotropic Hardening is the fact that the yield surface expands uniformly in all directions with plastic flow [32]. Figure 19 shows graphically what Multilinear Isotropic Hardening curve looks alike.

![Multilinear Isotropic Hardening Curve](image)

**FIGURE 19: Multilinear Isotropic Hardening Curve**

**Contact Regions**

The proper contact behavior settings between the surfaces of the FEA model was one of the most important steps of the simulation process. The contact between the honeycomb structure and the supporting pins is frictional. As a result, this contact relationship should
be inserted in the designed model. However, frictional contact between surfaces requires very careful settings in ANSYS software, in order to get the desired solutions. Many contact formulations are available in ANSYS workbench. Some of them are the following:

- Pure Penalty
- Augmented Lagrange
- Normal Lagrange
- Multi-Point Constraint (MPC)

For frictional contact behavior the Normal Lagrange Method is usually proposed. The Normal Lagrange method can be used if the user does not want to bother with Normal Stiffness value and wants zero penetration. However, it is important to emphasized that the Direct Solver must be used, which may limit the size of the solved models [33].

### 4.2.2 FEA Results

Taking all the above information into account the FEA model has been built in ANSYS. As it has already been mentioned, the selected material for the current validation method is PLA and the material properties are presented in Table 3 (page 35). The FEA model is shown in Figure 20. There are 53693 nodes and 10474 elements in the created mesh.

![FIGURE 20: FEA Model(PLA)](image)

The simulation of the 3-point bending test ran in ANSYS and the results are presented below. The maximum Force of 392.2 Nt recorded during the experiment. Figures 21 and 22
represent the deflection of the honeycomb structure for 392,2 Nt Force (ultimate strength) and 285,5 Nt Force (Yield Strength) respectively.

As it is clear from the above Figure, the deflection that occurred after the Finite Element Analysis is really close to the experimental one, that has been presented in chapter 4.1. Experimental results gave a deflection of 9,497 mm at 392,2 Nt (Ultimate Force) and FEA model presented a deflection of 9,837 mm (+3,58%) for the same force. Figure 23, that follows, shows the force-deflection curve for both the experiment and FEA until the ultimate force. The yield points included in this diagram.
From the comparative force-deflection curve that presented above, there is a first strong evidence that the Finite Element Analysis Model is able to give reliable results, as the deflections, that have been recorded both in the experiment and in the simulation, are very close one another. The next figures, that show the plastic deformation in the FEA model and the fractured areas in the printed structure, will add one more important detail in the validation process that has been followed.
Figures 24 and 25 came to prove that the designed FEA model is able to simulate with high precision 3d printed PLA structures. The plastic deformation, that has almost started at 285,5 Nt, is easily noticed from Figure 24 and this is another important detail that proves that not only a macroscopic behavior (Deflection) of the FEA model is very close to the reality, but a microscopic behavior (Plastic Deformation) as well.

4.3 Finite Element and Experimental Analysis for Nylon and Fiberglass reinforced Honeycomb Structures

After having completed successfully the validation of the FEA model in ANSYS Workbench, the main study of the presented thesis made. The experimental and FEA results for two specimens, printed by Markforged Mark Two will be presented and compared. The material that selected for the first specimen was Nylon and for the second one Nylon reinforced with continuous 3d printed fiberglass.
4.3.1 Nylon Honeycomb Structure

The first material that has been tested in 3-point bending test was Nylon that Markforged printer uses. The dimensions of the specimen were the same as presented in figure 12. The material properties for nylon are shown in table 4. Markeforged material datasheet provided all this useful information [34].

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>1140</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>MPa</td>
<td>940</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>-</td>
<td>0.404</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>MPa</td>
<td>31</td>
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<td>Ultimate Tensile Strength</td>
<td>MPa</td>
<td>54</td>
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<td>Flexural Strength</td>
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<td>32</td>
</tr>
<tr>
<td>Flexural Modulus</td>
<td>MPa</td>
<td>840</td>
</tr>
</tbody>
</table>

Experimental Results

The results from the experiment are presented below. Figure 26 presents the Force-Deflection curve resulted from the contacted test.

By careful calculations, as those for the PLA experiment, it is easily noticed that yielding occurs at 110,2 Nt with Deflection at 7,08 mm. After that point, the specimen faces important plastic deformation until a deflection of 43,39mm. Then the test ended because the specimen slipped on the two supporting pins and results would not be reliable after that. The small increase in the force at the end of the graph is due to the phenomenon that has already been described. Figure 27 shows the nylon specimen during the bending test. Finally, the ultimate force measured at 181,4 Nt with a deflection of 17,906mm.
After having tested the Nylon specimen experimentally, a Finite Element Analysis has been modeled. The methodology that has been followed for the PLA specimen, applied for the Nylon specimen as well. Material properties from table 4 were used. The deflection and the shape of the specimen, that occurred for Force of 181,4 Nt (Ultimate Force) and 110,2 Nt (Yield Point), are presented in figures 28 and 29 respectively.

FIGURE 28: Deflection (m) of Nylon honeycomb structure at 181,4 Nt (Ultimate Force)
The FEA model seemed to give extremely accurate results, compared to the experimental ones. Deflection varied only for 1.3% at the maximum load after yielding. Figure 30 represents the FEA and the experimental Force-Deflection graphs in one diagram.

Furthermore, the plastic strain, that has almost started for 110.2 Nt, is distinct in Figure 31. This is another strong evidence that the constructed FEA model in ANSYS Workbench can give fast, useful and reliable results.
4.3.2 Nylon Honeycomb Structure-Reinforced with continuous fiberglass

Markforged is able to place the continuous fiber reinforcement wherever the user may choose. For this first test the fiberglass reinforcement placed in two different positions inside the honeycomb structure. Figures 32, 33 and 34 show how the reinforced specimen was built. The screenshots were taken from eiger online platform. The 5mm height divided in 5 parts and nylon placed in positions 1-3-5. In 2-4 internal parts, nylon with 2 walls of concentric fiberglass reinforcement have been built.
Experimental Results

The presented specimen tested in 3-point bending as well. The aims of these tests were to check how the bending behavior of the specimen ameliorated due to fiberglass reinforcement.
reinforcement and whether it was possible to simulate such a complex structure in ANSYS Workbench. The Force-Deflection curve from that bending test is presented below.

![Force-Deflection Curve](image)

**FIGURE 35:** Force-Deflection Diagram of 3-point Bending Test (Nylon Honeycomb Structure reinforced with fiberglass in parts 2 and 4)

It is clear from figure 35, that the new ultimate force recorded at 442,1 Nt, presenting an increase up to 143,7% in comparison to the Nylon specimen. In addition, the deflection at that point was 14,01 mm, presenting a decrease of 21,75 % compared to the Nylon specimen. Furthermore, after calculations on the curve’s slope the yield point found for 247,3 Nt Force (+124,4 % compared to the Nylon specimen) with a deflection of 6,03mm (-14,83% compared to the Nylon specimen).

**FEA Results**

The next step was to design the reinforced specimen in solidworks and simulate it in ANSYS. However, that was a project that no important research had been made. As a result, no important literature could be easily found, concerning similar structures. The decision to divide the structure in 5 parts (as in reality) and then make an assembly in Solidworks, so to combine them in the final assembly, has been made. The parts 1-2-3 are made of Nylon (figure 36), so one simple honeycomb structure, that has been placed in these positions, designed. After that, the concentric fiberglass reinforcement parts were designed (figure 37). The dimensions, that the printer is able to print, took into account in order to design these fiberglass structures. However, these fiberglass parts were surrounded by nylon. So in positions 2-4, a more complex assembly made. That assembly consisted of nylon structures with special designed gaps (figure 38) in order to place the fiberglass. The parts of this structure are presented below.
FIGURE 36: Nylon Part for positions 1-3-5 (1mm height)

FIGURE 37: Concentric Honeycomb Fiberglass Structure (1mm height)

FIGURE 38: Nylon part with gaps for fiberglass insert (positions 2-4,1mm height)
In order to make even more clear the way that the fiberglass reinforced honeycomb structure designed, an assembly taken from ANSYS workbench presented in figure 39. Both the nylon parts and the fiberglass ones, are distinct.

![Nylon Honeycomb structure reinforced with fiberglass in positions 2 and 4](image)

**FIGURE 39: Nylon Honeycomb structure reinforced with fiberglass in positions 2 and 4**

At this point it is crucial to present the fiberglass properties, that have been used in ANSYS Workbench Model. It is very important to emphasize that for fiberglass the tensile yield stress is indistinguishable from its ultimate tensile strength. So, the load from which it cannot recover to its original length is the same as the load required to break it [35]. Table 5 presents fiberglass material properties [33].

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Units</th>
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<td>Density</td>
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<tr>
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<td>Flexural Strength</td>
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<tr>
<td>Compressive Modulus</td>
<td>GPa</td>
<td>21</td>
</tr>
</tbody>
</table>

The simulation of the 3-point bending test for the fiberglass reinforced specimen is presented below. The deflection of the structure at the ultimate force and at the yield point, that have been found experimentally, are shown in figures 40 and 41 respectively.
The FEA model seemed to give extremely accurate results, compared to the experimental ones. Deflection varied only for 0.76% at the maximum load after yielding. Figure 42 represents the FEA and the experimental Force-Deflection graphs in one diagram.
Finally, the plastic strain, that has almost started for 247.3 Nt (yield point), is distinct in Figure 43. This is another strong evidence that the constructed FEA model in ANSYS Workbench can give reliable results.

To sum up, continuous fiberglass reinforcement can ameliorate at a great grade the bending behavior of the studied cellular structure. It also seemed that the proposed FEA model is able to simulate 3d printed materials and give reliable results as well. However, it is important to test how the position of the fiberglass reinforcement influence the
mechanical behavior of a structure. In order to test it, another important experiment has been made, combined with a Finite Element Analysis as well.

4.4 Central Fiberglass Reinforcement

The new design approach, that has been studied, was a nylon honeycomb structure (height of 5mm) reinforced with concentric fiberglass of 2mm height in the middle of it. In order to estimate how the position affects the bending behavior, the same quantity of fiberglass has been selected. The only difference was the position of it. The new honeycomb structure is presented in figure 44. There is a bottom and top part from nylon at 1,5 mm height. The core of the structure is a nylon part with gaps for concentric fiberglass reinforcement. Its height is at 2mm.

![FIGURE 44: Central fiberglass Reinforced Honeycomb Structure](image)

**Experimental Results**

The results from the 3-point bending test for the centrally fiberglass reinforced cellular structure are presented below. It is easily noticed that the yield stress is greater than the nylon structure but smaller than the other with fiberglass reinforcement in positions 2 and 4. This phenomenon is due to the fact that as the stiffer material (fiberglass) is placed near the bending surfaces (up and down), so stronger the whole structure becomes. This is the reason that until now the sandwich panels have so many applications.
By careful observation, the new ultimate appeared for 296,3 Nt, presenting an increase up to 63,3 % in comparison to the Nylon specimen. In addition, the deflection at that point was 19,139 mm, presenting an increase of 6,88 % compared to the Nylon specimen. Furthermore, the yield point appeared for 163,3 Nt (+48,18% compared to the Nylon specimen) with a deflection of 7,457 mm (+5,32 % compared to the Nylon specimen).

**FEA Results**

The Finite Element Analysis of the last proposed simulation has been also studied in ANSYS. The Finite Element Analysis methodology, that has been used for the previous simulations, seemed to work correctly for one more time. The figures, that follows, presents the deflection of the honeycomb structure with central fiberglass reinforcement for 296,3 Nt (Ultimate) and 163,3 Nt (Yield) (found experimentally).
From Figures 46-47, it clear that deflection varied only for 7.1 % at the maximum load during yielding. Figure 48 represents the FEA and the experimental Force-Deflection graphs in one diagram.

Finally, the plastic strain, that has almost started for 163.3 Nt, is distinct in Figure 49. This is another strong evidence that the constructed FEA model in ANSYS Workbench can give reliable results.
4.5 Fiberglass Reinforcement Position and Bending Behavior

Taking into account all the above results from the experiment and the simulations in ANSYS, it is crucial to make a comparison between the different kind of reinforcements that have been studied. This analysis will set the bases for further investigation in the fields of 3d printed continuous fiber reinforcement. The following figures compare the nylon specimen with the two kinds of fiber reinforcements that have been studied. Figure 50 contains the experimental results and figure 51 the FEA ones.

![Force-Deflection Graph for experimental Results](image_url)

**FIGURE 50: Comparative Force-Deflection Graph for experimental Results (until the ultimate force)**
It is clear from the above figures that fiberglass reinforcement ameliorated the bending behavior of the studied honeycomb structure. However, it seemed that central fiberglass reinforcement offered less improvement. That was an expected remark, as it is logical to notice better bending behavior as the strong material is placed near the top and bottom bending surfaces.

Finally, by careful observation to figures 50 and 51, it is obvious that the designed FEA models are able to give extremely reliable results. The two figures are almost the same, despite the fact that the first is from experiments and the second from computer simulations.

### 4.6 Evaluation of the Finite Element Models and a new design approach

Taking into consideration all the above results, it seems that the proposed FEA methodology gives extremely reliable results. All the studied design solutions presented similar behavior during the experiments and the simulations in ANSYS. The idea of inserting separated solid parts and giving them the proper material behavior, solved the problem of simulating 3d printed continuous fiber reinforcements.

At this point and after having studied (experimentally and with FEA) two different reinforcement solutions for the studied honeycomb structure, the idea of designing a new model and studying it only with the aid of simulations on ANSYS came. With this final design study, a more detailed perception on how the position of the reinforcement affect the behavior of the constructed model will be available. In addition, the proposed FEA
methodology has been used and one of the aims of this thesis, in the direction to save resources during future studies, seems to be fulfilled.

The new design model consisted of the same quantity of fiberglass reinforcement with the difference of placing it in 3 parts. The honeycomb structured divided in 7 parts. The height of each part is presented in table 6.

**TABLE 6: Heights of different parts in Honeycomb structure with reinforcement in 3 positions**

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,8</td>
</tr>
<tr>
<td>2</td>
<td>0,5</td>
</tr>
<tr>
<td>3</td>
<td>0,7</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>0,7</td>
</tr>
<tr>
<td>6</td>
<td>0,5</td>
</tr>
<tr>
<td>7</td>
<td>0,8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5</strong></td>
</tr>
</tbody>
</table>

The reinforcement placed in parts 2, 4 and 6 with the respective heights. Figure 52 presents this structure graphically with the aid of eiger platform.

The results from the Finite Element Analysis are presented below. Figure 53 shows the deflection of the specimen for Force of 373,5 Nt (Ultimate) and figure 54 the plastic deformation of the specimen for 208,9 Nt Force. The above values for forces selected due to the fact that plastic deformation had almost started for 208,9 Nt, so considering a yield point around that value, may be a reliable choice. The choice of the ultimate force, has been made taking into consideration all the previous experiments, so an ultimate force
between the values, that have been recorded for the other two reinforcement solutions, has been selected.

FIGURE 53: Deflection (m) of honeycomb structure with fiberglass reinforcement in 3 positions for 373,5 Nt (Ultimate Force)

FIGURE 54: Plastic Strain (m/m) of honeycomb structure with fiberglass reinforcement in 3 positions for 208,9 Nt (Yield Point)

The comparison among the nylon specimen and the 3 different reinforcement proposed solutions are presented in figure 55. It is clear that fiberglass reinforcement increases both the yield point and the ultimate forces for all the studied cases. However, central fiberglass reinforcement may not be a good choice. It is important to place the stiff (fiberglass) material near the top and bottom layers of the honeycomb structure. The two specimens that have the fiberglass reinforcement there, showed higher yield points and ultimate forces with decreased deflection. Finally, the quantity of the reinforcement in these top and bottom layers, seems to play an important role as well. The specimen with reinforcement of
1mm in positions 2 and 4 present the higher yield point compared with the specimen with reinforcement of 0.5 mm in positions 2 and 6 (table 6).

**FIGURE 55: Comparative Force-Deflection Graph for all the studied specimens (FEA Results)**
5. **Conclusions**

The main interest of this report was to study the mechanical properties of 3d printed fiber reinforced honeycomb structures. In addition, the great interest on simulating these structures with the aid of FEA software, born the idea of creating a Finite Element Analysis model that will be able to simulate the 3d printed fiber reinforced honeycomb structures. All the process was an extremely challenging project, as there are no many similar contacted scientific papers. There were 3 important points of innovative action in this thesis. The first one was the fact that the fiber reinforcement was 3d printed inside the honeycomb structure by Markforged Mark Two. The second one was the try to build a stiff honeycomb core that may be able to compete the mechanical properties of the stiff fiber panels in sandwich structures and the third one was the construction of FEA model that will be able to simulate 3d printed fiber reinforced materials in order to save costs in future studies.

The methodology, that has been followed, helped in the direction to build a reliable Finite Element Model in ANSYS Workbench. A honeycomb structure from PLA has been used in the validation stage of the study. Experimental results of 3-point bending tests compared with simulation ones and a first FEA model designed. A slight difference of 3,58 % for the deflection at the ultimate force has been found among the experimental and the FEA results. That was an important evidence of the reliability of the designed FEA model in ANSYS.

The next step was the research on how the fiber reinforcement affects the bending behavior of the designed honeycomb structure. Fiberglass reinforcement has been selected among the choices that Markforged offers. The basic material of the specimen was Nylon. Two different types of reinforcement have been studied, both with 3-point bending tests and FEA. The two models had the same quantity of fiberglass and the position of it was the studied parameter. The first specimen divided in 5 parts of 1mm height each one. In positions 2 and 4, 1 mm of fiberglass reinforcement has been chosen (figure 33). The second specimen had a central fiberglass reinforcement of 2mm height (figure 44). Experimental results showed that the recorded ultimate forces increased from 181,4 Nt to 296,3 Nt (+63,34%) and 442,1 Nt (143,7%) for the Nylon, central fiberglass reinforced and fiberglass reinforced in position 2-4, specimens respectively. Furthermore, the deflection at these points measured at 17,9mm, 19,14mm (+6,2%) and 14,7mm (-17,88%). The yield
points increased from 110,2 Nt to 163,3 Nt (+48,19%) and 247,3 Nt (124,4%) for the Nylon, central fiberglass reinforced and fiberglass reinforced in position 2-4, specimens respectively. The deflection at these yield points measured at 7,08 mm, 7,457 mm (+5,32%) and 6,03 mm (-14,83%).

In parallel with the above process, the design of the FEA models has been made. An innovative methodology in order to study fiber reinforced structures proposed. That was the first worldwide attempt to simulate continuous 3d printed fiberglass reinforcement in a FEA software (figures 36-39). The results were very encouraging as for the same experimental deflections, the respective ultimate forces were at 181,3 Nt (-0,0005%), 288,54 Nt (-2,61%) and 443Nt (+0,002%) for the Nylon, central fiberglass reinforced and fiberglass reinforced in position 2-4, specimens respectively.

After having found so similar results in experimental and FEA models, the decision to study another reinforcement type has been made. In that third type, the quantity of reinforcement remained the same, but it was divided in 3 parts of 0,5mm-1mm-0,5mm (figure 52). The ultimate force of this third honeycomb structure found at 373,5 Nt (+105,89%) with a deflection of 14,316 mm (-20%) (compared to the Nylon specimen).

At this point, it is crucial to notice one important detail that came out after the observation of the force-deflection graphs for the experimental and FEA results. From figures 23,30,42 and 48, it is evident that for the fiberglass reinforced specimens, the results from the experiments and the FEA were very close and an almost perfect representation of the reality has been achieved with ANSYS. On the other hand, results (FEA and Experimental) for the PLA and Nylon specimens seemed to have a little bigger deviation. This phenomenon may have been occurred due to the fact that the proposed methodology of simulating 3d printed fiber reinforced specimens, can be able to simulate the behavior of these specimens in a great grade by dividing them in separated parts and consider them perfectly bonded in ANSYS. The main difference between these parts and the others from Nylon and PLA, is the fact that the latest designed as uniform specimens and this is something that may not represents the reality perfectly, as the formation of porous inner structures may be present for 3d printed materials. However, as it has already been mentioned, the FEA and experimental results, for all the presented materials and structures, presented an important convergence and many futures studies can be based on the presented study.

To sum up, it is evident that 3d printed of continuous fiberglass reinforcement ameliorates in a great grade the behavior of the studied honeycomb structure. The possibility to replace
the lightweight honeycomb cores, with stiffer (fiber reinforced) ones, may be a very promising idea. Building a stiffer honeycomb core, the use of softer top and bottom sheets may reduce the costs significantly. In addition, the use of the proposed FEA model, will enable researchers all over the world to take reliable results with important time and cost savings, in future studies.

However, at that point it should be emphasized that additional research on other fiber reinforcement types should be made in the future. Carbon or Kevlar fibers that are available by Markeforged should be studied as well. Aerospace, automotive and other industries need 3d printed parts with high mechanical properties in order to use them in real projects. 3d printed of continuous fibers, seemed to be able to cover these needs, so much more investigation should be made towards that field that has almost appeared. Furthermore, it should be noticed that 3d printing of continuous fiber reinforcement has almost started and this is one of the first scientific research at this field. As these technologies will advance, much more possibilities will be given in order to use them in industrial applications that will enhance the mechanical properties of the conventional structures.
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