Investigation of 3D Printed Honeycomb Cores by Varying Printing Parameters for Different Loading Conditions

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A thesis submitted in partial fulfillment of the requirements for the degree of

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Thesis Supervisor:

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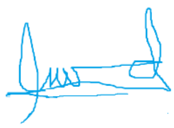

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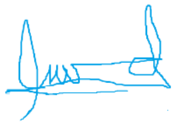

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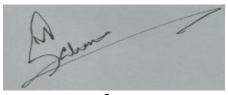

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Copyright Statement

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Indeed, nothing is possible unless ALLAH ALMIGHTY wills to do. First and foremost, I am thankful to Allah for His grace due to which I was able to finalize my thesis in MS in Design and Manufacturing Engineering. I am thankful to my parents whose desire of excellence has led me to believe in myself, pursue my dreams and strengthen myself both academically and personally. I am thankful to all my family members who have always been on my side and have helped me through thick and thin.

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This work is dedicated to love of knowledge, passion of independent enquiry and the thirst of excellence which has always led humanity to achieve the unthinkable, unconceivable and unimaginable.

Abstract

Light weight components having greater strength and lower manufacturing cost are the need of the hour especially for aerospace industries. For this, honeycomb sandwich structures of various materials and parameters are developed by Additive Manufacturing (AM) to meet the desired output of sufficient strength to withstand compression and flexural loading. In this paper, the honeycomb structures are fabricated using a fused filament fabrication (FDM) technique. The effect of different printing conditions on the compressive and flexural properties of the 3D-printed honeycomb structures made of PLA, ABS and PLA+ polymeric laminates are investigated experimentally and analyzed by Taguchi and ANOVA (Analysis of Variance). Three build orientations, i.e., 0, 45 and 90 degrees, with layer heights of 0.1, 0.2 and 0.3 mm are considered for the 3D printing. Moreover, Multi-objective optimization is performed to optimize the strength and printing time (cost) of L27 array samples. Results show that 90^{o} and $0°$ build orientations with 0.3 mm layer height being PLA and PLA+ the best materials are the optimum conditions for compressive and flexural mode of testing, respectively. The results deduced that compressive and flexural samples could withstand maximum load of 69,000N and 120 N with minimum printing time. Thus. it would be fruitful in harnessing energy for the development of sustainable printing of durable components.

Keywords:

Honeycomb Core, Additive Manufacturing, Fused Deposition Modeling (FDM), Multi-Objective Optimization, Taguchi DOE, ANOVA

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Chapter 1 : INTRODUCTION

This research case in this thesis has been presented in a total of six parts. At first, brief introduction and literature review of the research has been discussed. It amplifies the significance of the current research and the methods already applied for its implementation. In second section, novelty-based design has been presented to execute the Fused Deposition Modeling (FDM) technique.

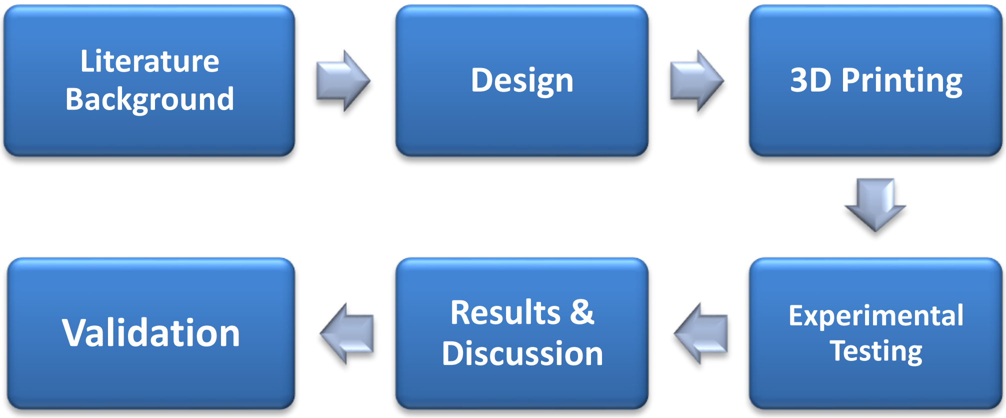


Figure 1: Process Flow of the Research

Third and fourth part concerns itself with the experimentation and testing procedure of the ongoing research and applies data analytics to optimize the results of the printing parameters of the structures under investigation. Fifth section summarizes the findings by Analysis of Variance (ANOVA) and figures out the optimum design. Finally, the last section validates the results obtained through the statistical approach to conform the output scores.

This research emphases on the additive manufacturing technique to manufacture a part with high strength and much reduced economics. This is done via the help of one of the techniques of additive manufacturing i.e. Fused Deposition Modeling or Fused Filament Fabrication by depositing layer upon layer to finally build whole component. In this chapter we will discuss some basic introduction about the additive manufacturing, its types and will focus on the FDM as it is our topic of interest.

1.1 Brief Overview

In this modern era, no one could deny the importance of Additive Manufacturing (AM). It is the process in which parts are generated layer by layer. AM allows the designer and manufacturer to generate complex parts and components without the aid of conventional tools and fixtures. It totally depends upon CAD Model which could then be transformed to physical product. In earlier stages, AM was only destined for developing prototype projects but nowadays these technologies are applied broadly in the manufacturing industries especially medical, aerospace and bio-engineering.

1.2 Additive Manufacturing

Additive Manufacturing (AM) is a process of creation of an object by using one layer at a time. AM is an alternative of subtractive production, where a product is fabricated by way of reducing away at a solid hunk of fabric until completion of the final part. It describes the technologies that create three-dimensional objects by building one incredibly thin layer at a time. Each layer that comes after is bonded to the partially or fully melted layer that came before it. Computer-aided design (CAD) software is used to digitally describe objects by creating STL files, which essentially slice the thing into extremely thin layers. This determines the direction of a print head or nozzle when it precisely deposits material on top of the preceding layer or when a laser or electron beam melts material in a bed of powdered fabric in a selective or partial manner. Substances fuse together to form three-dimensional objects as they cool or cure.

Unlike subtractive manufacturing in which the fabrication of a component is by removing extra material through different processes like turning, drilling, milling and grinding. Initially it was referred as Rapid Prototyping, the technology has since evolved with the common terminology of "3D Printing" in a non-technical context.

Due to the paradigm shift it has brought about in the way things are produced, additive manufacturing (AM) has been amplified the third industrial revolution. Traditionally, it takes several steps to go from a raw material to a fully fabricated, assembled, and useable product. By adopting this technique, functional items can be generated directly from the raw material at a fraction of the time previously consumed. As a result, AM has found numerous examples in multiple trades, including printed electronics, aerospace, automobile, and healthcare.

Given its ability to accurately and precisely build patient-specific customized implants, AM is employed and in use more frequently in healthcare industry. Some applications of AM technologies include rib cages, bones, and implantable heart valves manufacturing. Applying 3D printing in multiple aspects of the aforementioned domains have been created by processing a broad variety of materials, including metals, polymers, ceramics, and composites. Dental implants for the maxilla, dentures, and various prosthetic devices are among the dental applications of AM. The manufacturing of essential components like turbine blades and jet nozzles has been completely transformed by 3D printing. Strong aerospace component engines have advanced significantly as a result of additive manufacturing's use of complicated geometries and high-strength materials. The technology makes it possible to design complex interior cooling channels in components, which improves performance and heat dissipation.

1.2.1 Types of Additive Manufacturing

Broadly, AM is categorized into seven basic types i.e. VAT polymerization also called as Stereolithography, Material Extrusion (FDM), Binder jetting, Powder Bed Fusion (SLS), Sheet Lamination (LOM), Material Jetting and lastly Direct Energy Deposition as illustrated in figure 2. In our research, we will discuss only Material Extrusion type i.e. Fused Deposition Modeling.

Fused Deposition Modeling is the most widely used and convenient 3D printing process, as its name implies. Using a heated nozzle to extrude thermoplastic filaments like PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene), 3D printers melt the plastic layer by layer to create a construction platform. Layers are applied one after the other until the component is completed.

Figure 2: Types of Additive Manufacturing

The build platform in stereolithography (SLA) descends from the reservoir's top, which is filled with liquid polymer. Liquid resin is selectively cured in accordance with the pattern represented in the 3D CAD file using a UV light source. When the photopolymer comes into contact with the light source, it goes through a chemical process and solidifies. This procedure is referred to as photopolymerization or stereolithography in general. Next, layer by layer, the build platform descends, causing more resin to pour over the print bed's top. In order to ensure that a thin coat of liquid resin is distributed uniformly on the surface, a sweeper blade passes over the preceding layer. Layer by layer, this process is carried out until the modeled component is complete.

Powder Bed Fusion (PBF) is a process that melts and fused powder materials together to form three-dimensional objects using a heat source, like a laser beam. You can use this method to make metal and plastic components. Depending on the source, powder bed fusion techniques can be broadly classified into four categories. Laser fusion is a source used in Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS), and Selective Laser Melting (SLM). Thermal fusion is used in Selective Heat Sintering (SHS) while electronic beam fusion is used in Electron Beam Melting (EBM).

Material jetting is a multi-color additive manufacturing process that works similarly to an inkjet printer in that it distributes individual ink drops just as needed. Droplets of polymers, particularly thermoplastic, are selectively deposited utilizing drop on demand (DOD) technology. The print head is not heated during material jetting in order to bond the material. Rather, to cure the liquid resin, an ultraviolet (UV) light source is turned off.

Laminated Object Manufacturing (LOM) is a fast-prototyping method where an item is made by joining sheets of material. It is frequently employed to create robust 3D things with intricate geometry. On the build surface, a roll of build material is directed. Subsequently, the construction material is coated with a bonding glue, and the material is bound by passing a hot roller over its surface. After that, the sheet is cut in accordance with the 3D CAD model using a sharp knife or computer-guided laser beam, eliminating extra material. This procedure is continued until the part is fully produced, with the subsequent layer of material being placed on the print bed.

1.2.2 Applications of Additive Manufacturing

AM has been in practice in almost every sector of technology ranging from medical to aerospace. Following is the illustration of the areas of application where AM has its wide domain.

Among the earliest businesses to use additive manufacturing were the aerospace sector. In this field, there are some of the strictest industry performance criteria that need parts to function well under adverse circumstances. High-performance materials are necessary for the creation of flight-worthy components by engineers working on both military and commercial aircraft systems. These are only made feasible by the technology. Medical innovation is moving quickly, and additive manufacturing is helping to bring new advances to physicians, patients, and research facilities. Medical practitioners are customizing designs like never before by using the vast array of biocompatible, high-strength 3D printing materials, which vary from opaque to transparent and hard to flexible.

It is worth-mentioning here to have some basic difference between 3D printing and additive manufacturing. Additive manufacturing is a broader term involves the creation of objects by adding material, which involves a much more complex and in-depth industrial manufacturing process, including the entire print workflow for instance, Selective Laser Melting. However, 3D printing is a category of additive manufacturing specifically involves the creation of objects for demo or proof of concept by adding layers of material. FDM, SLA, LOM are some of the techniques.

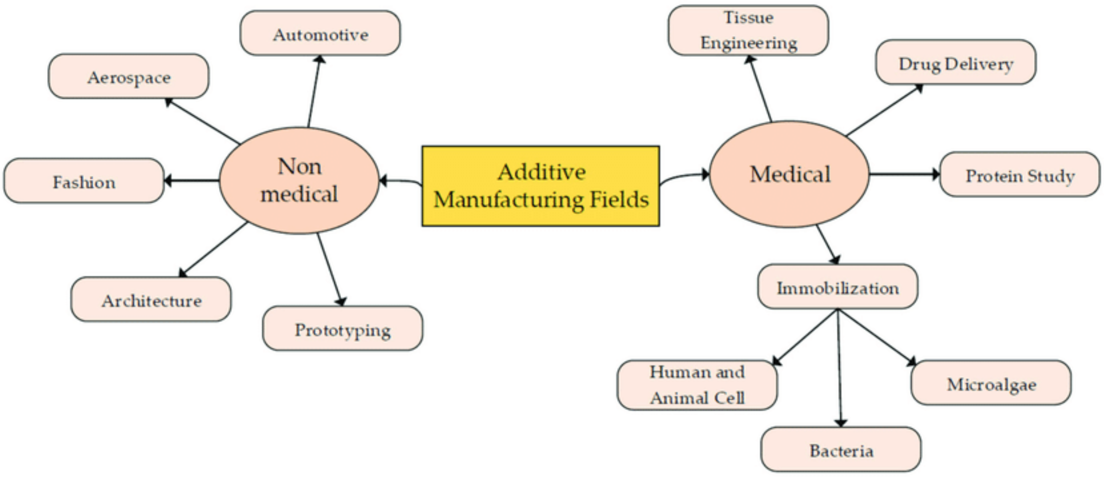


Figure 3: Areas of Additive Manufacturing

1.3 Honeycomb Structures

These structures employ a honeycomb-like design to minimize the amount of material needed, resulting in a lower weight and less material usage. The cells typically have a hexagonal shape and are columnar in shape. A material with a honeycomb-formed shape has relatively high out-of-plane shear and compressive characteristics and low density.

Honeycomb structures are perfect for aircraft manufacturing because of its excellent strength-to-weight ratio, where weight is an important consideration. Additionally, very rigid and able to hold their shape even in the face of significant loads or shocks are honeycomb constructions. Typically, the cells are hexagon-shaped and columnar in form. A material with low density and comparatively high out-of-plane compression and out-of-plane shear characteristics is offered by a honeycomb-shaped structure. The illustration of a general honeycomb structure is shown in Figure 4. When flat or slightly curved profiles are required, honeycomb materials are frequently employed because of their great strength. This is a major reason why the aircraft industry uses them a lot. Since the 1950s, aircraft and rockets have used materials including aluminum, fiberglass, and sophisticated composites, which are used in honeycomb structures. They are also used in a wide range of other industries, such as recreational products like skis and snowboards and packaging materials like cardboard with a honeycomb structure made of paper.

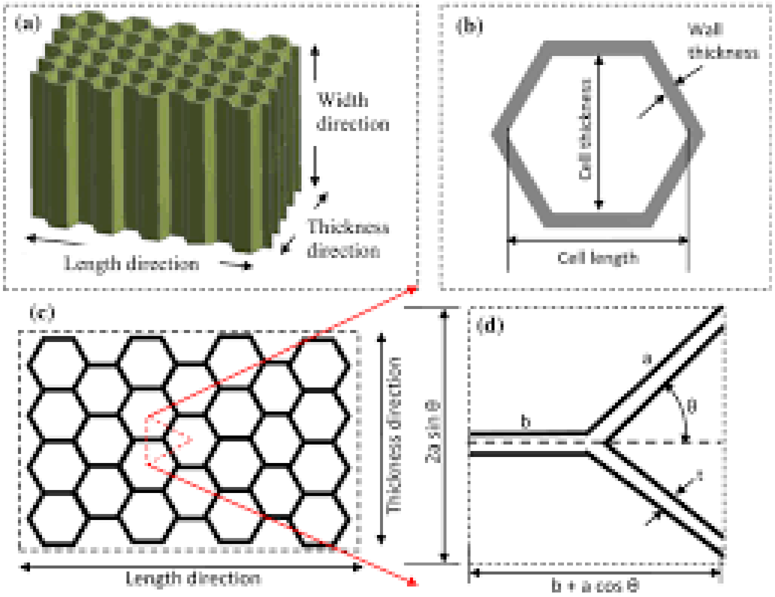


Figure 4: A General Honeycomb Structure

1.4 Types & Application of Honeycomb

Numerous materials are used to create honeycomb cores. They vary from low strength and stiffness materials like paper and cardboard for low load applications to higher strength and stiffness materials for improved performance applications like airplane constructions. They constitute multifaceted intricate shapes without additional mechanical stress or heating. The types are based usually on the material from which honeycomb is composed. Some of which are listed here:

- Paper Honeycomb
- Aluminum Honeycomb

- Reinforced Plastic Honeycomb
- Kevlar Honeycomb

Also, honeycombs are applied in multiple industries ranging from aerospace, sporting goods, automotive to construction sectors. Applications include:

- Racing shells
- Gliders
- Jet aircraft
- Rocket sub-structure
- Automobile structures
- Snowboards
- Bulkheads
- Train doors

1.5 Multi-Objective Optimization

A subfield of multiple-criteria decision-making known as "multi-objective optimization" (MOO) deals with mathematical optimization issues where numerous decisive functions need to be simultaneously maximized. Many scientific domains, including engineering, have used multi-objective optimization to solve problems where choosing the best course of action requires making trade-offs between two or more objectives. When choosing the final set of conflicting parameters, it is useful.

MOO provides a systematic tactic to analyzing and comprehending trade-offs between conflicting objectives. It assists decision-makers in deducing the best compromise solutions that balance different objectives, considering relative significance and constraints. Informed decision-making that reflects multiple perspectives and participants is enabled through this process. Some of the common applications of multi objective optimization are:

I. **Engineering Design:** MOO is broadly used in engineering design processes to optimize multiple objectives, such as cost, performance, reliability, and safety. For instance, MOO can help find the best compromise between curtailing material usage and enhancing structural strength in structural engineering.

II. **Supply Chain Management:** Optimization of supply chain networks often involves multiple contradictory objectives, such as lowering costs, maximizing customer service levels, and reducing environmental impact. MOO could help find optimal trade-offs and make well-informed decisions on supply chain design and operations.

III. **Energy Systems:** MOO is decisive in optimizing energy systems that involve objectives of multiple domains, including cost, environmental impact, and energy efficiency. For example, in renewable energy planning, MOO will help find optimal results that maximize the integration of renewable sources while minimizing carbon emissions and running costs.

1.6 Research Scope & Motivation

No doubt, today in order to compete in the global market and to be among a developed nation, aerospace exploration and saving natural reserves could not be denied. For this, sustainable and high strength-to-weight ratio components play a dominant and massive role. Developing and manufacturing such durable and light weight structures like Honeycomb cores either for commercial or defense sector is an essential factor in nation's progress. By the development of Honeycomb structures based on polymeric material, the conceptual idea could be got materialized as it would be highly favorable in contributing towards reducing the excessive weight of (aerospace, automotive) components along with sustainable energy provision.

Developing the honeycomb structures by additive manufacturing not just saves time and money, but also helps in curtailing natural reserves and resources. Contrary to the conventional, AM technology helps in durable and material saving deliverables that could be utilized in the best possible interest of automotive & aerospace sector.

1.7 Research Objective

The key objective of this current study is to optimize the 3D printing technology that would result in harnessing the energy with minimum usage of resources. This is also the crux of developing additive manufacturing in this era to discourage the tooling expense being used in conventional manufacturing. Following is some of the key objectives of this research:

1. Designing of Compressive and Flexural Honeycomb Structures.
2. Development of the structures by additive manufacturing technology (FDM).
3. Compressive and Flexural load testing of the developed structures.
4. Taguchi and ANOVA Analysis along with Multi-Objective Optimization to figure out best and optimized parameter.
5. Validation of the designed structures (through ANOVA) by experimentation.

The research would be fruitful in harnessing the energy and curtailing the manufacturing resources to its minimum value, thus contributing to sustainable manufacturing. Using 3D printing in dispersed manufacturing would be beneficial for low-volume replacement parts as well as high-value components used in the aerospace and medical technology sectors. Honeycomb structures would suffice the desired strength and durability as these got the intrinsic nature of being light and strong. Thus, fulfilling all the design safety criteria with much reduced economics.

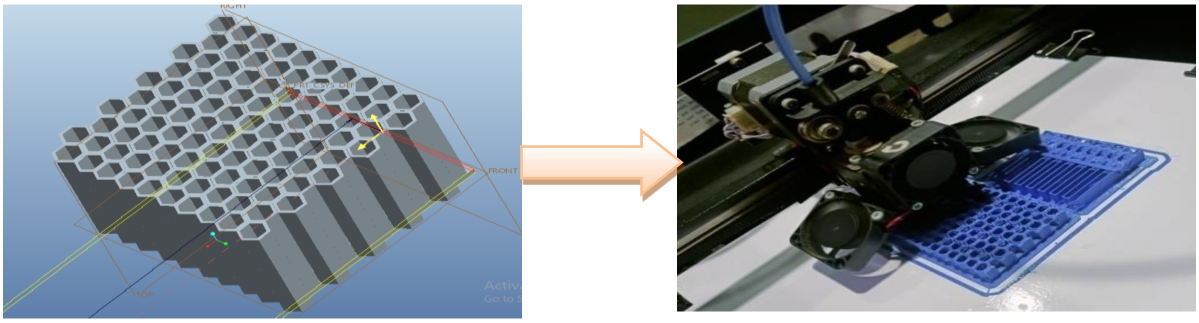
Chapter 2 : THEORETICAL BACKGROUND

2.1 Literature Review

Latest AM opportunities and applications that have been recently appeared in the literature, although their economic impact is still modest. According to X. Tian, 3D printing will accelerate the revolution in fabrication methods [1] and introduce a new avenue for specialized fabrication through the printing of any part for any industrial application using practically any material. Today, the honeycomb cores are printed using additive manufacturing (AM) technology [2]. Fused Deposition Modeling (FDM) is a type of additive manufacturing in which material is selectively deposited layer by layer to form a productM. Samykano used it to investigate how process variables affected the characteristics of ABS [3]. FDM Printer is used to print the model structure. Naik M and Thakur proved that parts fabricated by FDM can enhance mechanical properties by choosing the optimum printing parameters [4]. Honeycomb structures have been in use for centuries as nature has provided the clue for being the strongest. According to M. Dazaki, honeycomb and grid patterns have the strongest structures and the lightest weights when compared to solid, honeycomb, wiggle, grid, and rectilinear patterns [5]. Among multiple shapes of core, honeycomb i.e. topology of the hexagon is widely used and studied by the research authors. Feli S. khoshrwan, and Lee H analyzed honeycomb structures in different modes i.e. Impact, compressive likewise [6] [7] [8]. Sandwich beams' appropriate strength to weight ratio and high energy absorption have made them extremely important in industries like aerospace and automotive. It was proved that inner core of the sandwich structures plays a dramatic role in the flexural properties and contributes in their respective strengths [9] [10] [11] [12].

2.2 3D Printing Technologies

In various fields, design and development of 3D printers and printing have been in use since 21^{st} century such as aerospace, architecture, and sports industries [13]. Use of nomex, [14] light metal and composites for honeycomb cores have been studied and their strengths suggested honeycomb outstanding [15] [16]. One-step fabrication that increases accuracy and speed are two of the best aspects of using AM technology, particularly when making sandwich panels. [17] [18]. Characterization of honeycomb structures is also of paramount importance when determining the strength in different directions. Numerous investigations have been formulated in order to formulate the mechanical characteristics of these light weight structures [19]. 3D printing of light weight composite structures was also analyzed [20]. The flexural characteristics of sandwich panels made of materials with cellular cores were examined by Ochsner [12]. Honeycomb structures have been found to have a higher specific load carrying capability. Mechanical properties of 3-D printed lattice core sandwich structures were assessed by Azzouza et al. [21]. Their findings showed that this 3D printing technology would be practiced in order to fabricate low cost, high strength-to-weight ratio structures. Luca Di Angelo stressed on the significance of build orientation in FDM and formulate methods to figure out the response of printing orientation on the manufacturing cost and surface quality [22]



Modeling of Samples in ProE

FDM 3D Printing in progress

Figure 5: The Honeycomb samples fabrication process

The compression strength of the printed composite structure having sandwich face sheets with a corrugated core and 1.5 mm Kevlar-nylon skins was tested by Dikshit [23]. Salvatore [24] utilizes FDM to build sandwich constructions that are easier to assemble with a cheap 3D printer and have stiffer and lighter qualities. Sandwich specimens with an outside ABS shell and a PLA honeycomb center are the novel sandwich structure that is being suggested here [25]. The 3D printing of composite sandwich constructions utilizing continuous carbon fiber reinforced polylactic acid (PLA) material was covered by Sugiyama et al. [26]. In his demonstration, Rodríguez compared the tensile mechanical behavior of test specimens (FDM) printed with PLA and ABS, finding that PLA prints more rigidly and with a higher tensile strength. [27]

Table 1: Summarized Literature Review

Sr#	Research Topic	Parameters	Methodology	Optimized Results
1	Experimental investigation of effect of printing parameters on impact strength of the bio-inspired 3D printed specimen. *Sādhanā*, *46*(3), 151. Naik, M., & Thakur, D. G. Springer (2021).	**Build Orientation**: Flat & On-edge **Infill density**: 20 – 100% **Layer Height:** 0.15 mm	Fused Deposition Modeling (FDM) Only Experimental Impact Testing	Infill density: 20% Vertical edge orientation has highest impact strength
2	3D FDM production and mechanical behavior of polymeric sandwich specimens embedding classical and honeycomb cores. *Curved and Layered Structures*, *5*(1), 80-94. Brischetto, S., Ferro, C. G., Torre, R., & Maggiore, P. (2018).	**Orientation:** a crisscross lamination –stack Sequence of 45∘ /−45∘ Cross-head **speed**:2.45-2.55 mm/min.	Fused Deposition Modeling (FDM) of 8 samples. Flexural 3 & 4 point bending Test	Replacement of PLA through ABS for the external face lead to lower performances. Worst Case; 8.39 MPa.
3	3D printed parts with honeycomb internal pattern by fused deposition modelling; experimental characterization and production optimization. Metals and Materials International, 25(5), 1312-1325. (2019).	**Build Orientation**: 45\` **Nozzle Dia:** 0.45 mm Tensile Specimen	FDM RSM	a. Thick layers : Tough Properties b. Higher Temperature : Better Fusion Properties
4	Optimizing the FDM additive manufacturing process to achieve maximum tensile	**Material:** PLA, ABS **Orientation:** Flat & Upright	Tensile strength evaluation FDM	PLA 1.35 times the Ys of ABS 0.2 mm layer significantly better

	strength: a review. *Rapid prototyping journal* (2019)	**Layer Thickness**: 0.2 , 0.4		
5	Effect of geometrical parameters on the flexural properties of sandwich structures with 3D-printed honeycomb core and E-glass/epoxy Face-sheets. Elsevier (2021)	**Orientation**: Horizontal & Vertical **Cell wall thickness:** 1, 1.5, 2 mm **Layer Height:** 0.2	FDM followed by flexural analysis. Finite Element Analysis	Horizontal Orientation Cell wall thickness 1.5 Transition from Nomex to the PLA material.
6	Influence of slicing parameters on surface quality and mechanical properties of 3D-printed CF/PLA. Taylor & Francis (2021)	**Structures:** Rectillinear, Honeycomb, Triangular **Layer height:** 0.25 & 0.64	Tensile test followed by flexural & 3 point bending	Hexagonal Structure Infill densiy 60% Layer height 0.25
7	Enhanced out-of-plane compressive strength and energy absorption of 3D printed square and hexagonal honeycombs with variable-thickness cell edges. Extreme Mechanics Letters, (2018)	4 each samples of square & hexagonal Radius of Intersection variable **wall thickness:** 0.4,0.6,0.9	compression properties (Out-of-plane) FDM	Square Honeycomb 57% hexagonal 19% I compressive strength >>
8	Load Distribution on PET-G 3D Prints of Honeycomb Cellular Structures under Compression Load, mdpi (2021)	**Infill Density:** 30%,70%,100% **Orientation:** Flat, Edge, Upright (90)	FDM followed by Compressive & Impact Testing	100% Infill density Upright Direction i.e.90˚

In table 1, literature review of the concerned research articles is summarized. This clearly illustrates the areas where already some working has been performed. Now, we will continue the discussion regarding the methodologies applied for 3D printing.

2.3 Effect of Printing Parameters

Mahesh [28] noticed at how printing orientation and infill density affected the results. The outcome shown that multi-infill pattern specimens printed in the flat on-edge orientation have a higher value for the impact strength-to-weight ratio. The impact of three slicing parameters—layer heights, infill densities, and layer patterns—was examined by N. Vinoth [29]. This demonstrated why it is best to avoid printing in the "upright" configuration, as samples printed in this orientation may be as much as 50% weaker [30]. By using the fused deposition modeling (FDM) technique, three-dimensional honeycomb structures made of PET-G material were created with various printing orientations and infill density values. According to O Basurto [31], the construction that had 100% infill density and an upright printing direction showed an increase in strength. According to R.S. Jayaram [32], the polyester pin reinforcement in the foam-filled honeycomb sandwich panel significantly improved the compression and flexural capabilities.

Sabah came to the conclusion that, in comparison to vertical orientation, honeycomb sandwich constructions had much better flexural capabilities [33]. Using the response surface approach, the maximum failure load (N), part weight (g), and construction time (min) were examined. [34]. It had proved that the geometrical properties of honeycomb structures such as cell wall thickness, the cell size and the core height affect the mechanical properties of sandwich panels [35] [36]. Maximum failure load (N), part weight (g), and build time (min) were analyzed by response surface method [34]. C Camposeco-Negrete [37] investigated and optimized printing parameters specifically layer thickness, filling pattern and printing plane using the ANOVA and Taguchi methodology. Annuha Peng also optimize multiple process parameters for FDM with the formulation of Response Surface Methodology [38]. S R Kumar and M F Arif experimentally concluded weaker flexural strength in 90^{o} orientation as compared to horizontal build orientation. [39] [40]. These findings help in ignoring vertical build orientation for flexural loading.

2.4 Research Gap

Based on the above discussion, it was concluded that the dominant significance of this research is to investigate the effect of printing parameters on the compression and flexural behavior of honeycomb sandwich structures. As in numerous literatures, mainly cell structures have been the focal point for most of the researchers. But how these structures could be developed efficiently, that remained ambiguous. No any work has been done so for in establishing not only the optimum parameters but also cost-effective printing.

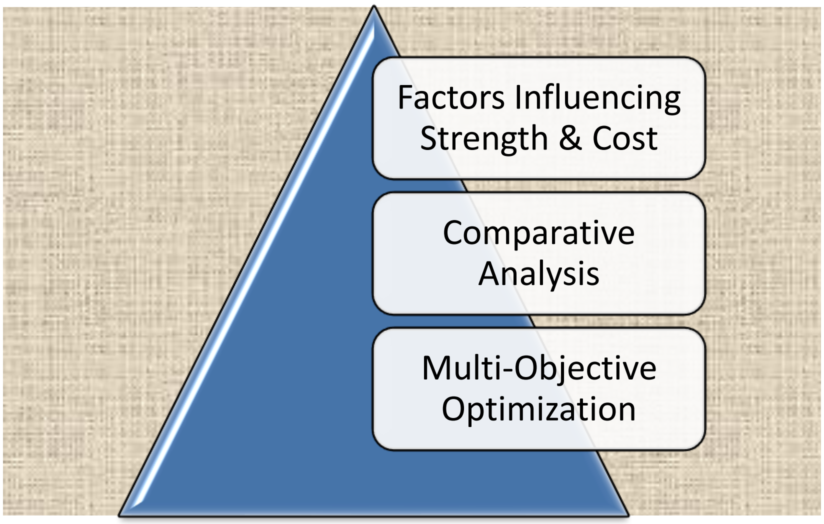


Figure 6: Research Gap Deduced

Thus, it was deduced as a gap in finding the optimum parameters for 3D printing with much reduced economics. Eventually, for the investigation, at first compression and flexural samples were 3D printed followed by ASTM testing guidelines. Then, optimum printing measures were evaluated by applying response surface methodology and Analysis of Variance (ANOVA). Finally, for validation, optimized samples were printed and analyzed on three varying parameters namely material, build orientation and layer height. Based on the results, optimum conditions were finalized with the objective of developing sustainable products in a least possible energy consumption.

Chapter 3 : MATERIALS AND METHODOLOGY

Polymeric materials were chosen i.e. In this research, PLA, ABS and PLA plus for the investigation. PLA is more brittle as compared to ABS. To lessen the brittle nature and improve the ductility of PLA, some additives and modifiers were incorporated to make it PLA plus. Thus, it was also opted to evaluate its properties. The integrated additive manufacturing process used was Fused Deposition Modeling (FDM). In order to assess the flexural and compression characteristics, many test groups were taken into consideration.

3.1 Process Flow of Research

Based on the literature review discussed, in order to determine the research gaps and objectives of the study, subsequent research methodology was formulated as illustrated Figure 7. Firstly, experimentation is conducted based on Taguchi design of orthogonal array L27. Then, strength was calculated and based on the experimental results optimization is carried out using Multi-Objective Optimization (MOO). Finally, validation was performed by the actual experimentation and variation was analyzed.

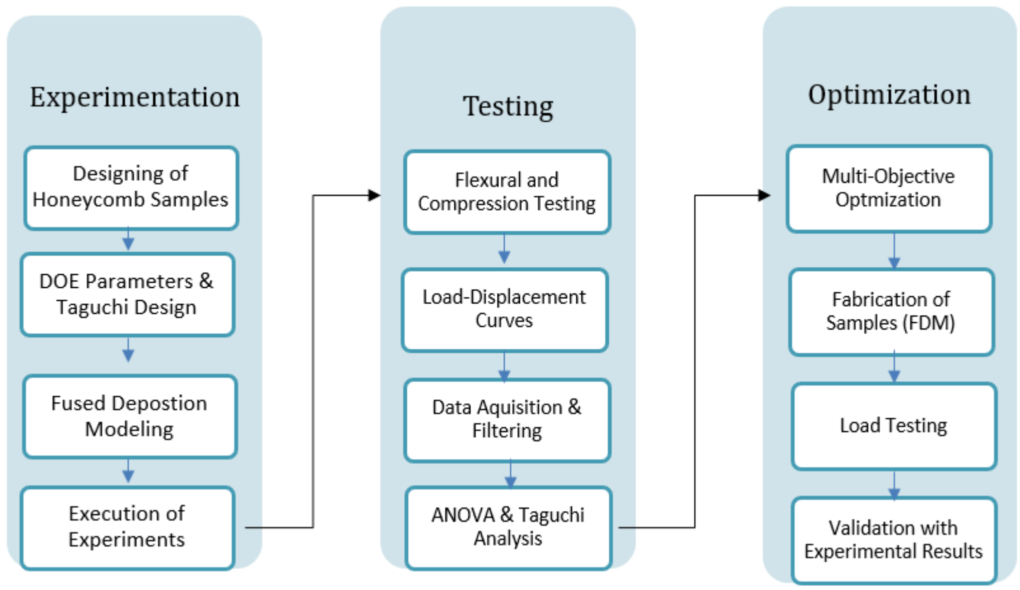
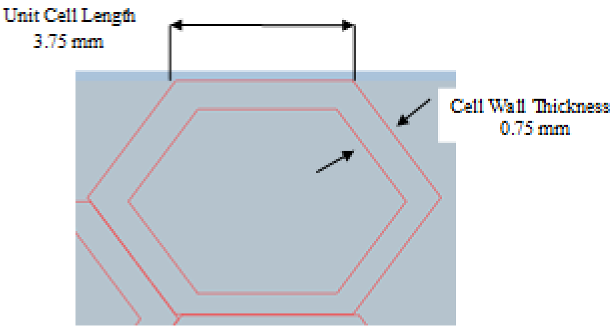


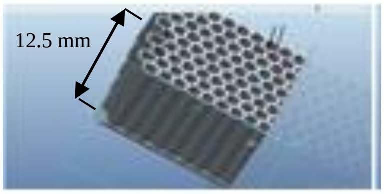
Figure 7: Process Flow of Research (Methodology)

3.2 Designing of Samples

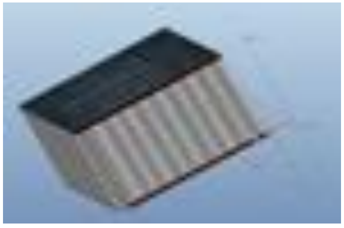
Initially, a CAD model in ProE software was modeled that was truly the replica of ASTM C365 and D790 standards for the compression and flexural testing respectively. The geometry specifications of these standards is listed in Table 3. It is worth asserting here that geometry of all samples were remain fixed, so no any alterations required in drawing. A unit cell drawing suffices the need for all other printing samples.



(a)



(b)



(c)

Figure 8 : Design for Honeycomb samples

Twenty seven test groups of each type of loading were designed by Taguchi L27 array in order to analyze printing parameters on the flexural & compression properties of honeycomb structures as tabulated in Table 2. In the upcoming sections, these test sets were presented in detail. The unit cell configuration and the printed honeycomb and sandwich panels have been demonstrated in figure 8 and 10 respectively.

3.3 Design of Experiments

The first step in Design of Experiments is the test to analyze the flexural and compression strengths of the ASTM samples that were manufactured using fused deposition modeling (FDM). The Taguchi technique of orthogonal array was used to optimize for the optimal combination. The Taguchi technique of orthogonal array was employed to test and determine the optimal outcome in order to validate the flaws. Taguchi has developed a brand-new technique for testing experiment design. This technique conducts a minimal run of tests using a set of orthogonal arrays to provide a concise explanation of the factors influencing performance metrics. Detailed information about the design parameters is summarized in Table 2. Signal, noise and control factor are the basis for the mode of orthogonal array.

An orthogonal array was formulated to test the design parameters. The initial array, L27, for 3 factors and 3 levels were selected to hold for full factorial design. 27 runs for each mode of loading were executed and analyzed, each for a single run. The output values are improved by maximizing the signal to noise ratio for the respective group of combinations. Taguchi resilient design of experimental design module may be used to compute the signal to noise ratio. Thus, Taguchi helps out in extracting the best possible combination. Analysis of variance (ANOVA) is a decision-making tool for evaluating the average difference in performance of tests conducted. the ANOVA evaluates the variables by mean of squaring and measuring the experimental errors at predetermined levels. P and F tests are commonly used in analysis of variance to examine a given design. P value (<0.05) suggests whether the factor under investigation has any significant effect on output or not. The analysis of variance is executed by using the equation below.

$$SS_T = \sum(\tau_i - n_m)^2 \quad [41]$$

where, SS_T is total sum of squared deviation, n_m is the total S/N ratio of mean, n is number of experiments conducted in orthogonal array, i is the mean S/N ratio for the experiment. This equation is really helpful and supportive when one has to calculate and find the significance values of the parameters under investigation. In our case, we will utilize it to formulate the best possible significant values effecting the process.

3.4 3D Printing

AM (Fused Deposition Modeling) technique was used to fabricate the cores. Initially, ProE software was used to model the structures. Next, FDM 3D printer was used to produce the modeled cores using the defined parameters as illustrated mentioned in previous section.

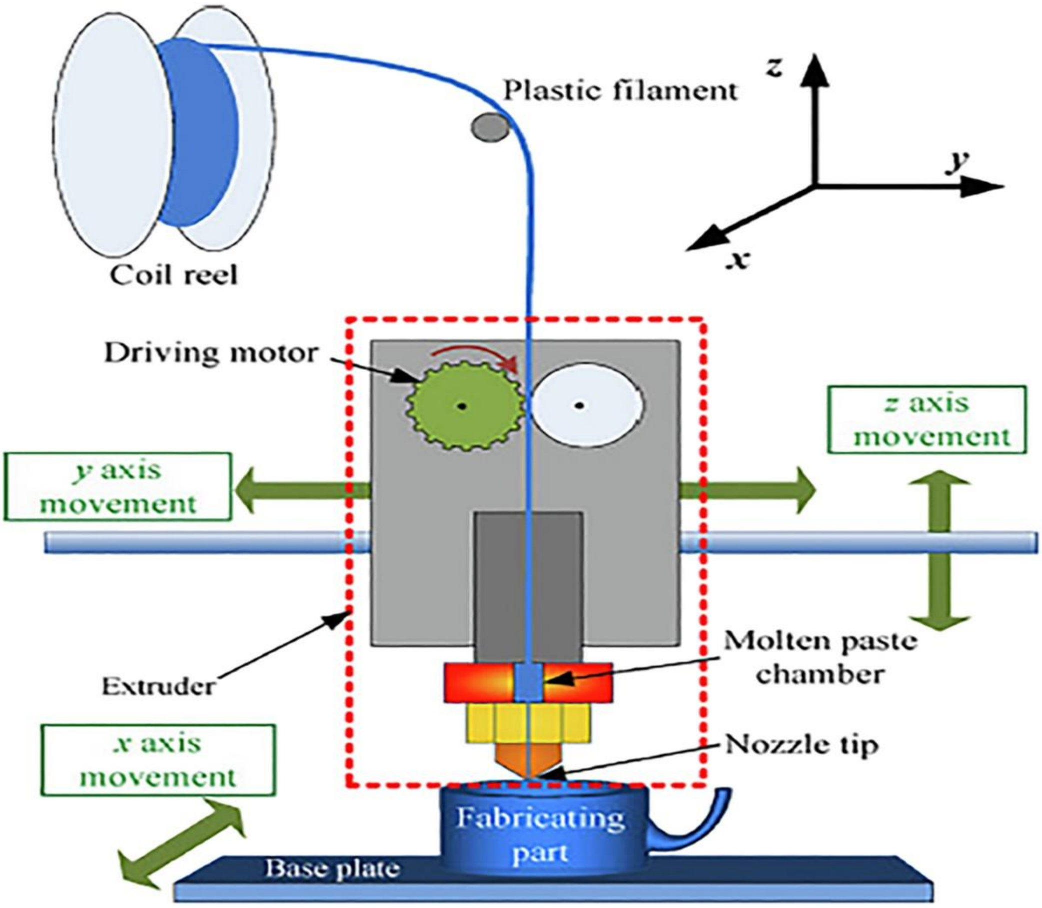


Figure 9: FDM Machine Illustration

As shown in above figure 9, the machine or setup used for printing has its reel where the material of the final product is coiled. After then, driving motors pull the filament through the heated chamber where material gets semi-solidus. After then, final nozzle deposit layer by layer as per the CAD model. Same process was also followed in this experimentation. Simplify 3D software was used for printing. Infill density of 50% was set to print these honeycomb cores.

There is built-in feature in latest 3D printing softwares that assists in setting these infill density from a wide range of almost equal intervals to the maximum filling percentage.

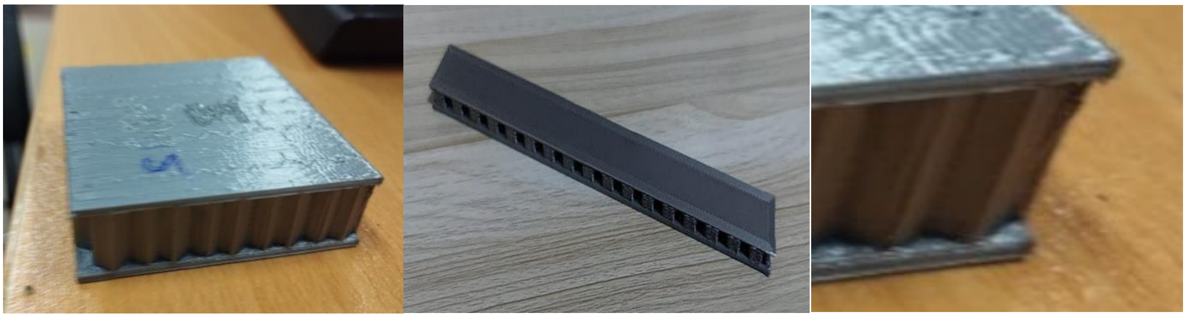


Figure 10: Printed Honeycomb Samples illustrating no any prominent printing defect. No any Stringing, curling and weak infill observed.

A filament having 1.75 mm diameter was used to print the modeled structures. Twenty-seven (27) samples of both standards were fabricated to find the strength, cost and energy absorption of printed system. Initially, each combination of L27 array was printed one-by-one. After each set, 3D printer was counter checked for XYZ accuracy. Printing time was being noted by the software automatically. Then, the structures were tested conferring to ASTM D790 for flexural and ASTM C365 for compression analysis. The geometry of the complete data set measured according to ASTM D790 and ASTM C365 are listed in Table 3.

Table 2

Designed Combination L27 for Samples Printing

S. No	Material	Assign No.	Build Orientation (°)	LH (mm)	S. No	Material	Assign No.	Build Orientation (°)	LH (mm)
1	***PLA***	1	0	0.1	**15**	***ABS***	2	45	0.3
2		1	0	0.2	**16**		2	90	0.1
3		1	0	0.3	**17**		2	90	0.2
4		1	45	0.1	**18**		2	90	0.3
5		1	45	0.2	**19**	***PLA+***	3	0	0.1
6		1	45	0.3	**20**		3	0	0.2
7		1	90	0.1	**21**		3	0	0.3
8		1	90	0.2	**22**		3	45	0.1
9		1	90	0.3	**23**		3	45	0.2

10	***ABS***	2	0	0.1	**24**		3	45	0.3
11		2	0	0.2	**25**		3	90	0.1
12		2	0	0.3	**26**		3	90	0.2
13		2	45	0.1	**27**		3	90	0.3
14		2	45	0.2					

Table 3

The dimensions of honeycomb samples according to ASTM Standards [36]

S. No	ASTM Standard	Mode of Loading	Length (mm)	Width (mm)	Thickness (mm)	Unit Cell
1	C365	Compression	50	50	12.5	3.5
2	D790	Flexural	125	12.7	3.2	3

Mechanical and thermal properties of the materials being tested are crucial for 3D printing. As there are some limitations and constraints when executing this technique. Hardness, rigidity, impact resistance, chemical and heat resistance are some of the decisive properties which should be known for selecting the suitable materials for FDM. Thus, PLA, ABS and PLA plus are found to be qualified based on the criteria just mentioned.

3.5 Flexural and Compression Load Testing

Flexural loading is the mode of loading in which a bending of beam or slab take place. In other words, simply it is a bending mode of loading. For this, it is important to have support structures at the extreme ends of any specimen under loading, while a load is applied at the centre mostly as demonstrated in the figure 11. It is necessary that the point load should act in the centre most region so that the response could be evaluated accurately. For the implementation, initially a ruler having maximum range up to 140 mm was used to mark the central position of the specimens under observation.

In this investigation, the specimens were subjected to flexural stress in order to determine the mechanical characteristics of the cores (Fig. 12). As per the ASTM D790 standard, the samples were tested using three-point bending loads and displacement control conditions. Every sample was tested using a universal testing machine (QCHaida-20) to record the load (P) against the load point deflection curve. A load cell with a capacity of 2 kN and a quasi-static flexural test

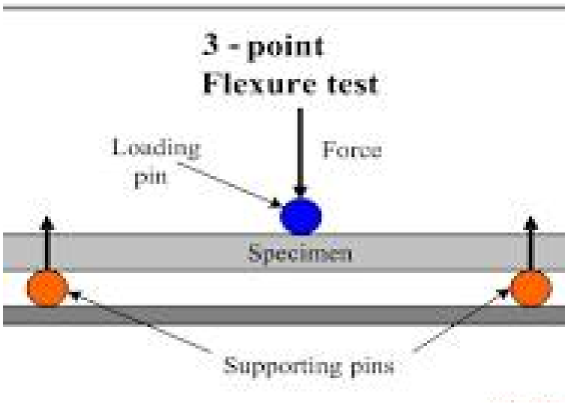


Figure 11: Illustration of Flexural Loading

with a crosshead speed of 2 millimeters per minute were taken into consideration. The three-point bending test has a span length of 70 mm. Four millimeters is the radius of the punch used to provide load to the samples or to serve as supports. It is specified that all the samples were verified for the same environment conditions and working boundaries. The developed samples and the working system used to test them have been illustrated in *Figure 12*.

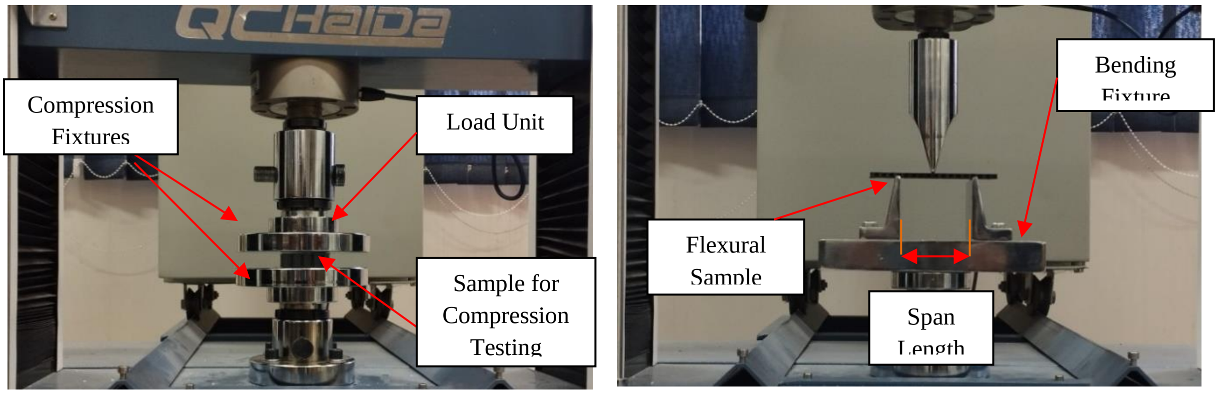


Figure 12: Testing Samples to Investigate the Mechanical Properties

In compression mode, simply a load is applied while a specimen is placed on the bed surface of universal testing machine. In the research, same conditions were also applied for the compression test but according to ASTM C360 standard. This standard is much helpful when considering any mode of loading that is compressive in nature. Also, it truly holds valid for the polymeric materials. ABS, PLA and PLA plus compression materials were that is why been opted.

3.6 Response Data Schemes

As per ASTM C365, sandwich structure samples that are subjected to flexural loading can have certain parameters including flexural rigidity, face bending stress, and core shear ultimate strength calculated. The shear ultimate strength of each core of a sandwich panel is determined as follows [36]:

$$F_s^{ult} = \frac{P_{max}}{(d+c)b} \qquad \text{Eq. (a)}$$

$$\sigma = \frac{P_{max}\, l}{2t(d+c)b} \qquad \text{Eq. (b)}$$

where P_{max} is the maximum load in the flexural load–deflection curve, d is the height of sandwich panel, c is the core height and b is the sandwich panel width. In addition, bending stress of each face-sheet is obtained as mentioned in eq. b where, l and t are the length of the support span and the skin thickness, respectively. One of the mechanical properties that may also be utilized to compare various samples is energy absorption during bending up to the plastic limit. Consequently, it was possible to calculate the honeycomb samples' energy absorption. Using the trapezoidal integral approach, the area under each sample's load-displacement curve was calculated in order to ascertain this attribute.

3.7 RSM –Multi Objective Optimization

For final optimization, to single out the optimum combination by setting the larger the best criteria for the strength and the smaller the best for Printing time i.e. cost, Multi objective optimization was carried out using Minitab. Response Surface Methodology involves factorial variable optimization processes to adjust the response to the intended maximum or lowest value. ANOVA and factorial methods are used to describe the response; however, they are expanded for more in-depth modeling of the impacts. In this situation, our two main goals are to increase strength and decrease economics. So, RSM is essential for developing these statistical values. Also, Multi-Objective Optimization aids in minimizing the effort and redundancy for any set of data.

The optimization executed is shown in Figure *27*. The optimization singles out only 1 combination for each type of loading. Compression is optimized at conditions of 90^{o} orientation, 0.3 mm layer height by using PLA material. While for flexural mode, 0^{o} orientation, 0.27 mm layer height by PLA+ has been optimized. Here it is noteworthy that due to min. printing time 0.3 mm layer height is selected, although no significant difference among strengths in varying layer height. The final parameters deduced by optimization are presented here in table 4.

Table 4

Optimized Parameters by MOO for Both Modes of Loading

S.no	**Material**	**Orientation**	**Thickness**	**Mode of Loading**	**Max Load/ Force (N)**	**Printing Time (Mins)**
1	PLA	90	0.3	Compression	69,000	105
2	PLA+	0	0.27	Flexural	106	50

It could be deduced without any contemplation that upright orientation for fused deposition modeling is the best position whenever any 3D printing has to be done. Whereas, for flexural mode of loading, due to anisotropic behavior of the samples, it withstands much of the load in the horizontal build orientation. Anisotropy is the intrinsic material property that shows different behavior or response in different directions. This is due to the highly randomized orientation of macromolecules in polymeric materials. Other scientific details will be discussed in the next section.

Chapter 4 : RESULTS & DISCUSSION

4.1 Material Properties Effect

Load displacement curves for the samples under investigation have been extracted. To figure out the best worst scenario, each factor\s response has been segregated. These responses are elaborated one by one. Mostly polymeric materials like ABS, PLA etc have been in use since the dawn of FDM. These materials have got their pros and cons against their application i.e type of loading. So, in this investigation, three materials PLA, ABS, and PLA+ were considered to evaluate the effect of these polymeric sandwich structures in flexural & compressive loading.

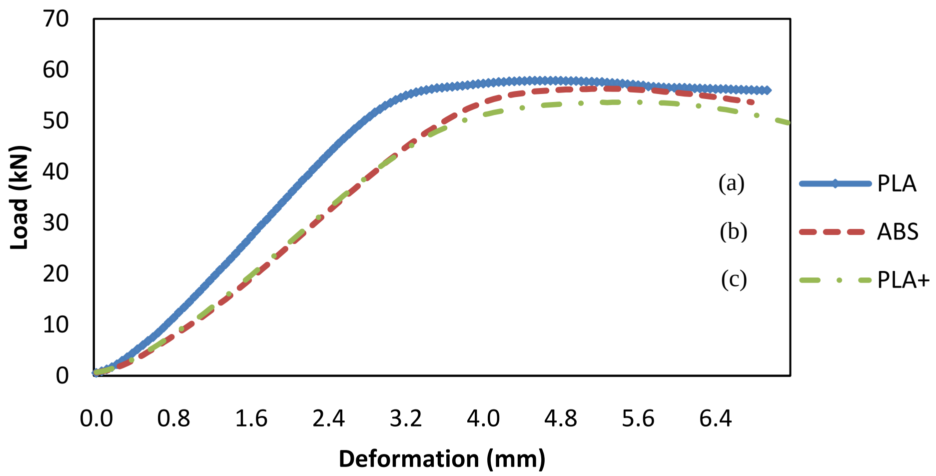


Figure 13: Representation of load-displacement curves of a). PLA b). ABS c). PLA+

From Figure *13* It has been observed in the result section that PLA+ being tougher possesses the best flexural properties keeping other parameters constant. It has been observed that by the use of PLA and PLA+ for flexural mode, the ultimate load of the honeycomb samples increased apparently. However, in compression mode, a bit cumbersome to decide between PLA and PLA+ as minute variance obtained. In PLA, the inherit built in properties of this polymeric material is quite brittle. Thus, in order to curb these rigidness, some additives are added to enhance the resilience and ductile properties and thus introduced this PLA plus material.

4.2 The Printing Orientation

Honeycomb core systems were designed to fabricate in three orientations, i.e., 0° (horizontal), 45° (inclined) and 90° (vertical). The honeycomb cores have been shown in Figure 10. For this orientation, the core-cells were fabricated in the route or path of the applied load. While, for the inclined and base i.e. 0 ° build core orientation, the load was directed on the wall of core cell. The effect of printing orientation on the compression and flexural properties of the manufactured honeycomb structures and its face sheets were investigated. The response of printing orientation on the flexural and compression properties of the printed honeycomb core and its face sheets were investigated and illustrated in Figure 14. The dimensions of honeycomb cores for the compression and flexural samples were designed according to ASTM C365 and ASTM D790 [36] as mentioned in Table 3. Face sheet thickness was selected as 1 mm. It is important to know the engineering reason behind these responses. The fact is that in case of load acting perpendicular to the direction of the deposited arrangements of material, it is quite cumbersome to resist but contrary if it is applied parallel to the direction then layers added extra resistance to deformation.

4.3 The Layer Height

It was investigated how the layer height and thickness of the honeycomb samples affected the printing time as well as the core's flexural and compression characteristics. Three layer heights—0.1, 0.2, and 0.3 mm—were taken into consideration in this study. As previously stated, load–displacement curves serve as an illustration of the outcomes of the compression and three-point bending tests performed on the honeycomb samples. The maximum bearable load is above 55.0 kN or 23.5 MPa.

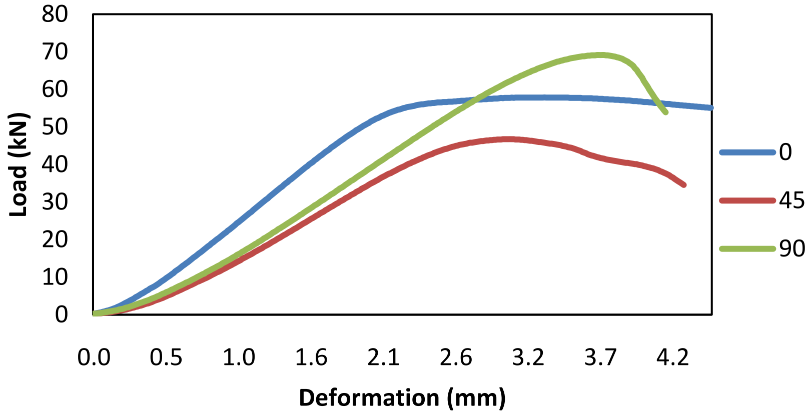


Figure 14: Honeycomb samples printing along a).0° b) . 45° c). 90° orientation under compressive loading condition.

Typical load–displacement curves of the samples under investigation with layer height/thickness of 0.1, 0.2 and 0.3 mm have been respectively illustrated in Figure *15*.Also, when considering layer height factor, PLA+ shows considerably improved response being the added advantage of ductility imposed in this innovative material. [42] This enhancement in the result obtained for the PLA+ is formulated by incorporating compounds having higher ductility as compared to PLA.

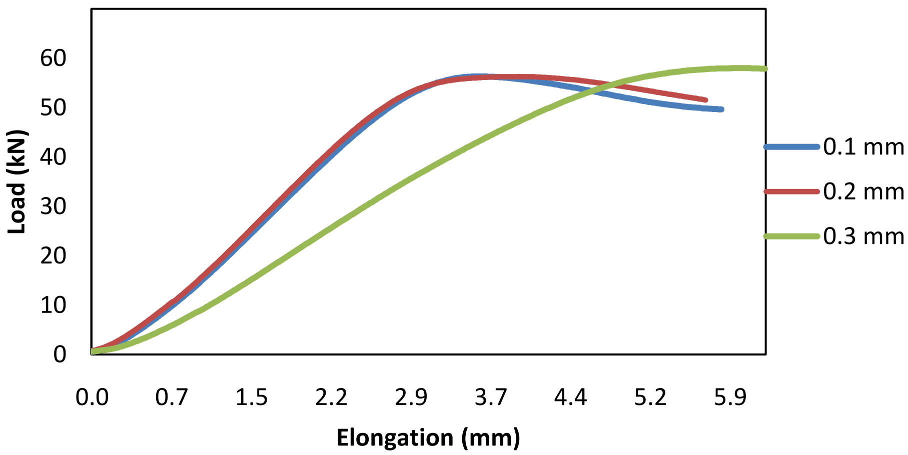


Figure 15: Load-Displacement Curve for Compressive Honeycomb Samples of a) 0.1 b) 0.2 c). 0.3 mm layer height

4.4 Failure Mechanism

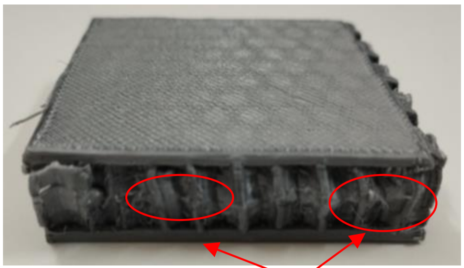
The main failure mechanism in the compression test of honeycomb sandwich structures is fracture between layers at the maximum buckling condition at center in case of 0° as shown in Figure *16* and Figure *17*. A higher upright 90° orientation will strengthen the bond between successive layers in the FDM process. The reason behind this is due to anisotropic behavior of the honeycomb structure.

a). 0° b). 45° c). 90°

Figure 16: Compression Samples Behavior at different Orientations. The circles showing the plastic deformation. Axial compressive failure at 0° and 90° while shearing rupture at 45°.

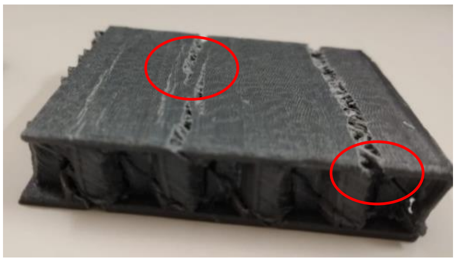
Similarly, in case of inclined orientation of 45°, crack propagates in the specified direction of printing orientation. Thus, slicing of the samples then would be executed in the given direction. However, in vertical upright orientation, the failure occurs at the root that could be the reason that proper binding of face sheet with the cores have not been established. Also, compressive load assists in slippage of the columnar cores to the face sheets, thus inhibiting strength and toughness in face sheets of the honeycomb structures.

In fig 16 a). it has been deduced that the core columns buckle at the center most region. On contrary, in part b). it could be seen easily that shearing at 45 degrees causes the columns to disintegrate in the inclined direction. Moreover, the different failure zones against different loading directions strengthens the case under investigation.



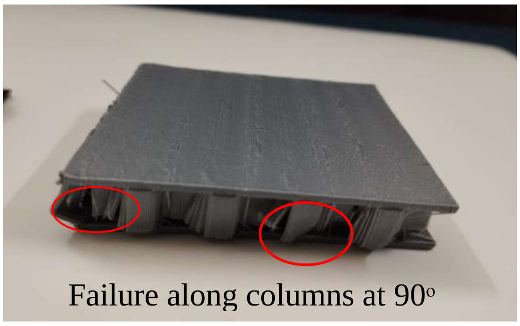
Fracture zone plastic deformation

(a)



Shearing zone along Face-sheet

(b)



(c)

Figure 17: Failure Zones of ASTM Samples under Compressive Loading. Inclined and vertical columnar cracking zones at middle points of the structures.

It is well observed that the lesser height corresponds to more defects such as warping and poor surface finish, but the maximum loading capacity has not much affected by layer height. Although, for printing time i.e. cost, layer height plays a significant role. Similarly, it could also be extracted based on the flexural testing performed on the testing samples as shown in Figure 18 that the bottom region is under tension whereas the top region is in the compression mode. This dual mode generates a counter load which is inclined to the surface and it tears apart as demonstrated in the figure above. It is to be mentioned here that the mode of failure as well as their corresponding zones in the flexural loading condition behave in a different manner when compared to that of compression mode. Thus, it should be discouraged to compare these mode of loadings simultaneously.

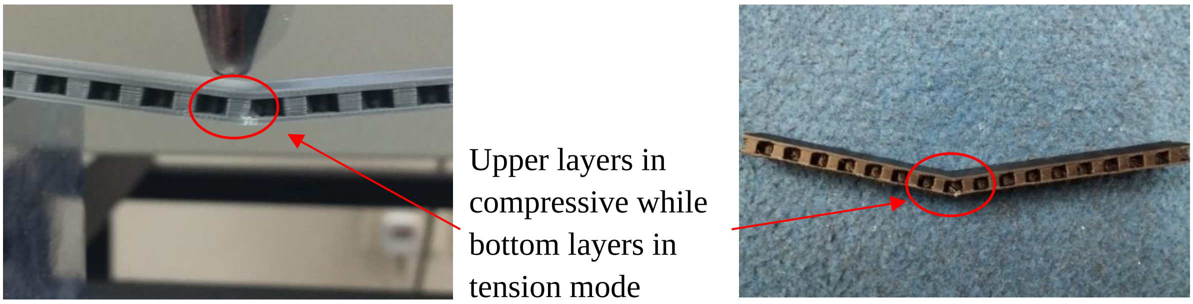
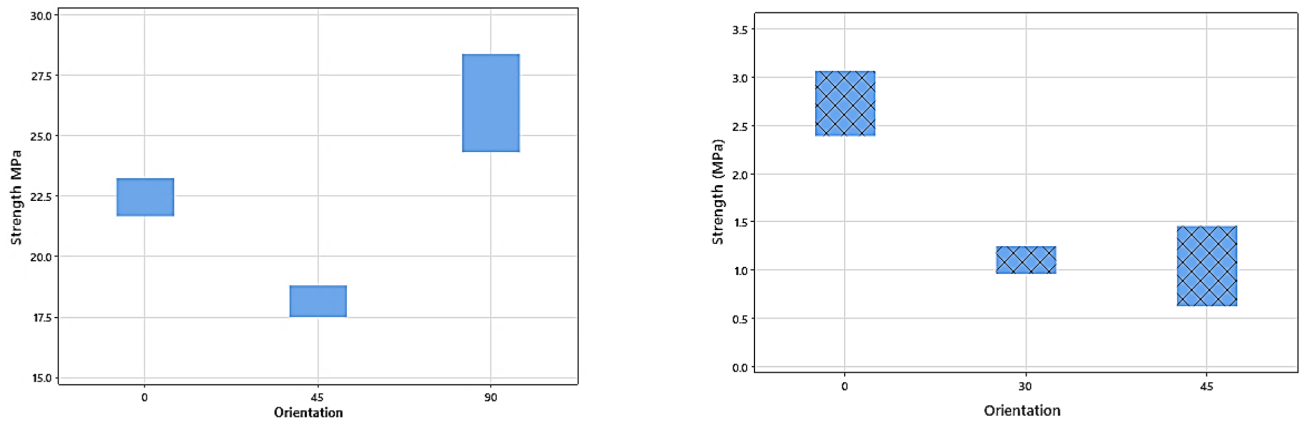


Figure 18: Failure Zones of ASTM Samples under Flexural Loading. Lower region of sandwich panels break under tension while top layers under compression.

4.5 Parametric Analysis

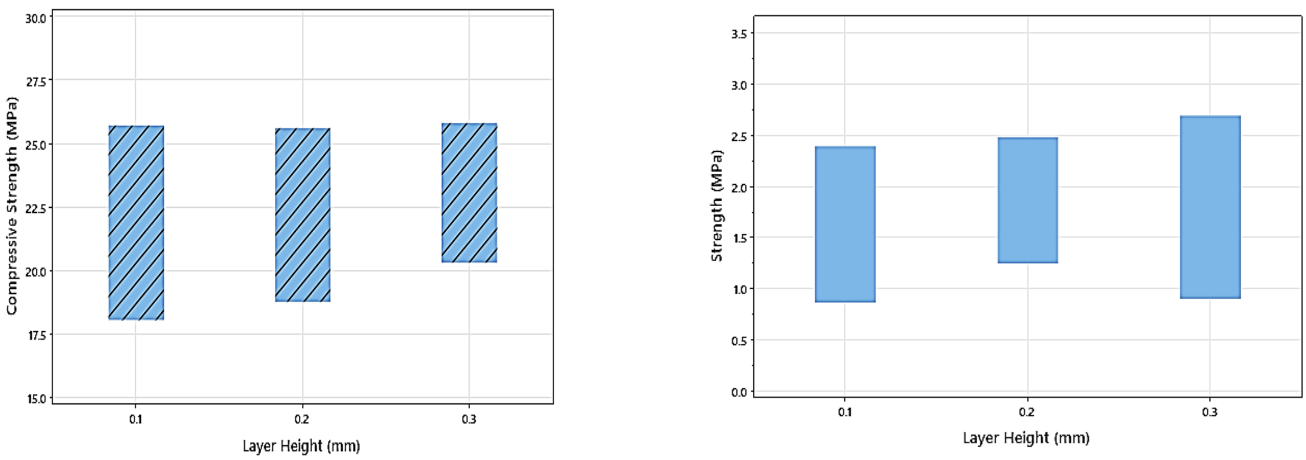
Parameters under investigation have been compared one by one based on the varying factors. Each factor has its significance on the strength and printing time of the sample being printed. Presented here are some of the concrete data figures showing the relation which then will be discussed in the upcoming section. The response of honeycomb samples for various orientations under compressive and flexural loading has been depicted in Figure 19. Three zones can be distinguished based on how 3D-printed specimens react. When exposed to flexural stress, the vertical honeycomb cores in area I exhibit an elastic characteristic. These samples behave non-linearly in area ii. It is reduced following the peak load (region iii). Eventually, the load abruptly drops and the core fails altogether.

It is deduced that using the vertical 90° orientation, compression strength has been increased to around 30-50% when compared to horizontal and inclined direction. Additionally, it is evident that the vertical printing orientation increases the slope of the linear section in the honeycomb sample's load-displacement curve. Additionally, the load-displacement curves for the sandwich constructions may be separated into three zones. Every sandwich panel in area I behaves linearly. In area II, a nonlinear reaction is then noticed. First, the load in area III is nearly constant. then went up first and then down later.



(a) (b)

Figure 19: Effect of Build Orientation (^{O}) on a). Compression and b). Flexural Strength



(a) (b)

Figure 20: Effect of Layer Height on a). Compression and b). Flexural Strength

It is worth noting that the strength has almost negligible variation irrespective of the change in layer height as demonstrated in Figure *20*. Also, this trend is common in both types of loading i.e. compression as well as flexural. This might be due to the fact that minute intervals have been chosen in this investigation. It could also be verified by the correlogram presented below in Figure 21.

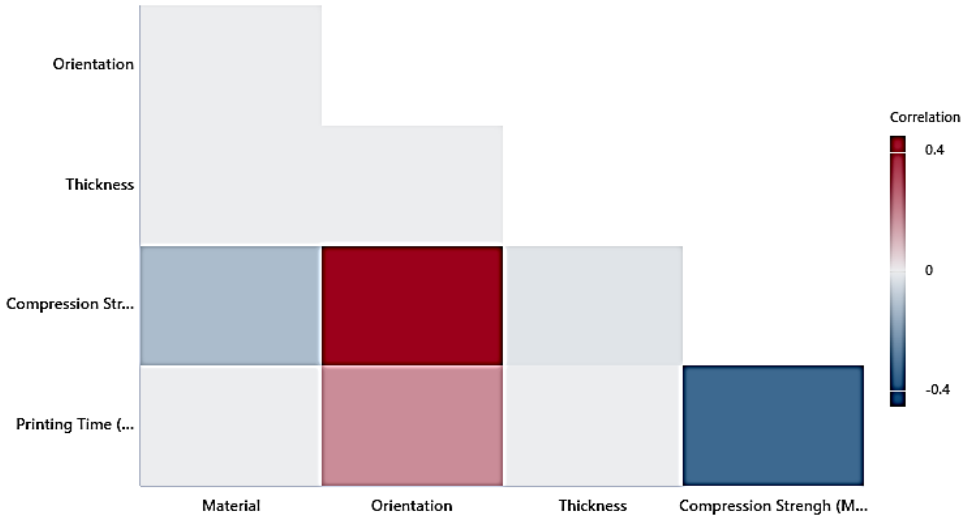


Figure 21: Correlogram Illustrating Effect of the Parameters

A correlogram has been illustrated in the above figure. A correlogram matrix consents to analyze the relationship between each pair of numeric variables of a dataset. The relationship between each pair of variables is visualized through a scatterplot as seen from the above representation. Positive correlations are shown in blue and negative correlations in red. The correlation coefficient and color intensity are directly correlated; that is, the closer the correlation is to -1 or 1, the stronger the color, and the darker the boxes.

From Figure *21*, it is obvious that orientation has dominant effect on strength and is the only considerable factor among all others to have a significant effect. Thus, all factors have their respective effectiveness on strength and printing time of the samples.

Chapter 5 : ANOVA AND TAGUCHI ANALYSIS

5.1 Data Analytics

Printing parameters were investigated by Taguchi method and ANOVA General Linear Model to verify the parameters that have drastically affected the strength and time characteristic. Taguchi method identifies the significant level of a factor which affects the particular performance parameter. ANOVA is used to figure out the critical factor for a specified response. It groups variances by comparing the means of each set and includes spreading out the changes into diverse sources.

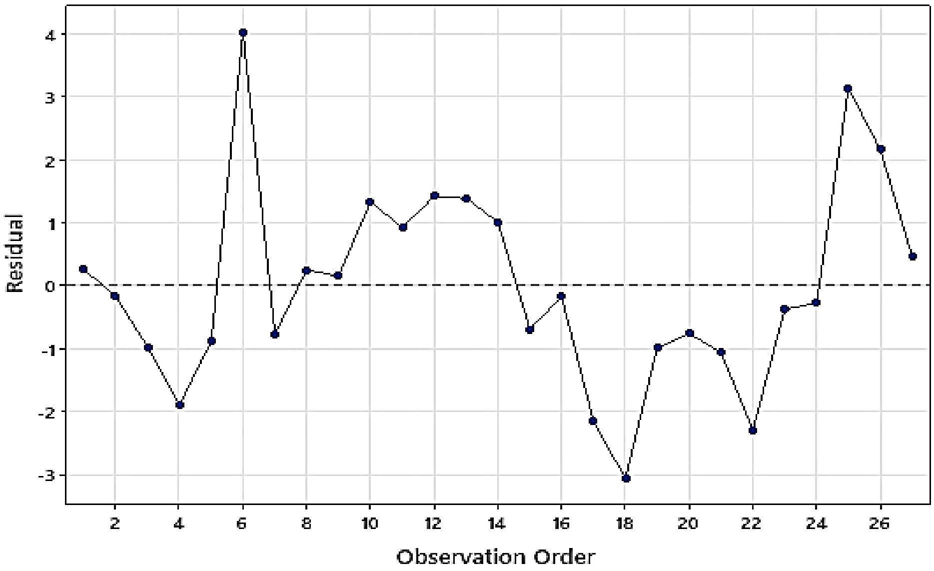


Figure 22: ANOVA General Linear Model set for 27 S-N Ratio Values (Compressive mode)

Analysis of Variance was conducted for the range of L27 array, and the properties were obtained. The ANOVA result of material, build orientation and layer height is analyzed and its response measures are tabulated in the given section respectively. The values of the F-statistic, sum of squares, means square, and P-value were also recorded in the tabulation. The findings of a standard sample are shown in Tables 7 and 8, together with tabulated data on printing time, flexural strength, and compression strength. Build orientation ranks 1st followed by layer thickness and material among the parameters under investigation. Taguchi analysis shows us that in both modes of loading, printing orientation is the dominant one.

Table 5

Taguchi Analysis for Different Loading Conditions

a) Flexural Loading

Level	Mat	Orientation	LT
1	3.4848	8.6612	1.3193
2	2.2852	0.7746	4.7212
3	2.5543	-1.1114	2.2838
Delta	1.1996	9.7726	3.4019
Rank	3	1	2

b) Compressive Loading

Level	Material	Orientation	LT
1	27.33	27.03	26.74
2	26.69	25.38	26.94
3	26.84	28.46	27.18
Delta	0.64	3.08	0.44
Rank	2	1	3

Taguchi Analysis was formulated to figure out the best dominant factor. As illustrated in Figure 16, Build orientation ranks top among the other influencing parameters. As only, this mentioned factor has its wide range and different responses when going from zero to ninety degrees orientation. The output of the printing parameters is described in Figure 22 above and may be measured in terms of noise and signal factor.

Table 6:

ANOVA General Linear Model for Compression Mode

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Material	2	14.701	7.350	2.19	0.138
Orientation	2	278.609	139.305	41.44	0.000
Thickness	2	4.394	2.197	0.65	0.531
Error	20	67.234	3.362		
Total	26	364.938			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.83349	81.58%	76.05%	66.42%

Table 7

ANOVA for Flexural Mode

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Mat	2	0.0501	0.02504	0.15	0.857
Orientation	2	16.7276	8.36381	51.75	0.000
LT	2	0.7708	0.38538	2.38	0.118
Error	20	3.2324	0.16162		
Total	26	20.7809			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.402021	84.45%	79.78%	71.65%

The output of strength and time is shown in this graph by summing the S/N ratios for the material, orientation, and layer height of the printing process. If the SNR is low, it means that the signal being measured (e.g., the strength of a material) is relatively weak compared to the background noise, which can make it difficult to accurately measure the signal. This can lead to poor accuracy and precision in the results. On the other hand, if the SNR is high, it means that the signal is much stronger than the background noise, making it easier to accurately measure the signal. This can result in more accurate and precise measurements. Therefore, to analyze the perimeter effect accurately and precisely on strength, it is important to ensure that the SNR should be pre-defined and set. Thus, The S/N ratio of strength is calculated by the larger-the better formula and is given by [41]:-

$$\frac{\mathrm{S}}{\mathrm{N}}\,(larger - the\ better) = -10log_{10} \sum_{i=1}^{n} \frac{\left(\frac{1}{\mathrm{y}^2}\right)}{\mathrm{n}}$$

Similarly, the S/N ratio for Printing time is calculated by smaller-the best ratio.

$$\frac{\mathrm{S}}{\mathrm{N}}\,(Smaller - the\ better) = -10log_{10} \sum_{i=1}^{n} \frac{\mathrm{Y}^2}{\mathrm{n}}$$

The result for flexural loading shows that the build orientation has delta 9.77 signal to noise ratio with the corresponding printing time signal to noise ratio of -13.12. Thus, orientation ranks 1st and has the highest S/N ratio for the optimum printing quality. Layer height ranks 2nd having 3.40 signal-to-noise ratio whereas Material stands 3rd in the row being least effective and having signal-to-noise ratio of just 1.19. *Table 5* demonstrates Taguchi Analysis for flexural and compressive mode and also deduced orientation at the top influencing factor having ratio of 3.08 compared to 0.44 and 0.64 for layer height and material.

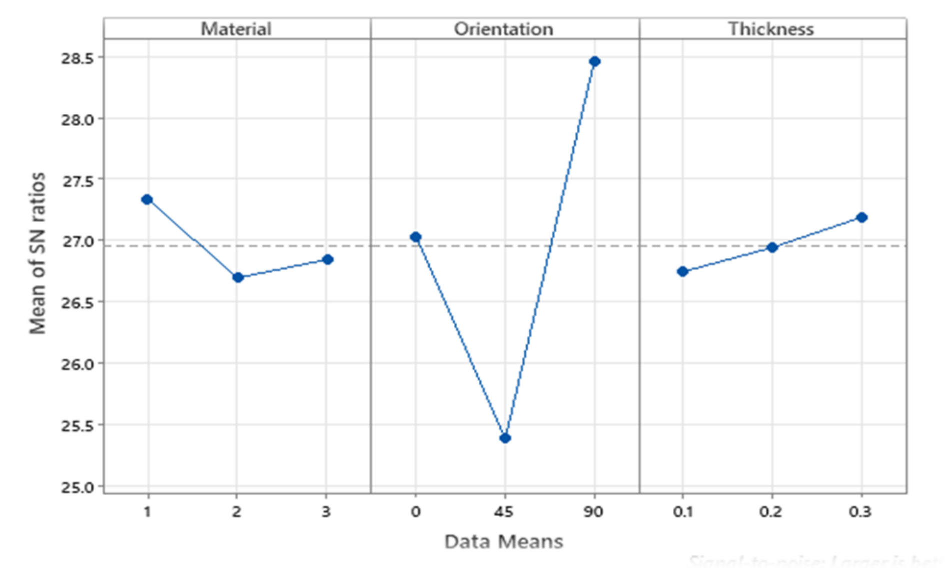


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Figure 23: Taguchi Analysis S-N Ratio

ANOVA General Linear Model was used to formulate the results for these modes of loading. In table 6, Compression strength and printing time is tabulated. Based on P and F-value It could be categorized whether the factor that has been chosen for investigation is significant or not. If P value falls below 0.05, then the factor is significant. Similarly, R-sq values can give an idea up to what extent the responses could be explained by the factors selected. Small error contributions indicate that it is justified to assume no interactions between factors affecting responses. Table 6 shows the f and p values for the flexural loading. Here, it could be observed that orientation clearly stands out as contributing around 80% of the variation in the result. Contour plots of compression response have been illustrated in Figure *24*. It can be clearly demonstrated that at upright orientation strength is maximum and printing time is consumed significantly greater at inclined build orientation.

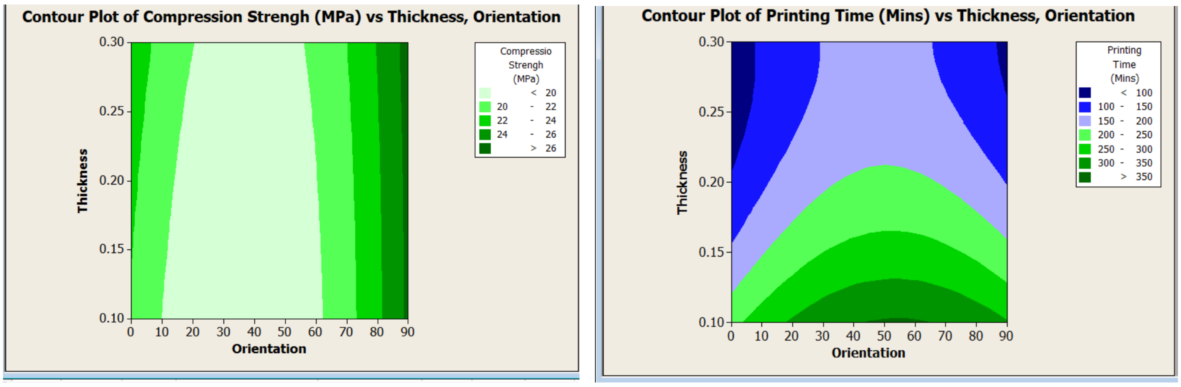
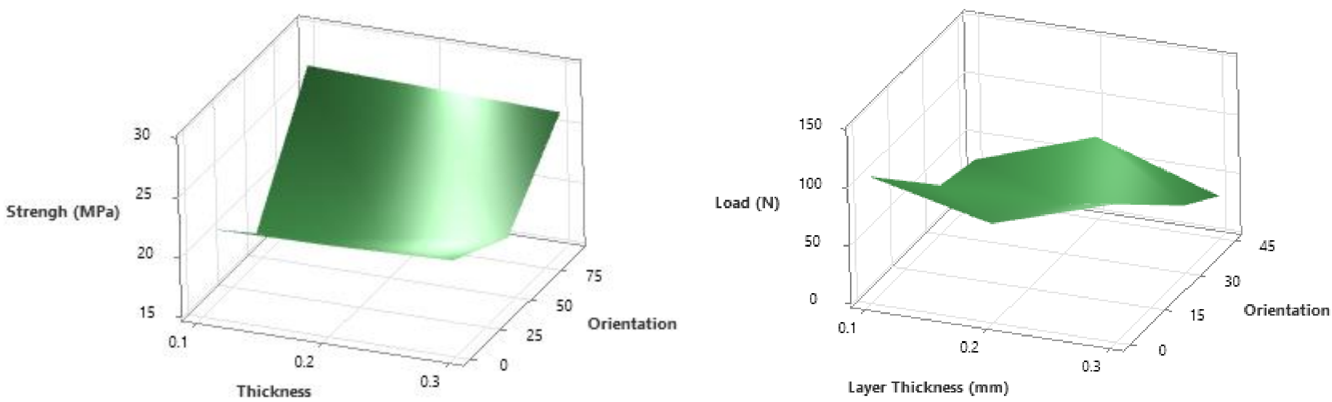
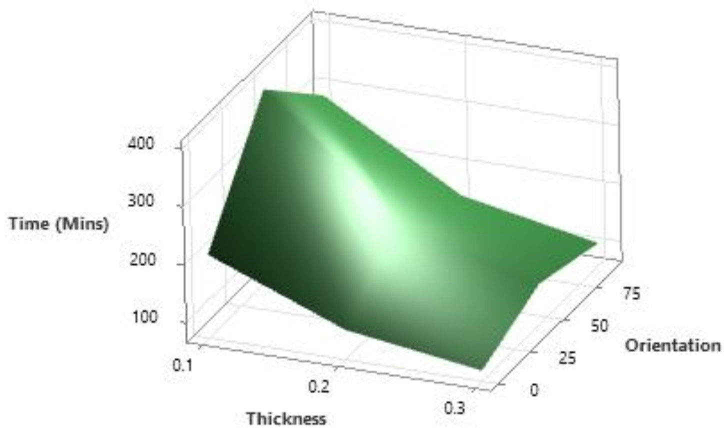


Figure 24 **:** Compression Strength & Printing Time Contour

In Figure *25*, 3D contours of all data sets have been plotted. Here again it is verified that build Orientation is maximum at vertical direction. It is also significant as its P value lies below 0.05 for all cases. P value is the probability value that corresponds to second the null hypothesis. It means that the results before and after the execution of experiments were quite similar. But in our case, it could be visualized from p-values that only material and layer height have some probability of setting the null hypothesis true otherwise false. Thus, alternate hypothesis will be only valid for the said parameters under investigation. P-value also tells that whether our selected parameter is of paramount consideration or not. Same criteria just mentioned above will also be valid for this proposition.



(a) **(b)**



(c)

Figure 25: Response of a). Compressive and b). Flexural loading and c) Printing Time against different parameters

Similarly, (also in Figure *25*) Layer height is the only significant factor in case of printing time. Material is overall stagnant in most of the conditions. R-sq value suggests that the factors contribute to more than 80% of the responses and it's quite justified in both experimentation and validation phase. Printing time has got some decreasing trend when going from layer height 0.1 to 0.3 mm but for build orientation, first increasing then decreasing trend which clearly specifies that at the inclined position the time has been consumed much due to the added support structures for its stability.

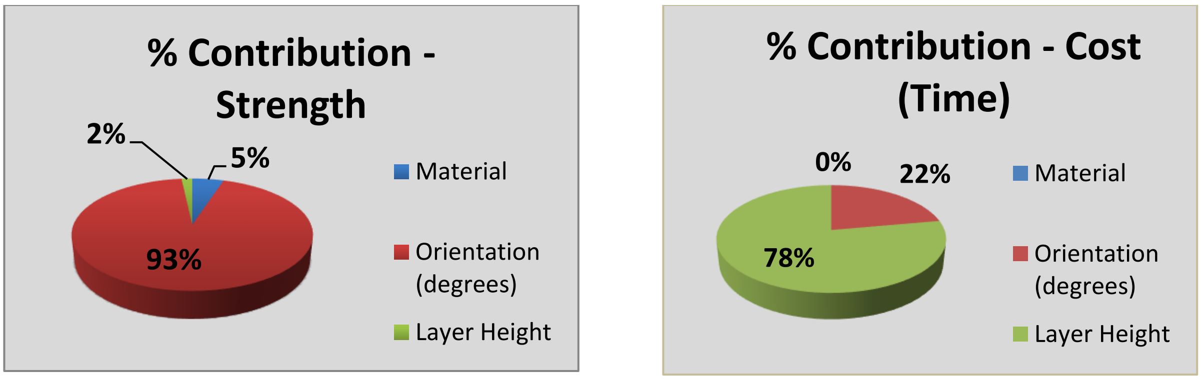


Figure 26 : Pie Chart Illustration for Overall Strength & Printing Time

Pie chart (in Figure 26) illustrates the contribution % for each of the factor. Orientation affects more than 75% of the total variation among the selected parameters. It has been displayed here just to obtain a summarized finding of all the work done. It is worth noting here that layer height that is of least significant in case of strength is of paramount consideration in economics i.e., printing time. Another take-away point here is that in both modes of loading either flexural or compression build orientation is of paramount consideration. Effect is dominant in both of the modes. However, in compression mode, when considering economics only, then layer height contributes to 78% which is relatively a high value in this regard.

5.2 Multi-Objective Optimization

For final optimization goal, Multi-Objective Optimization was carried out using Minitab software. It could be seen that values against which the optimization could be achieved were explicitly deduced. These are somewhat the expected optimized values of compression and flexural mode.

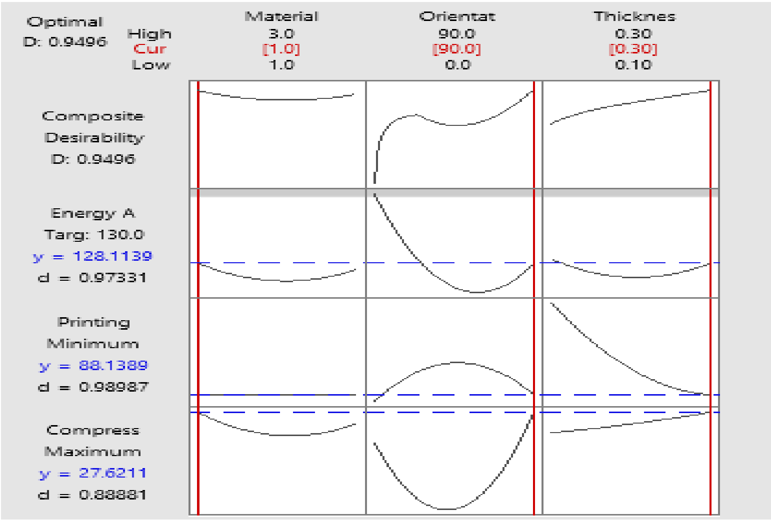


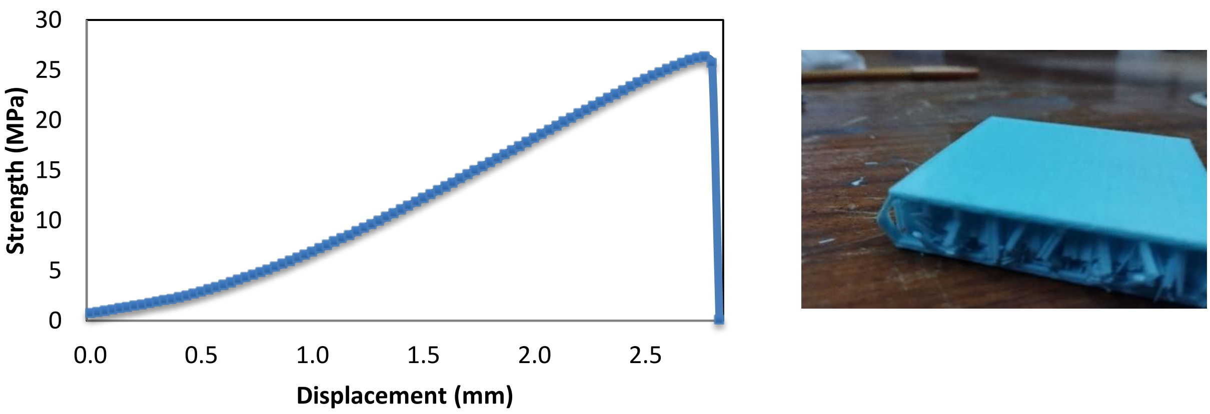
Figure 27 **:** MOO (Response Optimization)

Multi-Objective Optimization is shown in Figure *27*. Here it demonstrates the optimum parameters for the compression testing. It is quite vivid that ninety-degree orientation and layer height of 0.3 mm are the optimized conditions aiming to maximize strength and minimize the printing time. The curves of this optimization clearly illustrate that material is somehow constant or minute depression is being observed. But for orientation, steep slope is observed which illustrates strong relation of this parameter on strength and also on printing time. At last, layer height has got some curves quite significant for printing time but less vivid for the strength case. Based on this optimization run, samples were printed again and tested on the same previous conditions mentioned earlier.

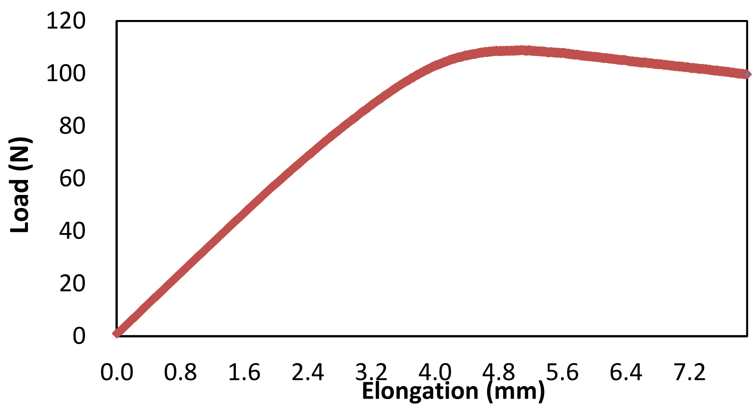
5.3 Validation

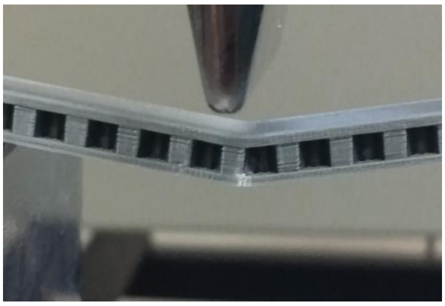
To validate the ANOVA results, the optimized samples obtained have been also tested and analyzed. For this purpose, three samples of each mode of loading were printed first on the same parametric values that have been obtained by MOO. Later on, these were tested on the same previous standards. Their average values were taken in order to converge the results. For better accuracy, it is of paramount importance to run the experiments on more than one sample. Finally, experimental results obtained were compared to that of theoretical results.

The same printing parameters were chosen in order to ensure the conformance in the experiments. Bed temperature, printing speed and extruder temperature were also kept same. Loading conditions were also similar so that minimum variance could be obtained between the initial and final experiments. This was also the reason to go for three samples in each mode of loading an taking their mean average values to determine the optimum values of the compression as well as flexural mode of laoding.



(a)





(b)

Figure 28: Optimized a). Compressive & b). Flexural load displacement curves

In the above figure, it was tested that the same optimized parameters for the compression strength that were deduced through optimization would also be verified experimentally or not. Upon testing the printed compression samples, it has been observed that no any significant changes in the load-displacement curve. Similarly same conditions were also applied for running the flexural testing. This time three samples were repeated for the testing in order to compensate any built-in issue or bugs in the material or testing apparatus.

Table 8

Comparison of Finalized Results

S.no	Mode of Loading	Predicted Failure Load (N) based on ANOVA	Actual Failure Load(N) Based on Experimentation	% Difference
1	Compression	69,020	65,950	- 4.44%
2	Flexural	106.13	108.93	+ 2.63%

It is noticed that there is a minute variance or difference among the results deduced from compressive optimization study and the experimental testing. However, flexural optimization results were true depicting the experimental investigation. As could be seen clearly from the

Table 8 that experimental testing of PLA+ somehow overshoots the multi-objective optimization results. The added advantage of enhanced ductility in PLA+ material improves its strength considerably.

It could be seen clearly from the Table 8 that experimental testing of PLA+ somehow overshoots the multi-objective optimization results. The added advantage of enhanced ductility in PLA+ material improves its strength considerably. But as for compression mode, due to inherent brittleness of PLA, it was unable to resist the load further and tear down suddenly as can be demonstrated in graph (Figure 28). The flexural loading of PLA+, however, is extended due to the reasons mentioned above.

Chapter 6 : CONCLUSIONS & RECOMMENDATIONS

In this present study, the compression and flexural responses of 3D printed honeycomb samples were experimentally investigated and optimized. The investigation examined the impact of honeycomb sample layer height on the compressive and flexural characteristics of sandwich constructions consisting of pure PLA, ABS, and PLA+. Additionally, the effect of the honeycomb cores' construction orientation—horizontal, inclined, and vertical—on the samples' mechanical characteristics under both loading modes was investigated. The following succinctly sums up several significant conclusions:

- The result stats presented that the compression and flexural strength of the samples surged to **8% and 17%** when PLA+ material was being used instead of ABS and PLA. This is due to the fact that PLA+ has improved toughness as compared to PLA conventional.
- In the printing of layers at the vertical i.e., 90° build orientation of the honeycomb core, the compression properties are dramatically improved **up to 37%** when compared to 45° build orientation. compressive Force up to 69,000 N could be bearable in this condition.
- The lesser layer height and build orientation of 45°, the printing time as well as manufacturing cost is maximum. In contrast to the build orientation, for the maximum compression strength and load of the sandwich structures are not dominantly changed by altering the honeycomb layer height.
- It was also deduced that by printing the core structure form inclined orientation to horizontal orientation, the flexural strength and the energy absorption were also enhanced significantly **More than 76%** increase in the strength was noticed when printing in the upright orientation Bending force up to 109 N could easily be withstand if three-point loads are applied.
- The experimental testing of optimized samples proved that their flexural and

compression strengths correspond to the optimized one. However, a bit variation around 2-5% in optimized and actual tested samples could be due to warping and poor adhesion defects among printed layers.

This article provides valuable insights for assessing the best possible fabrication parameters for honeycomb structures with much reduced economics plus time consumption. Ultimately contributing to aerospace industry for vital enhancement of their additive manufacturing processes. There are however, many prospects still unexplored in this area including the results of simulated / experimental studies on other fabrication parameters of honeycomb cores for assessing the energy absorption or toughness criteria with advanced polymeric and composite materials.

Future Recommendations

This work has many domains for expansion and can form the basis for future research. Following vistas of exploration are highly recommended for future study:

1. Finite Element Analysis (FEA) approach for the investigation of compression and flexural strength based on the available data presented in the current research.

2. Formulation and execution of other Additive Manufacturing (AM) technologies like SLA, SLM, LOM etc to check and analyse the responses of the chosen samples.

3. Advanced materials and metals that are currently fulfilling the needs and resources of the modern aerospace technologies in order to minimize the reliance on conventional materials and manufacturing techniques.

APPENDIX A

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APPENDIX B

Relevant Figures

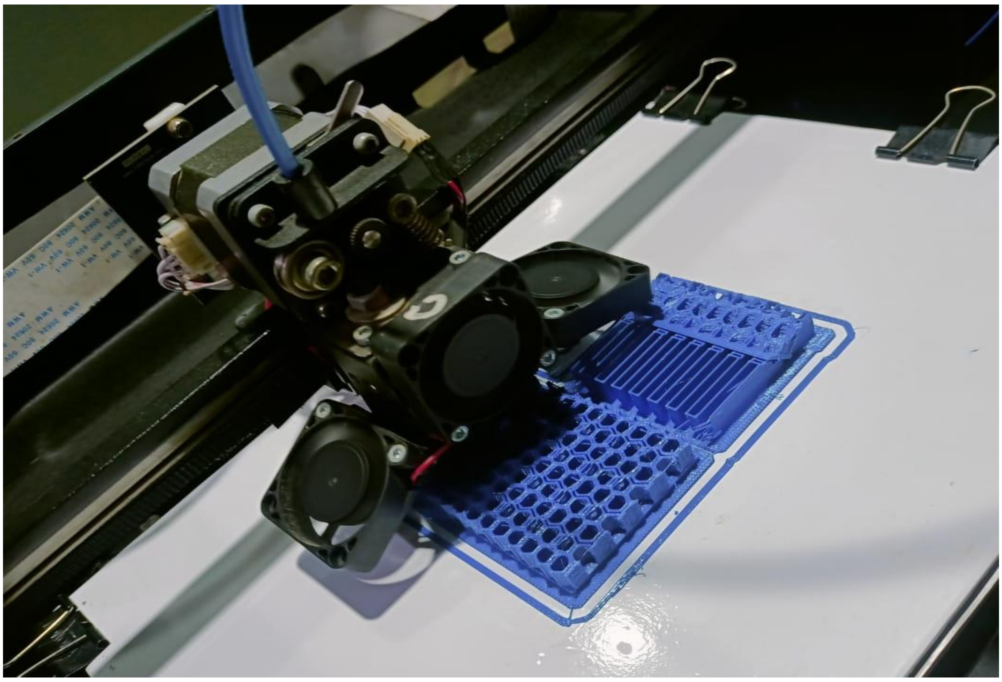

Figure 29: FDM Set-up

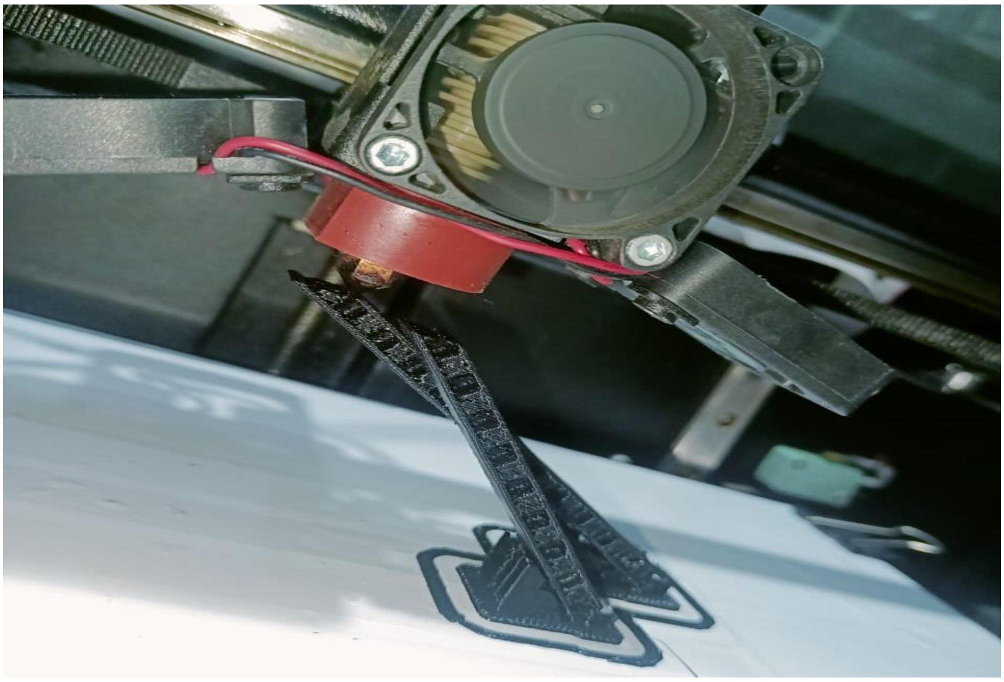

Figure 30: Printing at Inclined Orientation

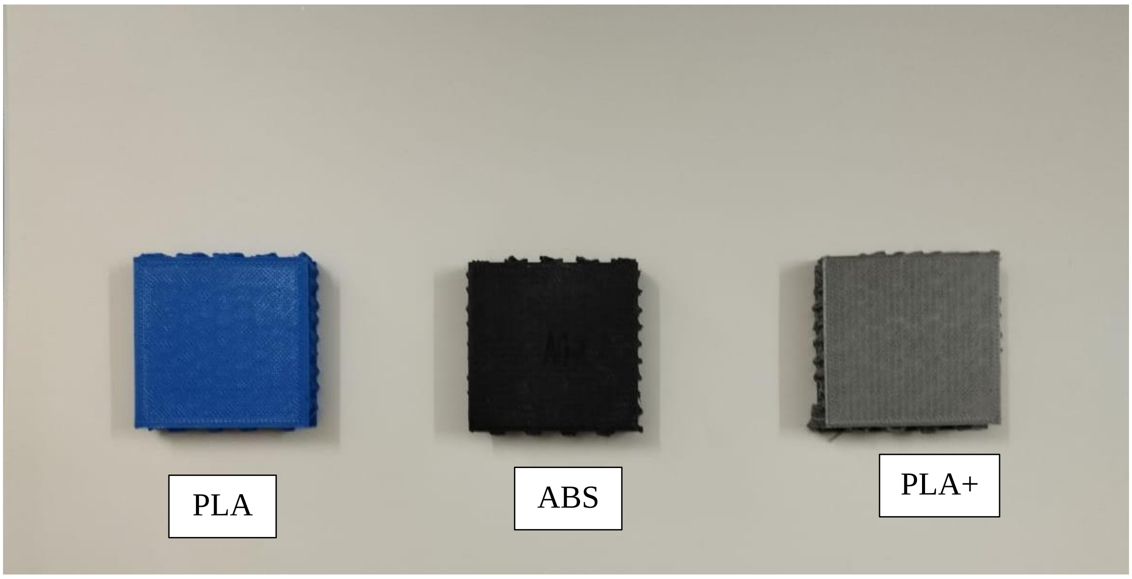

Figure 31: Compression Samples: PLA, ABS and PLA plus

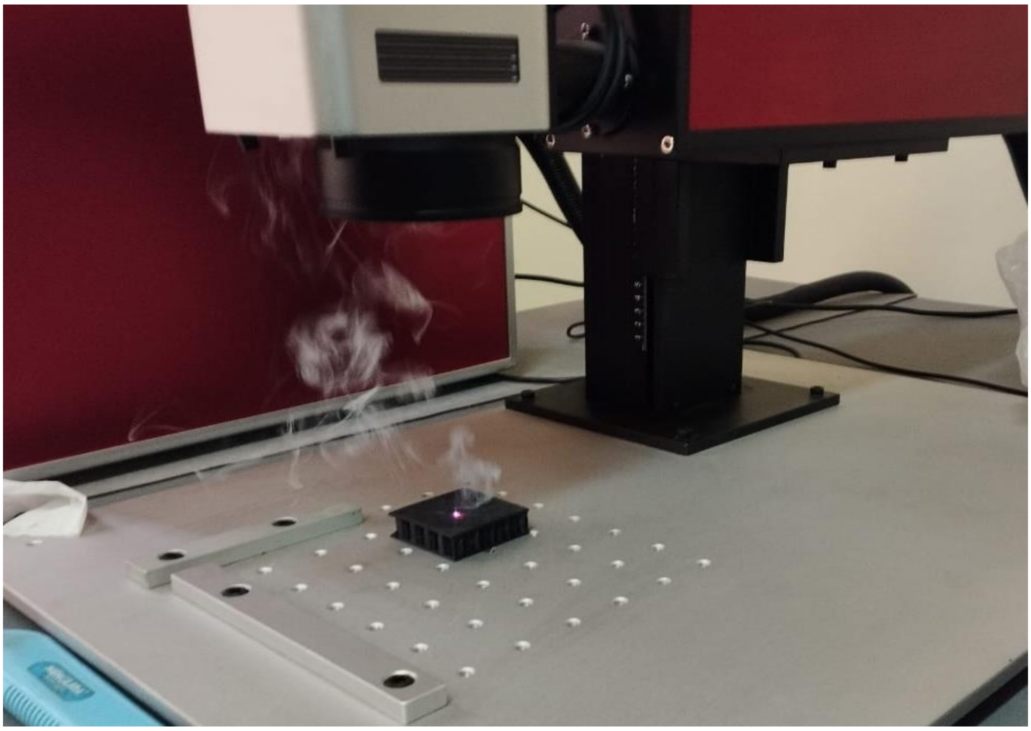

Figure 32: Laser Engraving U/P

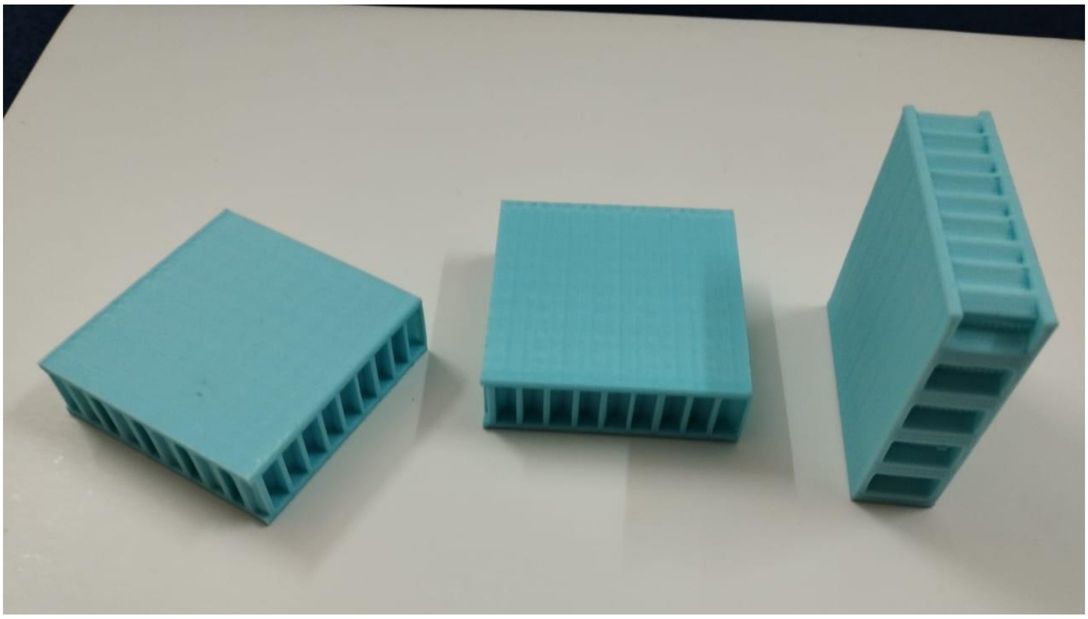

Figure 33: Optimized Compression Samples

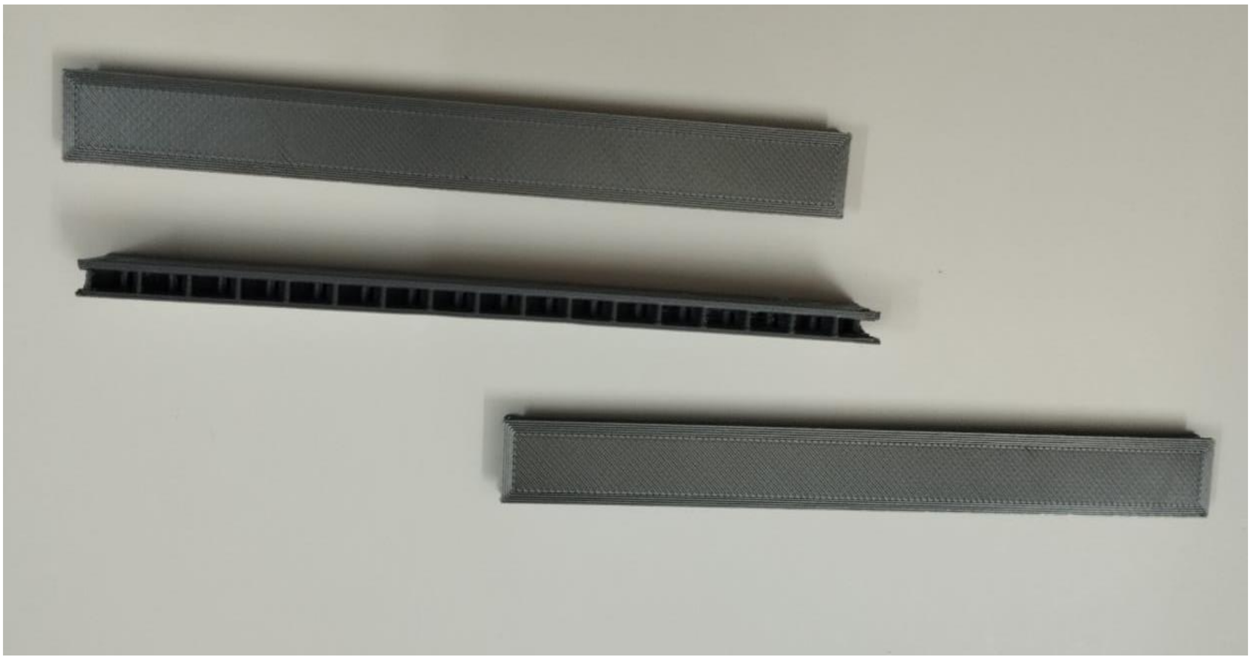

Figure 34: Flexural Samples – Optimized