Investigating the effect of various cellular configurations and geometrical parameters on the strength-to-weight ratio of honeycomb cores designed for Additive Manufacturing.

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A thesis submitted in partial fulfillment of the requirements for the degree
of MS Design & Manufacturing Engineering

Thesis Supervisor:
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Acknowledgments

Indeed, nothing is possible unless ALLAH ALMIGHTY wills to do it. 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 for 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.

I am profusely thankful to my supervisor Dr. Muhammad Salman Khan for his support and guidance throughout my thesis. His concern for my thesis and his interest kept me going and through his inspiration, I have been able to achieve this milestone. I am thankful to Dr. Rizwan for the technical assistance and guidance he provided. I am thankful to Mr. Ali Imran whose support led us to do the experimental testing of the honeycomb samples. I am thankful to Mr. Abdul Moiz and Mr. Sajid for their support without which it would not have been possible to do all the tasks necessary for this dissertation. Last but not least I am thankful to my classmate Mr. Muhammad Fahad Rashid for his support in my optimization, his valuable input made it possible to complete my thesis. I am thankful to all the people who have been associated with me and have helped me directly or indirectly to complete this thesis work.

Dedication

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

Abstract

Different industries, mostly aerospace and automotive, focus on designing components to increase their strength-to-weight ratio and reduce manufacturing times. Honeycomb structures are the most suitable solution for this demand. The different researchers made a bulk of investigations mainly focused on evaluating and analyzing the different cellular configurations. Also, additive manufacturing (AM) is becoming their 1st choice to print these honeycomb structures. The honeycomb structure's geometrical parameters i.e. cell wall length, cell wall thickness, and height are critical factors and greatly affect its strength. In the presented investigation, 48 honeycomb structures of different cellular configurations including hexagon, over-expanded hexagon, and square shape by varying geometrical parameters were manufactured using FDM (fused deposition modeling) including 16 samples of each shape. We obtain a new degree of control over the cellular architecture of honeycomb structures by utilizing cutting-edge AM techniques, which improve mechanical characteristics and reduce weight. The material used for printing these samples is PLA+. Testing was performed using out-of-plane loading to investigate the structure strength and analyzed using Taguchi and ANOVA (Analysis of Variance). Four levels of each i.e., the height of core 12.7, 25.4, 38.1, and 50.8mm, cell wall length 3, 6, 9, and 12 mm, and cell wall thickness 0.5, 1, 1.5, and 2 mm are considered for designing and printing samples having 80x80 mm cross-sectional area chosen by following ASTM C365 standard for compression testing. Moreover, multi-objective optimization is performed to optimize the strength-to-weight ratio and manufacturing cost using the Taguchi method. Hexagonal cellular configuration is selected to have better configuration than square and over-expanded because hexagonal shape structures are less costly have less printing time, contain less weight, give better strength-to-weight ratios, and prove more economical than others. And optimum geometrical parameters resulting from ANOVA for hexagon shape are the height of core 12.7 mm, cell wall length 6 mm, and cell wall thickness 1mm to increase strength-to-weight ratios and reduce manufacturing cost. Thus, it would be fruitful to develop more economical structures or components with less weight and high strength that are undergoing compression loading.

Key Words: 3D printing, Fused Deposition Modelling (FDM), honeycomb structures, compression loading, strength optimization, ANOVA, Taguchi analysis.

Table of contents

List of Figures

List of tables

Chapter 1: Introduction

1.1 Background

The compression resistance and shear strength of honeycomb structures are often higher. The structure's isotropic geometry and hexagonal lattice compactness allow for minimal material use. The narrow vertical walls next to each other contain hexagonal cells. The very compressible structure is a result of its geometric design, which results in very low density. Among the many uses for honeycomb structures are paper-board packaging, aerospace, the medical field, snowboards, and many more [1]. Honeycomb structures are advantageous due to their lightweight, resilience, resistance to fire and high temperatures, and lack of susceptibility to moisture. The honeycomb construction has a continuous and isotropic lattice pattern, which requires a long time to manufacture and results in a very high manufacturing cost when compared to alternative infill structures. Despite the large number of studies investigating the mechanical properties of honeycomb structures by varying cell thickness and edges, there are few studies on the compressive properties of honeycomb structures. The introduction of additive manufacturing (AM) innovations has caused a stir in many sectors because they provide novel, inexpensive, and efficient ways to create complicated structures with improved mechanical characteristics.

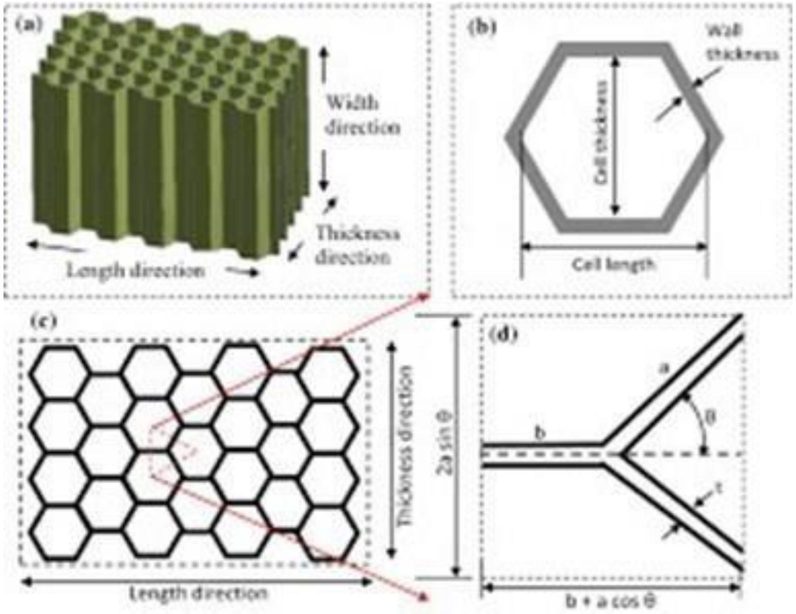


Figure 1: Honeycomb Structure

More and more people are interested in energy-absorbing structures as a result of developments in manufacturing technology [1]. Structures like these are typically purposefully shaped parts made of various materials (e.g., metals, polymers, or foams) to absorb and distribute as much externally supplied energy as possible by plastically changing it into internal energy. That is why components that soak up energy lessen the load on the protected buildings. The key characteristics of these elements are their great plasticity and deformability as well as their high stiffness-to-density and mass-to-density ratios [2]. Many sectors, including defense, transportation, aviation, and the automobile industry, make use of energy-absorbing structures because of their many benefits. The behavior of a structure's crashworthiness is significantly impacted by the geometrical aspects of its topology. Elementary cells that are joined and repeated at regular intervals make up the most common regular cellular structure topologies. In engineering, irregular materials like foam can also be thought of as components that absorb energy. More intricate and accurate energy-absorbing structural designs [3] are now within reach, thanks to the rise of additive manufacturing and the widespread use of 3D printing and laser melting. It is possible to study the crashworthiness of cellular structures by analytical methods, experimental procedures, and computational models. For basic cellular topologies (such as circles, rectangles, triangles, and hexagons), analytical approaches can be used. Although experimental methods yield precise findings, they are labor intensive and costly, particularly when cellular structure samples are made from metal or ceramic powder. One of the many applications of numerical simulations is the investigation of intricate cellular topologies. Research has also focused on several cellular structure topologies that exhibit negative stiffness. Walls in such a construction experience elastic buckling instead of fracture, allowing it to return to its original shape following deformation. Negative Poisson ratios are indicative of another kind of cellular structure. For instance, even when subjected to significant plastic deformation, the utilization of two distinct materials in a single construction as demonstrated in reference [3] maintained a steady negative Poisson's ratio. Consequently, it is possible to create structures with consistent geometry and a range of auxetic features.

FFF production can benefit from PLA, a novel biodegradable polymer with high ductility and thermal stability. In addition, PLA's high specific stiffness and specific strength make it an ideal material for producing lightweight structures, and the material's good mechanical and physical qualities make it useful in many other contexts as well [4].

1.2 3D printing technology

The method relies on the additional substance assembly process, which involves building things up layer by layer across a cross-area layer arrangement. When it comes to making components for durability this layer assembly is often associated with Rapid Prototyping technology.

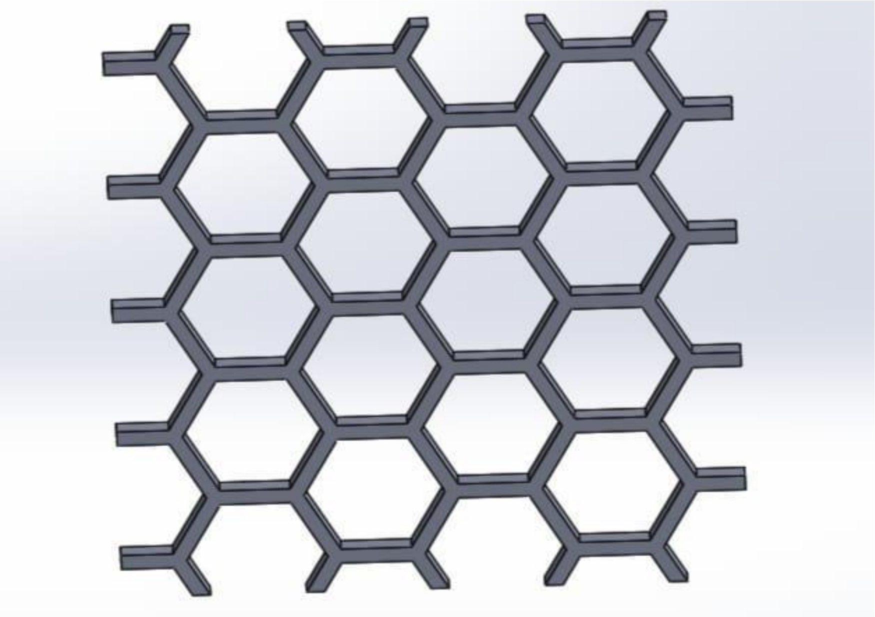


Figure 2: 3D Model

The process of 3D printing is quite like that of laser or inkjet printers; both employ feed material such as powder or granules to construct an image or structure layer by layer. With the use of 3D printing technology, buildings may be built from digital models instead of relying on labor-intensive and expensive manufacturing processes [5]. Growing numbers of businesses in the food, medicine, transportation, aerospace, and civil engineering sectors are putting this technology to use for mass customization and the creation of intricate patterns. Compared to traditional production processes, 3D printing is more environmentally friendly and economical since it deposits materials precisely where they are required. When applied to production processes, lean parametric design can save time, money, and resources; when used to 3D printed structures, components can intelligently integrate climate, cultural-aesthetic, and structural efficiency; and when assembled into large-scale structures, prefabricated integrated

3D printed elements can be assembled using state-of-the-art mass customization principles. To the point when 3D printing can produce large-scale, fully assembled structures, all of these developments are required. In the building and architectural industries, parametric design has been used previously. [6]. The use of parametric design in conjunction with 3D printing technology to construct architectural buildings, however, remains untapped. By combining these two techniques, the visual and tectonic attributes of professional handicrafts from bygone eras can be re-created in each architectural component, including outside walls, interior partitions, and interior walls.

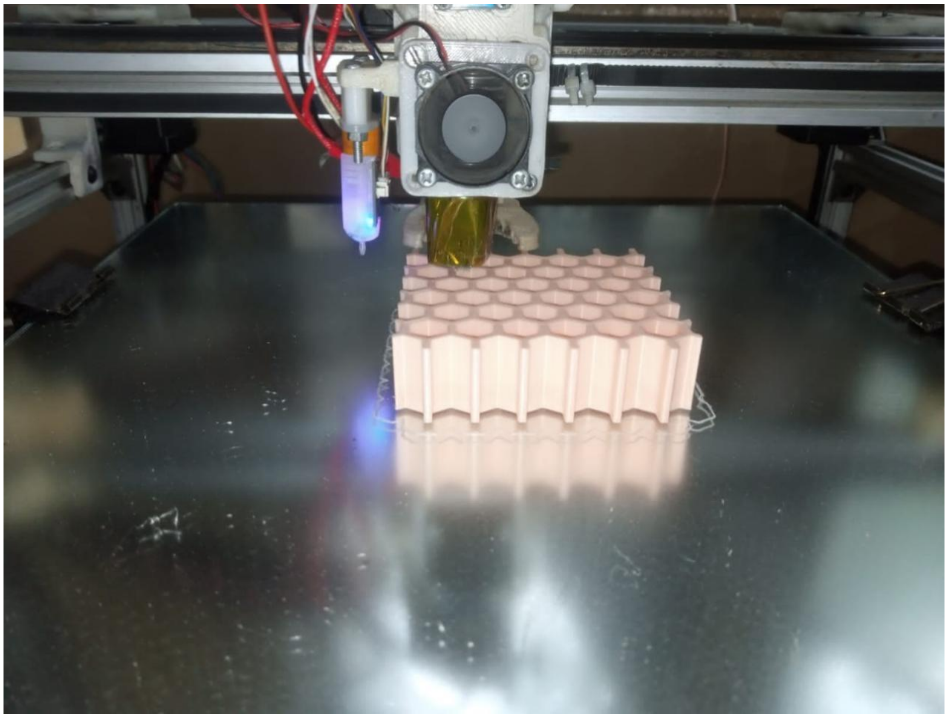


Figure 3:3D Printing Machine

1.3 3D printed objects' compression behavior and energy absorption

Researchers are now concentrating on creating cellular structures with low weight and great mechanical strength in response to the growing need for environmentally friendly product development. Traditional manufacturing processes like casting, machining, and forming might not be the best fit here due to the increased time and specialized tools needed to fabricate such intricate structures [7]. These production procedures have developed into the additive manufacturing (AM) method over the years, and it is an effective fabrication technology for rapidly creating items with complicated shapes. Fused deposition modeling (FDM), one of the most well-known additive manufacturing (AM) techniques, deposits layers of polymer materials in a temperature-controlled chamber to enable the creation of functional prototypes [7]. It is essential to comprehend the connections between process parameters and their properties to enhance the functional quality of the FDM printed prototypes. Developing new materials with better characteristics than conventional materials is one way to accomplish this, but it requires a thorough understanding of material science. Another feasible approach is to adjust process parameters during fabrication to improve the properties of the fabricated prototype.

In the aerospace, marine engineering, and transportation industries, lightweight cellular structures inspired by natural materials are being used more and more as the primary load-bearing and protective members due to their high specific stiffness/strength, excellent energy absorption capacity, and significant thermal insulation. [8]. A cellular structure's macroscopic performance can be fine-tuned by manipulating its microstructure and raw components to reduce high stress caused by external loads, these cellular architectures are typically designed to accomplish super energy absorption by transferring external work onto internal energy of the framework through easier plastic deformation [8,9]. In recent decades, a vast array of cellular topologies, such as chiral, hierarchical, bending, honeycomb, and combination structures, have become available. A novel quick prototype method called additive manufacturing, also referred to as 3D printing, makes it possible to create cellular structures with spatially customized material properties and geometries. With the use of 3D printing, designers may realize their visions of geometric shapes with endless possibilities for geometric design freedom and multi-scale molding capabilities. The rapid production of metallic honeycomb and truss structures using 3D printing has attracted a lot of interest and research because they have great potential as lightweight, energy-absorbing products. Considerable research has also been done on the advantages of 3D-printed polymer cellular architectures.

1.4 FDM (fused deposition modeling)

The most recently commercialized RP approach is fusion deposition modeling or FDM. High performance thermoplastics like ULTEM 9085 have been used by FDM to find applications in fixtures, jigs, check gauges, and aviation parts. Every day, discoveries are made. A portion of the method is breaking up the entire model into layers and then printing each layer independently. Thermoplastic filaments are the first step in the FDM process. Filaments are heated in the nozzle and deposited onto the printing plate layer by layer to generate the desired three-dimensional shape. Nowadays, low-volume manufacturing prototypes are built using FDM. Recent FDM research has focused on Unmanned Air Vehicles (UAVs) and other real-world constructions with lower mechanical stress needs [9]. Fused Deposition Modelling is one of the most widely used additive manufacturing (AM) processes because of its versatility, affordability, and ability to produce functional prototypes and finished products using thermoplastic materials. The capability of FDM technology to create strong, lightweight structures has attracted a lot of interest in fields including aircraft, renewable energy, marine, and automobiles. Honeycomb structures can be easily manufactured with FDM, which is a major innovation. Taking design cues from the topologies of living cells, honeycomb structures are incredibly strong and lightweight, making them perfect for uses where minimization of weight is of the utmost importance without sacrificing structural soundness. Sandwich panels, structural reinforcements, thermal insulation, and aerospace components are among the many uses for these structures.

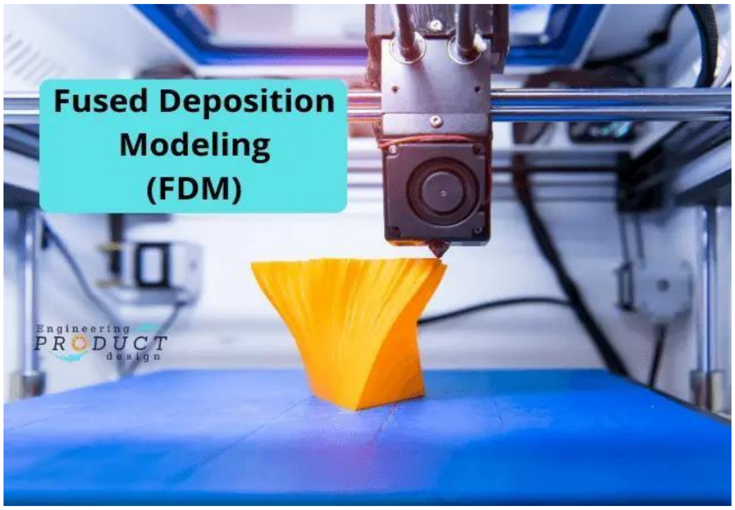


Figure 4: Fused Deposition Modelling (FDM)

1.5 Mechanical Properties

The shape, size, and placement of the cells in a honeycomb structure greatly affect its mechanical qualities. Extensive research has been carried out by researchers to optimize honeycomb designs to fulfill performance criteria. The literature is deficient in its description of the effects of cellular configuration on the mechanical characteristics of FDM honeycomb structures under compression force. It may be difficult to optimize the printed structure's mechanical qualities while simultaneously controlling costs and time constraints [10]. Therefore, it's crucial to examine the mechanical characteristics of the 3D-printed structures to determine their dependability for different industrial activities. And there are a lot of 3D printing settings that have an indirect or direct impact on the material's mechanical qualities. For example, the strength and stiffness could be enhanced by increasing the infill density, but the material consumption and cost would also increase. Therefore, the purpose and function of the 3D-printed components should inform the optimization process. Moreover, even a small adjustment to the 3D printing conditions will produce vastly different outcomes for material tests like tensile tests.

1.6 Statement of the Problem

Higher stress levels can lead to the emergence of flaws and anomalies in the industrial design process and a product's functioning life cycle. Researchers have focused a lot of attention on the difficult challenge of striking a balance between a structure's capacity for interim repairs and its energy absorption efficiency in recent years. Honeycomb structure and FDM technology are both widely used, however, there hasn't been much investigation into how cellular arrangement affects the mechanical behavior of honeycomb structures produced using FDM, especially when subjected to compression loads. It is essential to comprehend how different cell geometries and structural features impact the strength-to-weight ratio, material consumption, and manufacturing time to optimize the design and fabrication process of honeycomb structures using FDM.

1.7 Research Aim and Objectives

The primary goal of this research is to investigate how cellular layout and compression loading impact the mechanical properties of FDM honeycomb constructions. Using Fused Deposition Modelling (FDM) technology, this research aims to develop and produce various honeycomb structures. Then, they will be tested for strength by compression testing. This research endeavors to determine the best honeycomb core structure and geometrical parameters to get the best possible performance and find the most practical uses for them.

Here are a few important points:

- The goal is to learn about and experiment with various honeycomb core structure cellular arrangements, including square, hexagon, and over-expanded hexagon.
- Determine the cell size, weight, height, material, and sheet thickness as well as the other design parameters for the honeycomb core structures.
- Structures were developed using FDM, an additive manufacturing process.
- By evaluating the compression properties of three different printed structures, the honeycomb structures that show the best strength-to-weight ratios under out-of-plane compression stress will be found. Analyzing results using ANOVA and RSM helps achieve a superior strength-to-weight ratio.
- Simulation of optimized results and validation through experiment

1.8 Significance of the Study

Due to its many useful characteristics, the honeycomb structure is an important area of study. The significance of honeycomb structures of hexagonal shape is demonstrated by the extensive research conducted on them. Therefore, this research will examine changes to hexagonal shapes, as well as over-expanded hexagonal, squares, and basic hexagons. Compression analysis of certain cellular configurations in honeycomb structures made using the FDM technology will be the sole focus of this work. Both academics and industry recognize the value of this research. Contributing to the improvement of additive manufacturing techniques and structural optimization strategies, this work investigates the connections between cellular configuration and mechanical properties of honeycomb structures made using FDM. The results will be helpful for those working in the design, engineering, and manufacturing sectors of the automotive, aerospace, and other sectors that require strong, lightweight structures. In addition to bridging a significant knowledge gap, this study will set the stage for future investigations and advancements in structural design and additive manufacturing.

1.9 Structure of the Thesis

There are five primary sections to this thesis, and they all deal with distinct parts of the research:

Chapter 1: Introduction

This chapter presents the general ideas around the research topic, describes the problem area under study, and gives an account of the objectives and importance of the study, as well as its coverage. It forms the background to the whole thesis by establishing the research questions or hypotheses and offering a background to the research.

Chapter 2: Literature Review

In this chapter, you also present a literature review concerning the findings of previous studies on your research subject. It entails the examination of earlier research work, examining the literature and research problems to ultimately explain the contribution of your research to filling the gaps in the literature.

Chapter 3: Methodology

This section outlines the research proposal in terms of its design, methods, and procedures needed for the completion of the study. Therefore, it highlights how data is gathered, the sampling method used the tools or instruments that are used, and data analysis.

Chapter 4: Results and Discussion

This chapter contains the result, conclusion, or recommendation on your research. It entails quantitative and/or qualitative analysis of data collected as well as the discussion of the results obtained against the background of the research questions/hypotheses postulated.

Chapter 5: Conclusion and Recommendations

This chapter, as the final one, involves the synthesis of the major findings, the conclusion, and the response to the research questions. Also, the disclaimer of this section may include future directions for research, policy relevance, or applications as dictated by the results of the study.

Chapter 2: Theoretical Background

2.1 Literature Review

A study is conducted to investigate the numerical and experimental responses of various types of cellular structures to compression loading. The Honeycomb, Modified Honeycomb, and Spiral type topologies were selected for further study. The structural characteristics for each topology are examined in addition to the structures for the variable-size cells. The evaluation used a universal compression test to pressurize the specimens at various pressures to ascertain the mechanical characteristics of the materials and the amount of energy absorbed. For this reason, the implicit data processing technique was also used to ascertain the mechanical characteristics of the cellular structure. Simulations and testing show that a cellular shape with honeycomb geometry has a higher energy-absorbing capacity than any other rule-based architecture. Also, the statistics indicate that a construction's cell size increases with decreasing energy-absorbing capacity. Fused Deposition Modelling (FDM) is a highly versatile technique for producing intricate parts due to its many advantages, such as its fast-prototyping speed, low cost, and ability to be adapted to specific requirements. A numerical analysis of 3D-printed sandwich structures is included in the article's header. After the primary and zigzag bases of the buildings were designed, they were completed in either polygons or cells. Initially, the hardcore used the commercial finite element tool Simulia-Abaqus to do the numerical simulation. Thus, the study finds that the structural geometry and material density are the primary determinant elements influencing the intensity of the absorbed energy [18]. It is quite easy to provide a solution pattern that distributes the filler within the cell while also incorporating a structural unit with the appropriate variational honeycomb infill. The proposed infill structures and the honeycomb pattern are tested for plastic compression using the same call with striating and uniform patterns. The unified test samples that were suggested, consisting of two-dimensional patterns that are both uniform and variational, outperformed their traditional counterparts in terms of energy absorption specific to the X direction, elastic modulus, and collapse strength. The issue with this method is that the computed values for the patterns the scientists suggested drop as one proceeds from the X-axis to the Y-axis. Our findings are in line with those previous studies [20] as they resulted in two different materials (PLA and TPU).

This study lays forth a method for describing the dynamic behavior of this material that was made using Fused Filament Fabrication (FFF). Findings demonstrated that infills of varying densities, both low and high, were less expensive than solid samples. In comparison to regular hits, the material's dynamic behavior was significantly altered by the repeated impacts. Dynamic characteristics (e.g., dynamic modulus, maximum stress, etc.) drastically dropped as the number of impact loadings increased leading up to failure, and the material experienced catastrophic cumulative damage [22]. This study aims to gain a better understanding of mechanical behaviors, economic benefits, and environmental impacts by conducting compression tests and life cycle cost assessments. To compare the load and weight relations of all constructions, compression tests were performed on an Instron test platform, and the data was gathered. A thorough mechanical inventory will be made available for product design and manufacturing because of the research. Furthermore, this research finds openings for additive manufacturing infill pattern design that is more resilient [23]. Analyzing hexagonal honeycomb structures made in SolidWorks and manufactured using the FDM additive manufacturing technique is the focus of this research. The honeycomb structures can be customized to different dimensions. The designers created these buildings by manipulating the inner hexagon's side length and wall thickness. Results from the experimental and computational simulations of the three-point bending test were compared. Compared to the other specimens, the lightweight one printed faster while still showing good mechanical and thermal qualities, according to the experiments. The specimens with varying hexagonal cell diameters were presented and examined in detail [24]. The energy absorption and durability of a honeycomb structure printed from polycaprolactone in three dimensions are the main topics of this research. Honeycomb structures were studied mechanically by conducting in-plane quasi-static compression measurements. The selected stepping upward stress was used to investigate the energy absorption capabilities and efficiency at various temperatures and loading orientations [28]. Using continuous fiber additive manufacturing as its foundation, this study proposes and presents the performance of a lightweight CCFR (Continuous Carbon Fiber Reinforced) composite honeycomb under in plane compression. Experimental results of honeycombs made of various materials show that carbon fiber can alter the deformation characteristics of structures and improve their mechanical qualities [30]. You can change the stiffness magnitude by adjusting the cell size and wall thickness of TPU honeycombs, however you can only slightly change the stress-strain curve shape. Beyond the limitations of flat surfaces, 3D printing allows for the investigation of complex geometric forms. Research has shown that the buckling behavior of tubular structures can be affected by origami fold patterns [31].

2.2 3D Printing Technologies

Sandwich structures made from polylactic acid (PLA) material with honeycomb and rhombus core forms fused using an FDM 3D printer are the subject of this study's mechanical characteristics analysis. First, shape evaluations were used to quantify the functional aspects of the sandwich constructions. In our attempt to find out how well the samples mechanically performed we ran a series of tensile, three-point bending, and compression tests on them [15]. The current paper has results on a setup of investigating the effect of two different 3D printing technology parameters (number of shells: 2, 10) as well as on a subset of mechanical qualities on one of the parameters mentioned earlier. Two distinct specimens made of the same material (PLA) were printed using the Fused Deposition Modelling (FDM) 3D printing technique. Tensile and flexural strength as well as the creep phenomena were chosen as standards in the context of mechanical features. The five-parameter Kelvin-Voight model explained the creep curve obtained from the conducted tests. Through it, we have achieved a great match for an engineering calculation based on our results as well. Our research principle is devoted to scanning the top layer of a hot plate 3D Ulti maker printer, which makes honeycomb structures out of PLA and ABS filament, and then we measure their maximum compressed force. Each cell had a different wall thickness and surface, and three sizes were incorporated into the honeycomb structure design, however, the surface area stayed the same. Experimental findings were fully confirmed by a comprehensive (FE) analysis, using ANSYS® software with three elements of composite beam with varying cell widths, and thicknesses.

Therefore, even though the cell width of honeycomb constructions with comparable surface areas may be increased using both the experimental and finite elements approaches, it was demonstrated that a thicker wall was directly proportionate to a higher maximum compressive force [17]. In this work, thermoplastic composite filaments reinforced with polylactic acid, polycaprolactone, and basalt fibers are proposed and developed for 3D printing. The results show that circular honeycombs constructed with PLA-PCL30/KBF filament have a better energy absorption capacity because of the matrix's ductility and strong interfacial matrix/fiber adhesion. Hexagonal honeycombs may absorb about the same amount of energy as re-entrant honeycombs. As a result, PLA-PCL/KBF composite honeycomb structures exhibit potential as an FDM feedstock for energy absorption [21].

2.3 Effect of Parameters

Using the Voronoi approach, we randomly generated honeycombs with different meso-structural characteristics and 3D printed them. A universal test machine was used to conduct quasi-static compression testing. The findings showed that, in contrast to the regular honeycombs, the random honeycombs deformed more uniformly, resulting in a mild stress-strain curve. Based on the 1D shock wave theory and the Johnson-Cook material model, an empirical model was given that incorporates the state of inertia effect and strain rate effect of the base material [12]. Thermoplastic hexagonal honeycombs constructed of PET-G and ABS are 3D printed and placed inside thin-walled windowed metallic tubes to create hybrid specimens. Test results show that samples with a polymer core had better performance parameters than empty samples when subjected to out-of-plane quasi-static axial loading. After optimizing the sample, it was built and tested for axial compression to confirm the results of the optimization. Under these circumstances, this geometry proved to be the best option, as the optimal sample matched the estimated parameters in terms of performance [13]. A 3D printing process known as Fused Deposition Modelling (FDM) involves heating the material and then extruding it layer by layer through a nozzle. The FDM method of 3D printing provides more flexibility than more conventional methods, such as injection molding. A Stereolithography file (.stl) is created from the model of the specimen in the Solid Works modeling application. Using the same infill density and orientation, QIDI slicing software is employed. Unified Testing Machines (UTMs) are used to administer the test. We use infill structures such as tri hexagons, cubic, lines, cubic subdivisions, gyroid, triangles, octets, concentric, cross 3D, and grids. We did this to find out which infill structure and material is stronger and lasts longer [19]. To create bear-loading lattice structures, this research aims to develop biodegradable composite filaments based on PLA that can be 3D printed. The pore structure was found to be well-supported in TPMS-D but damaged in cubic structure as a result of vertical strut fractures. Consequently, this research emphasizes promising biodegradable lattice architectures that may be 3D printed. These structures have a high structural stability and a good capacity to absorb energy. Continuous carbon fiber-reinforced composites (CCFRC) made using fused filament fabrication (FFF) technology allow for the creation of sandwich structures with high mechanical performance. Manufacturing voids, because of insufficient penetration between the reinforcement and the matrix, are mainly concentrated in the printed carbon fiber bundles, according to the results. Fiber pull-out and breakage, delamination, local core compression, fiber/matrix and panel/core debonding, and localized core crushing were identified as the primary failure mechanisms under these stress levels according to fraction graphic analysis [26]. The specific energy absorption under quasi-static loads is ranked according to the load-displacement behavior of five distinct configurations of 3D printable lattice core structures, which are examined in this thesis. To begin, the optimal cell dimensions for each configuration were determined using finite element analysis (FEA) approaches that were either elastic or elastic-plastic. The samples were printed using a Stratasys print machine that is based on fused deposition modeling. The five different lattice structure designs were tested under compression load after printing the samples, and the resulting load-displacement behavior was studied and compared [27]. Using fused deposition modeling in PLA, twelve samples were created for this paper, and numerical simulations in Abaqus/Explicit were applied to each of the samples. The work develops, studies, and compares two new hybrid structures to basic structures in terms of experimental and numerical mechanical properties. Minimizing material consumption during 3D printing can be achieved by modifying the internal structure of the produced objects [29].

2.4 Summarized Literature Review

Different research papers are summarized in Table 1. All these summarized papers helped us to find the direction for our work.

Table 1: Summarized Literature Review

Title	Methodology	Parameters	Results	Reference
Load Distribution on PET-G 3D Prints of Honeycomb Cellular Structures under Compression Load	in-plane compression tests	1.75 mm in diameter filament 0.19 mm is the layer thickness Angle of raster 45°; the temperature of platform 30° Honeycomb infill pattern	The construction showed an extension to delamination and fragmentation with the vertical printing direction and 100% infill density.	(Basurto-Vázquez et al., 2021)
Printing parameters and materials affecting mechanical properties of FDM-3D printed Parts: Perspective and prospects	Tensile power Flexural power The Young's modulus FDM	Rectilinear Grid, Triangle PLA printing temperature 215 ° are the infill patterns.	Appropriate adjustments to the printing parameters cause the tensile strength to rise dramatically and Young's modulus to rise simultaneously and independently.	(Doshi et al., 2022)
Parametric	Finite element	Length 160 mm	The square core	(Rajpal et al.,

studies on bending stiffness and damping ratio of Sandwich structures	method (FEM 3D printing and experimental testing.	breadth 25 mm thickness 6 mm	orientated at 0° exhibited superior stiffness in bending loads, and the hexagonal core orientated at 0° displayed an admirable combination of both stiffness and damping properties.	2018)
Influence of 3D-printing Parameters on Mechanical Properties of PLA defined in the Static Bending Test	48 specimens in a static bending test	0, 25, and 50% infill printing at 220°C, layer height of 0.1 mm, and cooling rate the strength of the sample is influenced by the 50% line orientation 45° or 90° infill pattern.	The sample's strength is influenced by the infill design; the 50% grid infill pattern and the 25% honeycomb infill have comparable maximum stress values and moduli of elasticity.	(Kołodziej et al., 2019)
Effect of Infill Patterns on the Mechanical Performance of	Uniaxial tensile loading Flexural loading both edgewise	diameter of 1.75 mm, dimensions 127 mm × 12.7 mm × 3.2 mm,	The findings demonstrated that the strength was enhanced by	(Lubombo & Huneault, 2018)

Lightweight 3D-Printed Cellular PLA Parts	and flatwise FFF	ASTM D790-10 (flexural)	up to 82% and the stiffness by up to a factor of 2. Similarly, at the same density, using more perimeter shells for the same infill pattern increased the strength and stiffness by up to 84% and a factor of 2, respectively.	
Effect of infill density and pattern on the specific load capacity of FDM 3D-printed PLA multi-layer sandwich	Tensile testing Finite element analysis Virtual bending tests FDM	print speed of 60 mm/s nozzle diameter of 0.4 mm filament diameter of 1.75mm filling ratios 40%, 60%, 80%, and 100%	The modeling outcomes showed that the maximum load capacity that the outer and inner layers can withstand is different (the outer layer is always weaker). Further, the load capacity efficiency increases at a filling density of 40% regardless of the filling pattern.	(Dobos et al., 2022)
Experimental analysis of 3D printed specimens with different printing parameters for	The Izod impact strength 60 test specimens of ABS	Dia of filament 1.75mm, ASA Nozzle Temp 260 (oC) ABS Nozzle Temp 250 (oC)	The study concluded that the Izod impact strength of the specimen manufactured with the ABS has	(Raut & Kolekar, 2023)

Izod impact strength	60 test specimens of ASA	Bed Temp 100oC, Nozzle Diameter o.4mm, Layer Thickness o.2mm, Printing Speed 100(mm/sec)	more strength than ASA.	
Investigation of the effect of FDM process parameters on mechanical properties of 3D printed PA12 samples using Taguchi method	Impact and tensile testing Taguchi (L8) Method of Optimization investigation using statistics and experimentation FDM	Diameter of filament (mm): 1.75 PA12 kind of filter Bed temperature (C) 100 Nozzle diameter (mm) 0.40 (mm) Extrusion width: 0.35 Printing rate: 4200 mm/min	Because of this, layer thickness—rather than extruder temperature, occupancy rate, or filling structure—is the most useful element for improving mechanical qualities.	(Kam et al., 2023)
Mechanical performance of honeycomb sandwich structures built by FDM, printing technique	Flexural, edgewise compression, Interfacial bond strength tests FDM	Nozzle diameter (mm) 0.75 Layer height (mm) 0.5 Printing speed (mm/s) 30 Fill density (%) 100	An optimum combination of materials is ABS core with composite face sheets having a raster layup of 0°/90°.	(Gohar et al., 2023)

Flexural Strength Optimization as Effect of Infill Pattern Variation in FDM 3D Printing of Multi-layers ABS- PLA	Bending test using ASTM D790 FDM	Filament Dia 1.75 mm, Layer Height 0.08mm, Bed Temperature 220oC Extrusion Temperature 230oC printing Speed 38 mm/s	Increase in the flexural strength value (in percent) using the infill pattern Archimedean chords (20.72%), concentric (14.02%), cubic (11.66%), Hilbert curve, and honeycomb (5.7%). There is a decrease in flexural strength value (in percent) using the infill pattern gyroid (4.34%), rectilinear (18.57%), and octa gram spiral (21.29%).	(Triono et al., 2023)
A Study on the	FDM	Cross-section 12.7	A maximum	(Baig,

Effect of Infill Percentage and Infill Pattern on the Compressive Behavior of the FDM Printed Polylactic Acid (PLA) Polymer		mm × 12.7 mm Shell Thickness 0.3 mm, Layer Thickness 0.3 mm Extruder temperature 220o C Bed Temperature 65o C	yield load of 7.03 kN was observed for a hexagonal pattern with 50% infill while a minimum of 4.58 kN was for the triangular with 25% infill	n.d.)2023
Analysis of compressive strength of printed PLA sample through FDM	Tensile test Taguchi's L9 orthogonal array FDM	Thickness 0.1, 0.15, 0.2, Feed Rate 20, 40, 60, Raster Angle 0,45,90, Infill Density 80% Nozzle, Temperature (0C) 210 Bed Temperature (0C) 60	The mechanical properties of the samples are most affected by layer thickness and printing speed	(Pachauri et al., 2023)
Impact of multiple infill strategy on the structural strength of single-build FDM printed parts	Uniaxial loading using PLA material. Comparative analysis of cost FDM.	The diameter of the nozzle is 0.4mm Extruder width 0.4 mm Layer Height of layer 0.2 mm Solid layers (top & bottom) 3 Perimeter/outline	Experimental results have shown that the combination of rectangular and triangular patterns gives a 13 %, 20 %, 27 %, and 4 %	(Sajjad et al., 2023)

		shells 2 The temperature of the extruder is 205 ◦C The temperature of the heated bed is 65 ◦C Layer-1 0, Layer-2 100. Printing speed (default) 3600 mm/min, Infill percentage 80 %	increase in strength-to-weight ratio compared to rectilinear, triangular, rectangular, and honeycomb individual infills, respectively.	

2.5 Research Gap

Despite the growing interest in additive manufacturing techniques, specifically Fused Deposition Modelling (FDM), for designing and manufacturing honeycomb structures, there remains a significant research gap concerning the comprehensive investigation and selection of the most optimal honeycomb core structures among honeycomb core structures of different cellular configurations based on various performance factors. This study will be based on comprehensive research evaluating the 3 different cellular configurations of FDM-printed honeycomb structures, by performing compression testing and considering different factors.

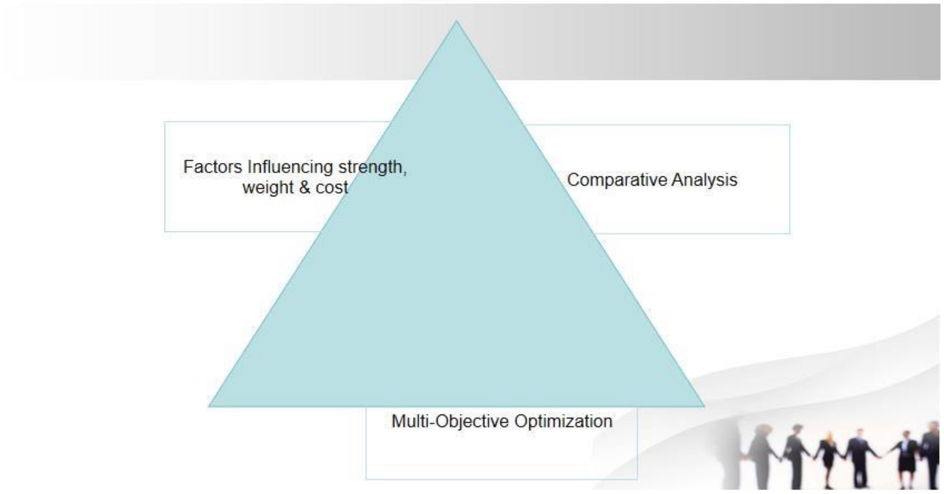


Figure 5: Research Gap Deduced

Chapter 3: Materials and Methodology

Polymeric material (PLA-Plus) has been selected in this research for the investigation. PLA + was created by using additives and modifiers to increase its ductility and reduce brittleness. Therefore, it was decided to analyze its features. Fused Deposition Modelling (FDM) was the additive. PLA-Plus was chosen above alternatives due to its excellent mechanical qualities suited for flexural and compressive stresses, compliance with Fused Deposition Modelling (FDM), simplicity of the printing process, affordability, biodegradability, and eco-friendliness. Its accessibility and engagement in the additive manufacturing industry also make it suitable for investigating honeycomb configurations, which aligns with the study's goals of accomplishing optimal strength-to-weight ratios, minimal material consumption, and minimized weight. Fused Deposition Modelling (FDM) is the additive manufacturing approach. One-of-a-kind check companies had been taken into consideration to evaluate the flexural & compression properties. FDM with PLA-Plus material will be utilized to fabricate detailed honeycomb configurations. The strategy to be able to be used to select the first-rate mixture of structures is based totally on the most strength-to-weight ratio, minimal cloth consumed, minimal weight, and decreased manufacturing time recommended for FDM generation. In this study hexagonal shape changes, over-improved hexagonal, and square and easy hexagonal shapes might be analyzed.

3.1 Process Flow of Research

The process draft of this study complies with comprehensive steps. Based on the literature evaluation conducted to decide the research gaps and targets of the observation, the following studies method changed into developed as illustrated. Firstly, the designing of cad fashions on solid works and three-D printing of the usage of FDM observed by way of fabrication process is conducted on Taguchi layout of orthogonal array L16. Then, power and weight are calculated and primarily based on experimental outcomes optimization process is completed. Finally, validation was finished by real experimentation, and variants were analyzed.

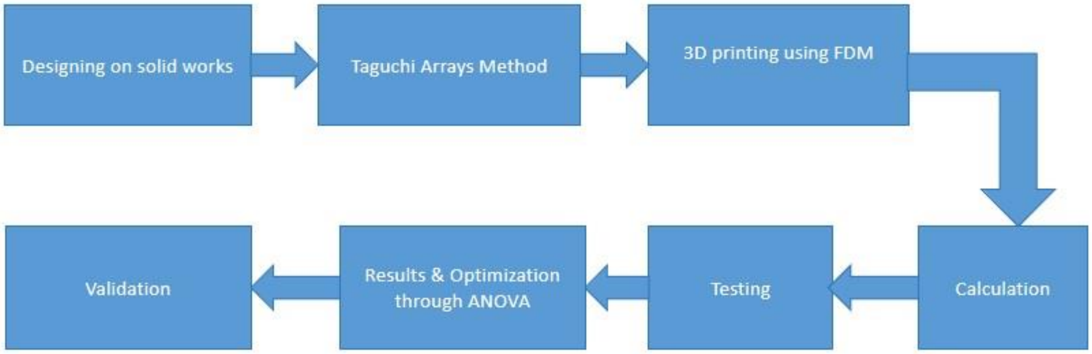


Figure 6: Process Flow Diagram

3.2 Designing of Samples

Initially, a CAD version of the Solid Works software program became a model for compression testing respectively as illustrated in Fig 7. With a keen eye for precision and a deep understanding of the ideas of compression, it meticulously translates conceptual designs into virtual representations, capturing every intricate detail and nuance of the intended specimen. Solid Works meticulously outlines the geometric shape, dimensions, and material homes of the specimen, ensuring utmost accuracy and fidelity to real-international counterparts. The honeycomb shape is a type of cellular structure with every day and periodically repeated arrays of hexagonal cells. It contains two skinny, stiff, robust sheets serving as the number one load-wearing elements and a thick layer of low-density center supplying shear resistance and stiffness. Three exceptional published structures of hexagons, over-increased hexagons, and square-formed honeycomb are applied for testing.

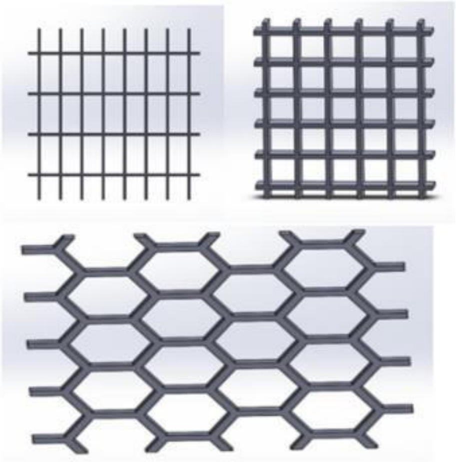


Figure 7: Design on solid works

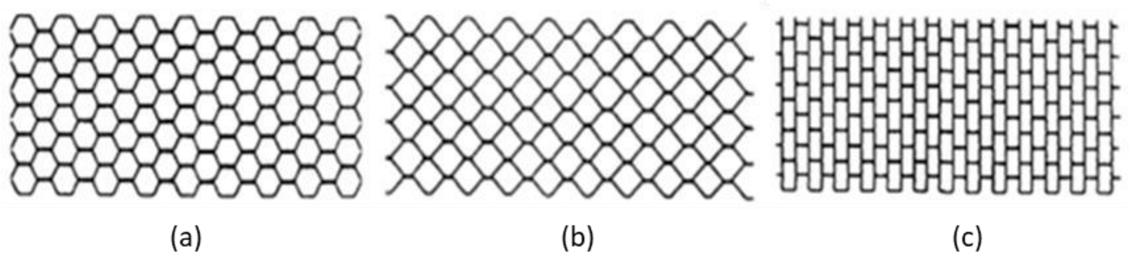


Figure 8: Cellular configuration (a) hexagon (b) square (c) over-expanded hexagon

3.3 Design of Experiments

The design of experiments starts with the evaluation of the compression power of the samples published with the aid of Fused Deposition Modelling (FDM). The optimization for the aggregate was done using the Taguchi method of the array. To validate the bugs, the Taguchi approach of the orthogonal array was used to behavior the take look for finding out a pleasant result. Taguchi has formulated a new method to perform a look at the design of experiments. This method uses hard and fast orthogonal arrays for accomplishing a minimum run of experiments that provide brief clarification on elements affecting overall performance parameters. An array changed into formulated to check the design parameters. The initial array, L16, for three elements and 4 tiers had been decided on to keep for full factorial design. Thus, Taguchi helps in extracting the pleasant viable aggregate. The design summary is as follows.

Taguchi Array L16(4^3)
Factors: 3
Runs: 16
Columns of L16(4^3) array: 1 2 3

Table 2: Structural Parameters

Parameter	Cell wall length (mm)	Cell wall thickness (mm)	Height (mm)
Level 1	3	0.5	12.7
Level 2	6	1	25.4
Level 3	9	1.5	38.1
Level 4	12	2	50.8

Table 3: Combinations

Sr no.	Cell wall length (mm)	Cell wall thickness (mm)	Height (mm)
1	3	0.5	12.7
2	3	1	25.4
3	3	1.5	38.1
4	3	2	50.8
5	6	0.5	25.4
6	6	1	12.7
7	6	1.5	50.8
8	6	2	38.1
9	9	0.5	38.1
10	9	1	50.8
11	9	1.5	12.7
12	9	2	25.4
13	12	0.5	50.8
14	12	1	38.1
15	12	1.5	25.4
16	12	2	12.7

3.4 3D Printing

The procedure normally starts with creating a digital 3D version using a computer-aided layout (CAD) software program as illustrated in Fig 7. This model is sliced into skinny layers, which generates commands for the 3-D printer. FDM printers use thermoplastic substances, along with PLA (Polylactic Acid) or ABS (Acrylonitrile Butadiene Styrene), even though there are many other sorts to be had. The choice of material depends on elements like strength, flexibility, warmness resistance, and value. We are using PLA-Plus. Filament is loaded into the printer. It's generally a filament spool fed into an extrusion nozzle. The FDM printer has a heated nozzle that melts the filament. The melted filament is then extruded onto the construct platform in skinny layers according to the sliced model. The nozzle acts along the X, Y, and Z axes to deposit the fabric precisely where it's wished. The model is built layer through layer. Once one layer is completed, the build platform is diminished (or the extruder raised) to make room for the subsequent layer. This method is maintained till the whole model is complete. As every layer is deposited, it quickly cools and solidifies. This lets subsequent layers adhere to the preceding ones, forming a cohesive shape. Overall, FDM 3-D printing is extensively used due to its relatively low value, ease of use, and flexibility. It's employed in various industries for speedy prototyping, custom manufacturing, and even in hobbyist settings for creating precise items.

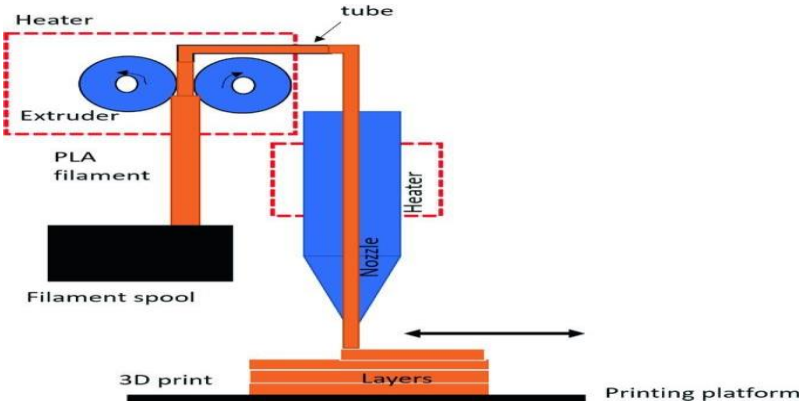


Figure 9: Additive manufacturing through FDM

Figure 10 shows the printing of a hexagon-shaped honeycomb core structure according to the process which is discussed above and elaborated in Figure 9.

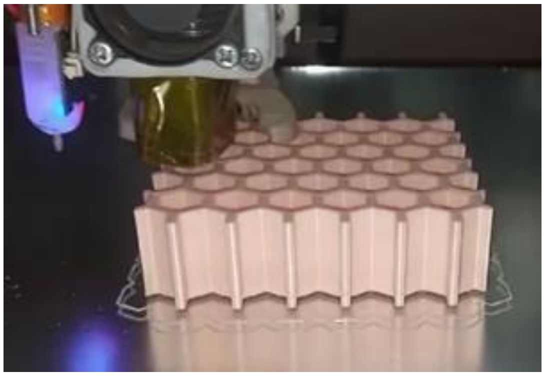
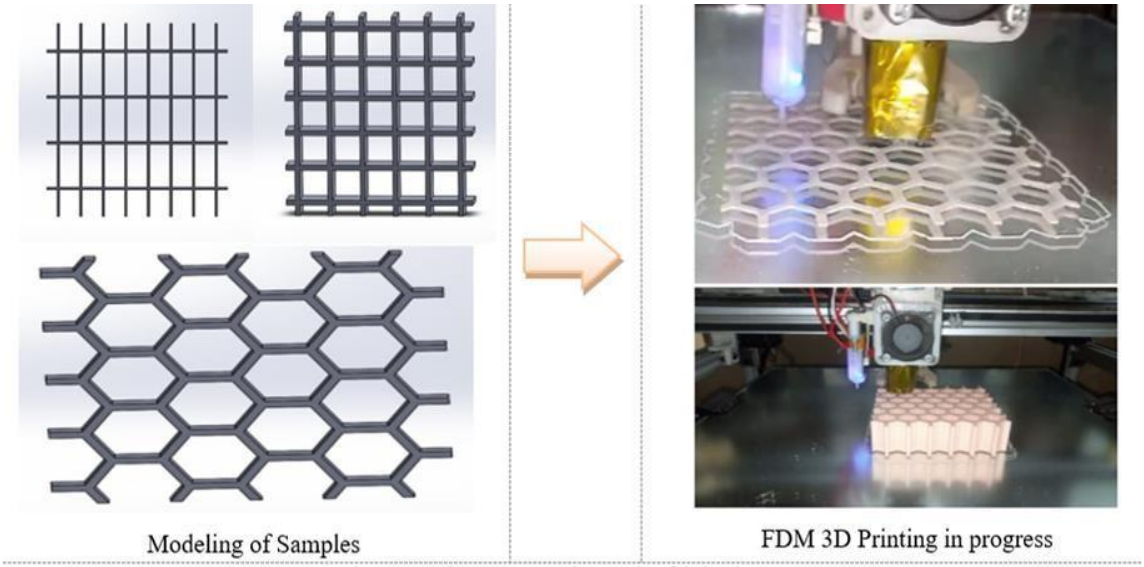


Figure 10: 3D Printing process


Modeling of Samples

FDM 3D Printing in progress

Figure 11: The Honeycomb Samples Fabrication Process

The below figure illustrates that there are no flaws in printing. In 3D printing, flaws or defects can occur due to diverse reasons such as incorrect printer settings, insufficient help systems, filament troubles, or layout errors. Achieving a perfect print commonly requires a meticulous interest in detail in the course of the whole printing system, such as the right calibration of the printer, deciding on suitable printing parameters, ensuring adequate cooling, and using extraordinary filament.

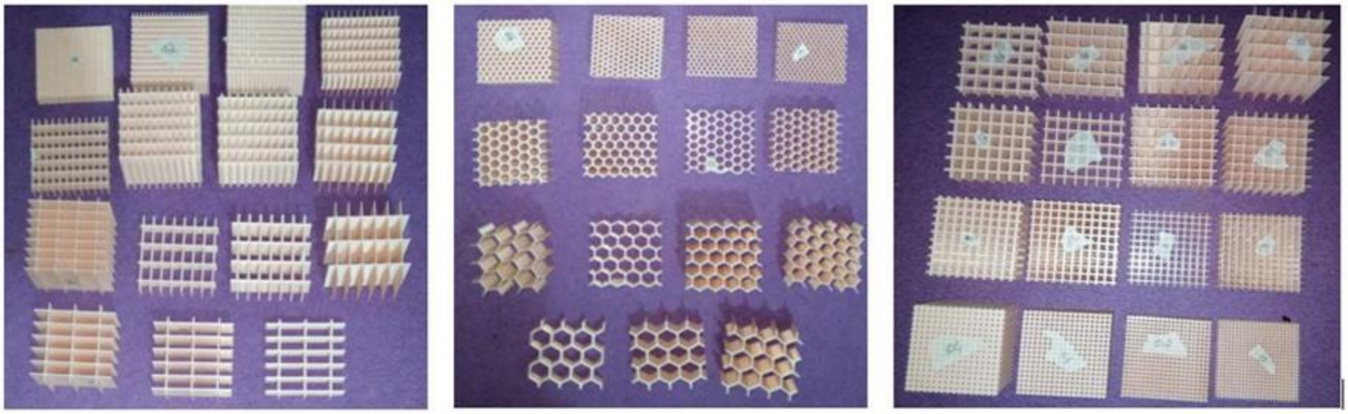


Figure 12: 3D printed hexagonal, rectangular, and square honeycomb structure

Figure 13. clearly showing the quality and accuracy of printing. It shows clearly that there are no flaws in the printing of structures.

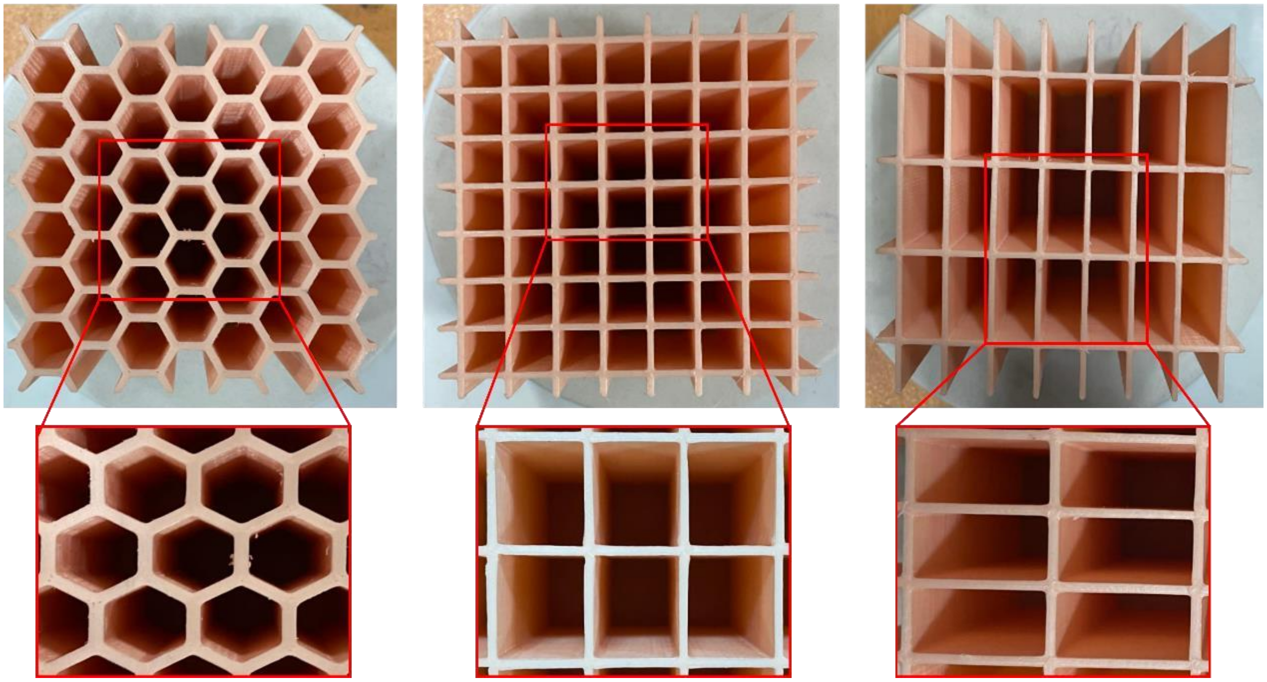


Figure 13: Figure showing no flaws in honeycomb samples

3.5 Weight Calculation

Fig. 14 explains the weight calculation process. Weight is measured in grams of the samples. After which their density is measured. Because we were required to measure strength to weight ratio. It was included in our objectives. So, to find this ratio, weight calculations were performed.

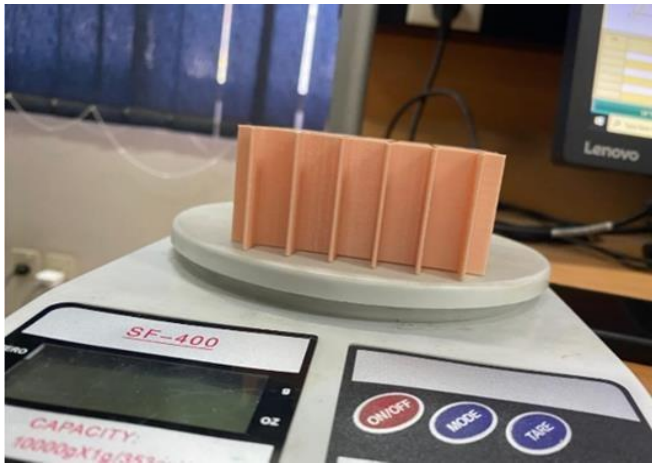


Figure 14: Weight Measuring Setup

Fig 15 depicts the graphical analysis of weight calculation. There are samples plotted horizontally and weight vertically. The graph is gradually increasing and decreasing. As we can see the weight of a hexagon is less than that of a square or rectangle. The cell aspect ratio is also examined. Where cell aspect ratio is defined as the ratio of height to cell wall length. This ratio is also mentioned in Fig 15. We have drawn certain imperial results from this ratio.

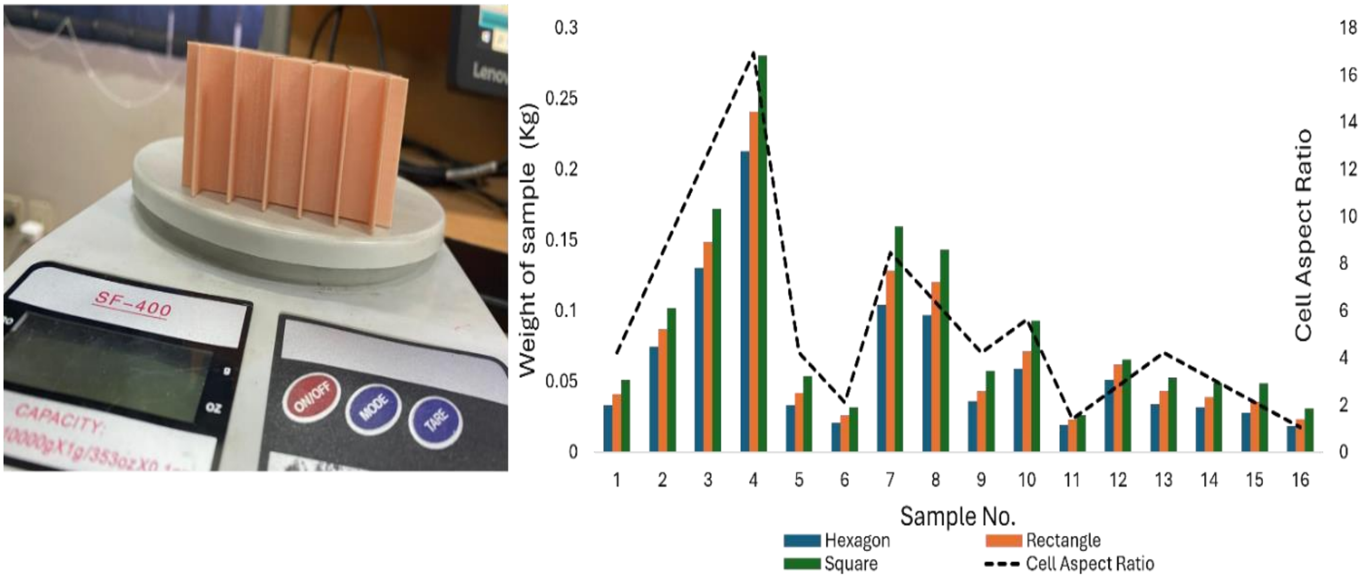


Figure 15: Graphical Analysis

3.6 Compression Load Testing

Compression load trying out is a way used to determine the compressive energy or the capacity of a material to face up to hundreds implemented in a compression route. The first step is to put together the look at samples in line with the requirements or specs relevant to the cloth being tested. The test pattern is then located between the compression platens of a checking out gadget, also referred to as a compression checking out gadget or a customary trying out device (UTM). The compression is commonly flat and parallel to ensure uniform loading. Before applying any load, the testing gadget is zeroed to make sure correct measurements. Calibration tests can also be carried out to verify the accuracy of the check-out device. A compressive load is implemented to the check sample at a detailed rate, commonly managed via the checking out device's software. The load is progressively elevated until the sample fails or till the favored load limit is reached. The rate of loading may additionally vary depending on the fabric being examined and the testing standards being followed. Throughout the test, statistics which include load and deformation (displacement) are constantly recorded through the check-out system. This record lets in for the era of a load-deformation curve, which gives insights into the cloth's conduct beneath compression. Once the check is finished, the statistics amassed are analyzed to determine the compressive strength of the fabric. This may also involve calculating the most load sustained with the aid of the pattern, the deformation at failure, and other relevant parameters. The effects are then in comparison to enterprise standards or specifications to assess the cloth's overall performance.

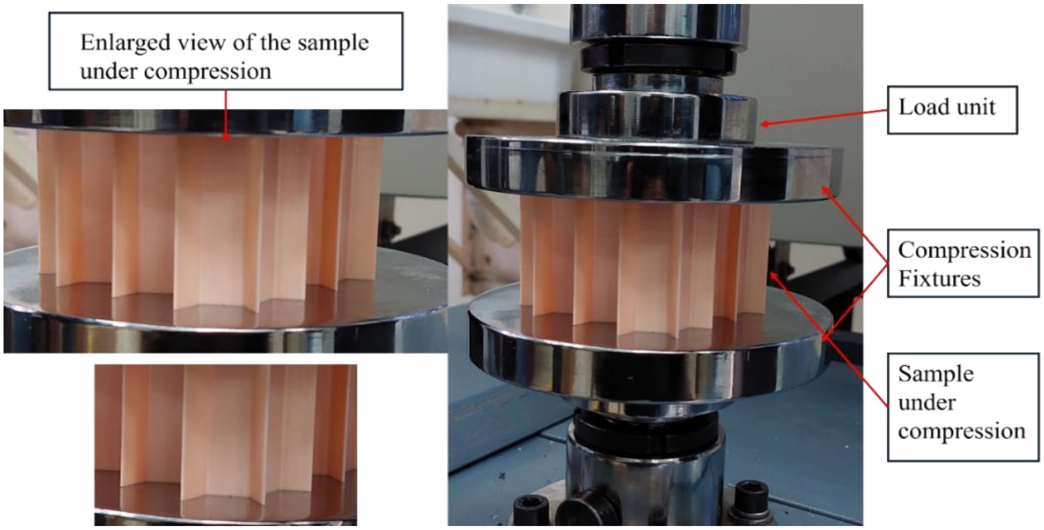


Figure 16: Compression testing setup

3.7 Fracture Mechanics

Fracture mechanics, as utilized in compression testing of FDM printed honeycomb structures, is the study of fracture initiation, propagation, and failure under applied stresses. It looks at how fractures occur inside the material, especially at stress concentration areas, and how they spread throughout the structure when it deforms. Fracture mechanics aids in structural failure prediction and honeycomb component durability by developing failure criteria based on characteristics such as maximum load-bearing capacity and crack propagation behavior. Fig 17 shows the load-displacement curve of this procedure.

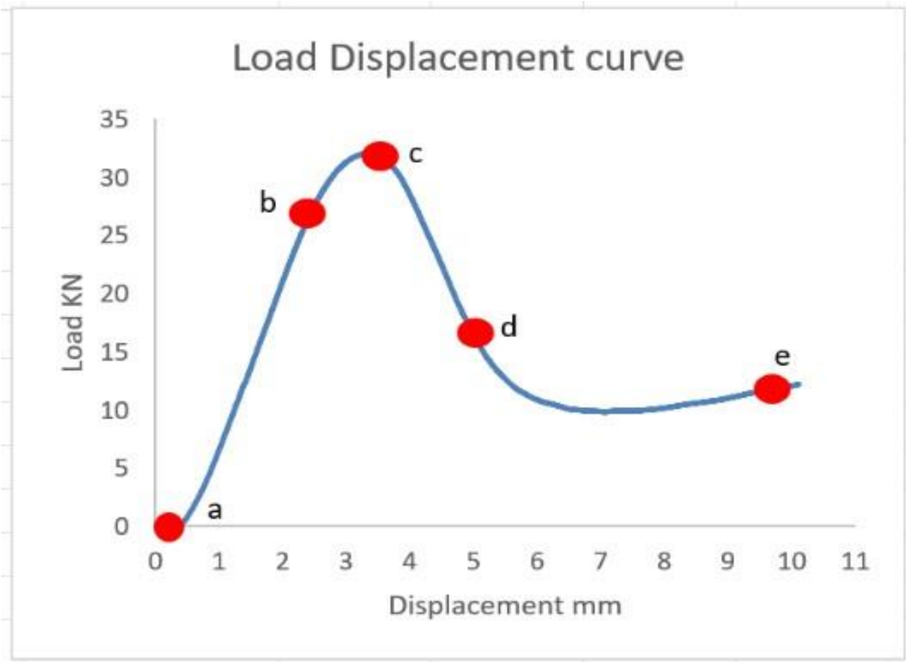


Figure 17: Load Displacement curve

Figure 18: The failure mechanism of honeycomb structure from initiation to propagation

The term "sample before compression" relates to the honeycomb structure's initial condition before the application of an external force. This stage acts as a reference point for comparison with the following phases of deformation. "Elastically deformed walls" refers to a phase in which the honeycomb structure experiences reversible deformation under compression, which means that if the load is removed, the structure recovers to its former shape. In contrast, "plastically deformed walls" refer to persistent deformation beyond the material's elastic limit, which causes irreversible structural changes. “Cell wall crushing" is a severe deformation in which the walls of honeycomb cells break under excessive stress, resulting in localized failure inside the structure. Finally, "densification of the sample" refers to a rise in material density caused by compression stress, in which vacant spaces between cells are minimized. Fig 18 explains the mechanical behavior of honeycomb structures under compression, providing insights into their resilience and failure causes, which are critical for maximizing their performance in a variety of industrial applications.

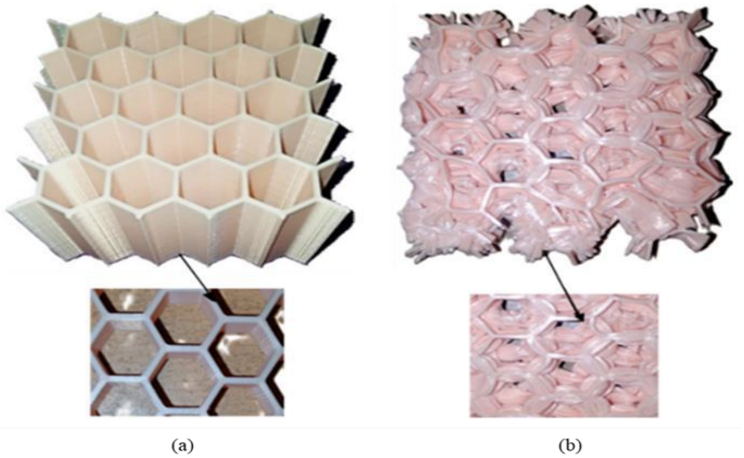


Figure 19: Honeycomb structure (a) before compression (b) after compression

3.8 Response Data Schemes

Below formulas are being utilized at different steps of testing and calculation. To measure compression, strain, density, strength-to-weight ratio, etc. Where F and A respectively define force and cross-sectional area. Strain and strength-to-weight ratio are dimensionless quantities.

$$S = {}^{P}\!/_{A}\,(MPA)$$

$$Density = \frac{Strength}{Density\ of\ Honeycomb\ structure}$$

$$strength - to - weight\ ratio = \frac{Weight}{Volume\ of\ honeycomb\ structure}$$

3.9 Optimization Process

For final optimization, single out the optimum combination by setting the larger the best criteria for the larger strength-to-weight ratio and minimum cost. Response Surface Methodology includes optimization procedures for the settings of factorial variables, such that the response attains a desired maximum or minimum value. The response is in effect modeled by factorial techniques and ANOVA, but these are extended for more detailed modeling of the effects. In our case, as have two prime objectives to optimize strength-to-weight ratio and reduce printing parts. 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.

FEA Analysis

Numerical analysis was also performed to validate the optimized parameters results. After optimization, three different shape structures were modeled again at their specified optimum parameters and then tested numerically on ANSYS 2024 R1 software. Compression testing is performed on the modeled structures and then the FEA analysis results are compared with experimental results and ANOVA optimum results. FEA analysis of tested structures is elaborated on in the next sections in detail.

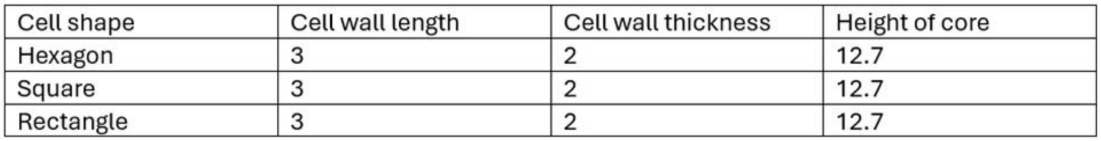
Chapter 4 Results & Discussion

This section contains the results drawn from the investigation of 3D-printed honeycomb structures of different shapes and the shapes that fulfill the objectives of this study are further discussed here.

4.1 Strength Optimization

Our findings indicated a clear link between cell wall properties and material strength. Lower cell wall length and core height, along with higher cell wall thickness, usually resulted in greater resilience. Statistical investigations, such as the ANOVA and Taguchi methodologies, validated the importance of these results. Table 4 depicts this pattern, with optimal parameter pairings.

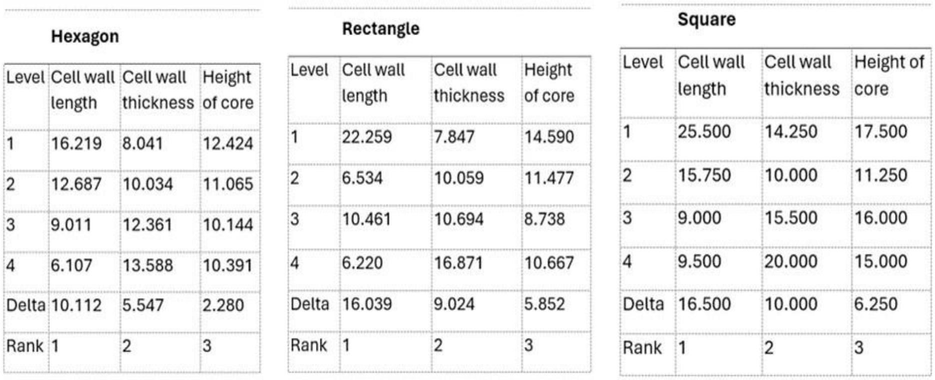
Table 4: Table of optimized parameters



Cell shape	Cell wall length	Cell wall thickness	Height of core
Hexagon	3	2	12.7
Square	3	2	12.7
Rectangle	3	2	12.7

4.2 Analysis of Variance (ANOVA) and Taguchi

Figure 20 shows the findings of Taguchi Analysis for three distinct arrangements: hexagon, rectangle, and square. This study investigates the effect of different cell wall characteristics, including length, thickness, and core height, on the material's strength within every arrangement. The investigation determines the ideal settings for optimizing strength for each design by methodically testing alternative parameter pairings. These results give important insights into the link between geometry and material performance, allowing for the educated design of structures adapted to certain configurations. Comparing the outcomes across forms helps us to analyze any specific benefits or disadvantages connected with each design.



Hexagon

Level	Cell wall length	Cell wall thickness	Height of core
1	16.219	8.041	12.424
2	12.687	10.034	11.065
3	9.011	12.361	10.144
4	6.107	13.588	10.391
Delta	10.112	5.547	2.280
Rank	1	2	3

Rectangle

Level	Cell wall length	Cell wall thickness	Height of core
1	22.259	7.847	14.590
2	6.534	10.059	11.477
3	10.461	10.694	8.738
4	6.220	16.871	10.667
Delta	16.039	9.024	5.852
Rank	1	2	3

Square

Level	Cell wall length	Cell wall thickness	Height of core
1	25.500	14.250	17.500
2	15.750	10.000	11.250
3	9.000	15.500	16.000
4	9.500	20.000	15.000
Delta	16.500	10.000	6.250
Rank	1	2	3

Figure 20: Taguchi Analysis for Different Configurations

With ANOVA General Linear Model for 16 S-N Ratio Values (Hexagon Scheme) we did a detailed summing of the S-N ratio alterations against different experiment environments. S/N ratio which is the ratio of signal magnitude (connected to interesting features) in noise is considered a critical statistic in experimental designs and data analysis. In Figure 21, the Order of observation designates the overall style of data points or observations set up in a particular data set. Observation order denotes the sequential organization of data points or observations in a dataset. It shows the sequence in which the observations have been documented or gathered during the procedure. The curve between residual and observation order reveals information about the distribution and pattern of residuals, which are the disparities between observed S-N ratio values and those predicted by the ANOVA General Linear Model. Residuals indicate the model's predicted accuracy and capacity to articulate the variation that was seen in the data.

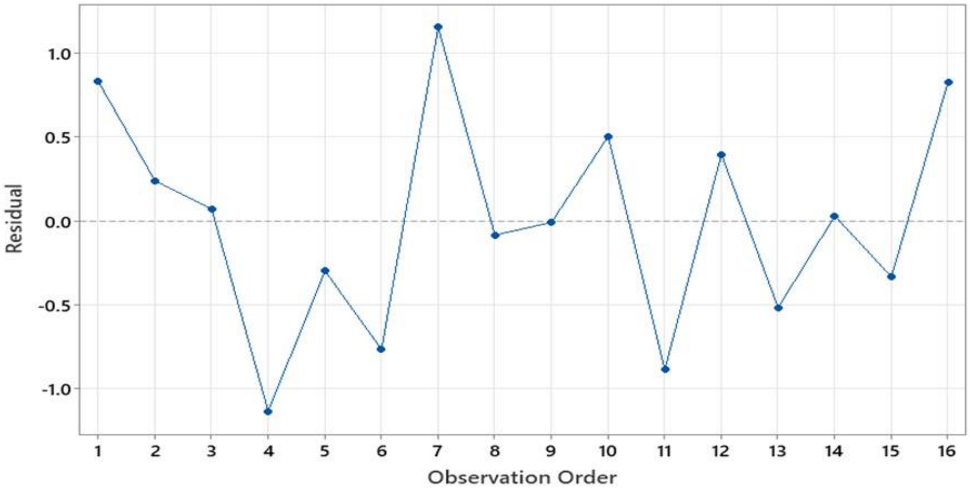
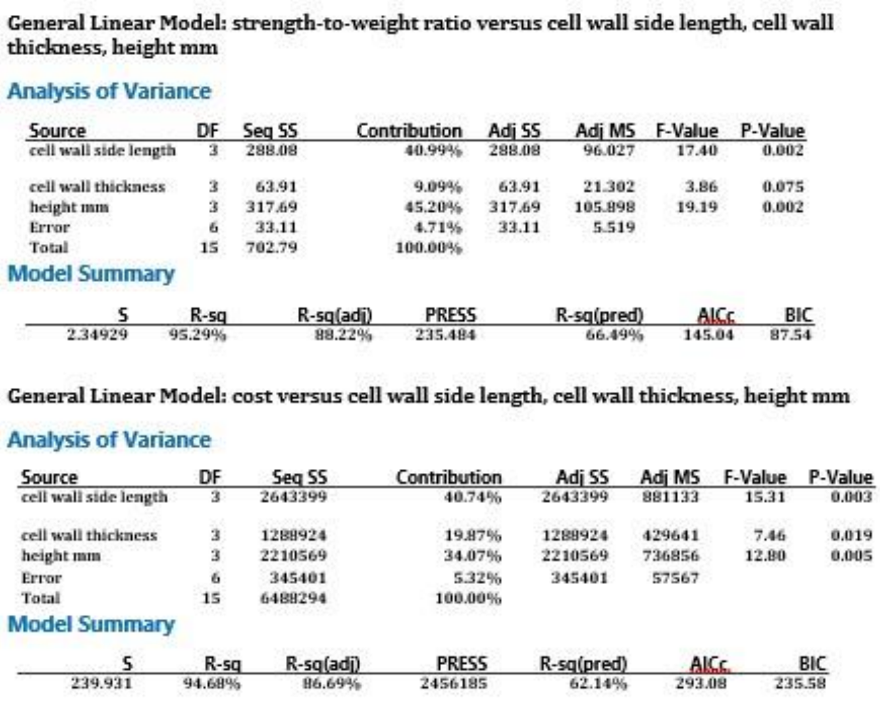


Figure 21: ANOVA General Linear Model set for 16 S-N Ratio Values (Hexagon)

Table 5: ANOVA general linear model for Hexagon shape



General Linear Model: strength-to-weight ratio versus cell wall side length, cell wall thickness, height mm

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
cell wall side length	3	288.08	40.99%	288.08	96.027	17.40	0.002
cell wall thickness	3	63.91	9.09%	63.91	21.302	3.86	0.075
height mm	3	317.69	45.20%	317.69	105.898	19.19	0.002
Error	6	33.11	4.71%	33.11	5.519		
Total	15	702.79	100.00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
2.34929	95.29%	88.22%	235.484	66.49%	145.04	87.54

General Linear Model: cost versus cell wall side length, cell wall thickness, height mm

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
cell wall side length	3	2643399	40.74%	2643399	881133	15.31	0.003
cell wall thickness	3	1288924	19.87%	1288924	429641	7.46	0.019
height mm	3	2210569	34.07%	2210569	736856	12.80	0.005
Error	6	345401	5.32%	345401	57567		
Total	15	6488294	100.00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
239.931	94.68%	86.69%	2456185	62.14%	293.08	235.58

The ANOVA General Linear Model (Table 5) was used to formulate the results. It is possible to classify whether the parameter selected for investigation is significant using the F- and P-values. A significant factor is indicated by a P-value of less than 0.05. Similarly, R-sq values can provide insight into the degree to which the answers can be described by the chosen components. It is reasonable to presume that there are no interactions between the factors influencing responses when there are little error contributions. Here, it could be observed that the height factor stands out as contributing around 45.20% of the variation in the result.

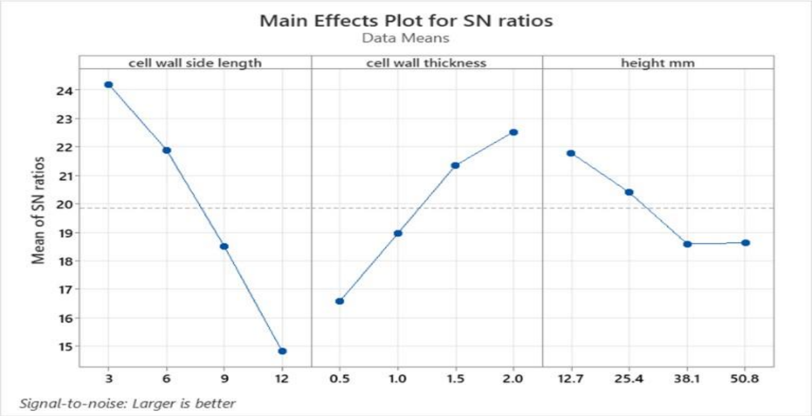


Figure 22: Taguchi Analysis S-N Ratio

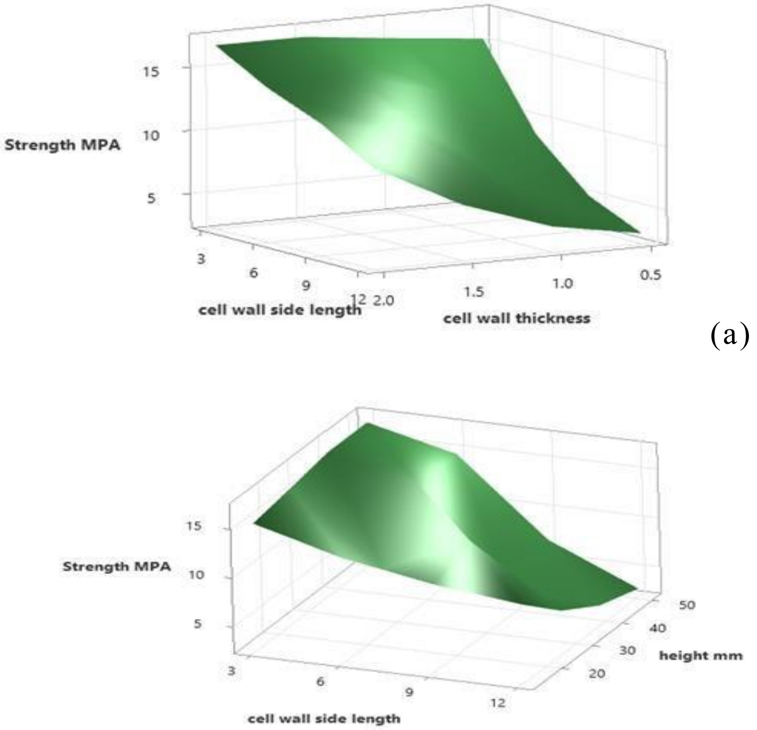


Figure 23: Surface Plot of Strength MPA vs (a) cell wall length vs cell wall side length (b) cell wall length vs height

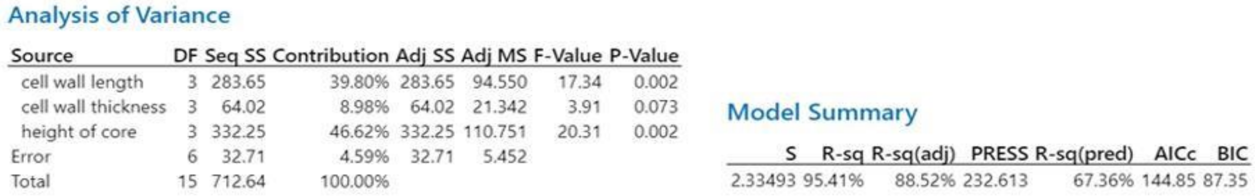
Table 6 shows a full overview of the optimum parameters for improving the strength-to-weight ratio and lowering costs in various cellular arrangements. The optimization procedure entails using ANOVA (Analysis of Variance) tools to discover the most important elements influencing these two crucial characteristics of material performance. Each cellular design is thoroughly analyzed to identify the critical characteristics that contribute most substantially to these goals.

A comprehensive evaluation of the trial data reveals the ANOVA-optimized parameters for enhancing the strength-to-weight ratio. Experts can identify the ideal design that provides the required balance of strength and weight effectiveness by assessing the effect of cell wall dimensions, core structure, and other relevant aspects on material strength relative to weight. Concurrently, the ANOVA analysis handles the issue of cost reduction by finding characteristics that impact production costs. This dual optimization method assures that the final material combinations have superior strength-to-weight performance while also providing cost-effective alternatives for practical application.

Table 6: optimized parameters for enhancing the strength-to-weight ratio and decreasing cost.

Cell shape	Cell wall length	Cell wall thickness	Height of core
Hexagon	6	1	12.7
Square	3	0.5	12.7
Rectangle	9	1.5	12.7

Figure 24-29 studied a case of the linear model ANOVA and Response surface methodology (RSM) graphs of the three cellular forms being investigated. In a nutshell, the ANOVA linear model indicated multiple correlated factors, such as power/terrain relationship, or how weight related to strength. This study serves to determine whether these observed variations are the effect of the already established components of material qualities or if there are new components. The ANOVA linear model has a strong advantage in that it can be used to understand the main blocks behind the materials' performance and can suggest optimizing the properties one would like to see enhanced.



Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
cell wall length	3	283.65	39.80%	283.65	94.550	17.34	0.002
cell wall thickness	3	64.02	8.98%	64.02	21.342	3.91	0.073
height of core	3	332.25	46.62%	332.25	110.751	20.31	0.002
Error	6	32.71	4.59%	32.71	5.452		
Total	15	712.64	100.00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
2.33493	95.41%	88.52%	232.613	67.36%	144.85	87.35

Figure 24: ANOVA general linear model of hexagonal configuration

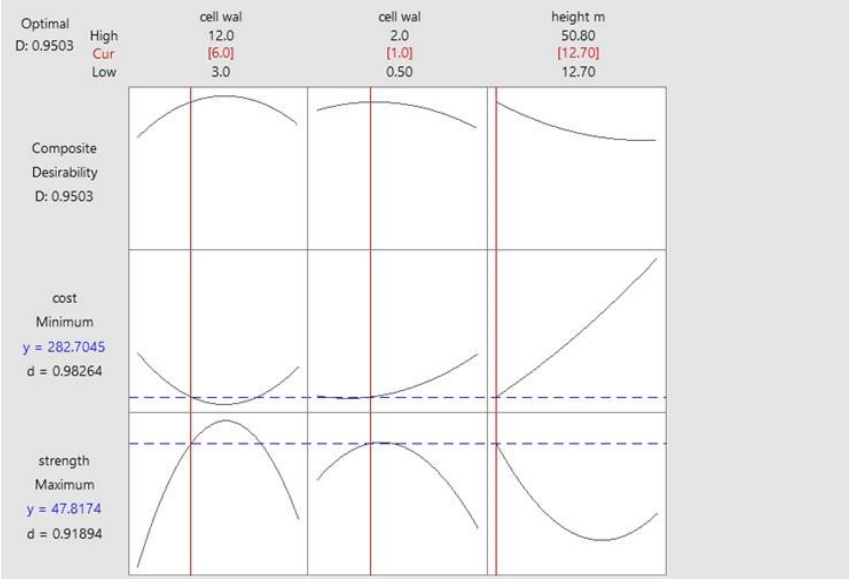
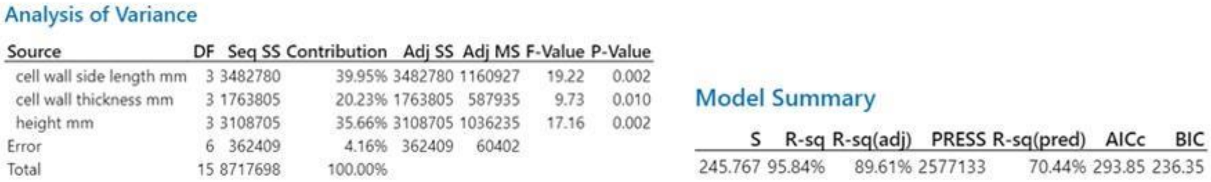


Figure 25: RSM of hexagonal configuration



Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
cell wall side length mm	3	3482780	39.95%	3482780	1160927	19.22	0.002
cell wall thickness mm	3	1763805	20.23%	1763805	587935	9.73	0.010
height mm	3	3108705	35.66%	3108705	1036235	17.16	0.002
Error	6	362409	4.16%	362409	60402		
Total	15	8717698	100.00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
245.767	95.84%	89.61%	2577133	70.44%	293.85	236.35

Figure 26: ANOVA general linear model for over-expanded hexagonal configuration

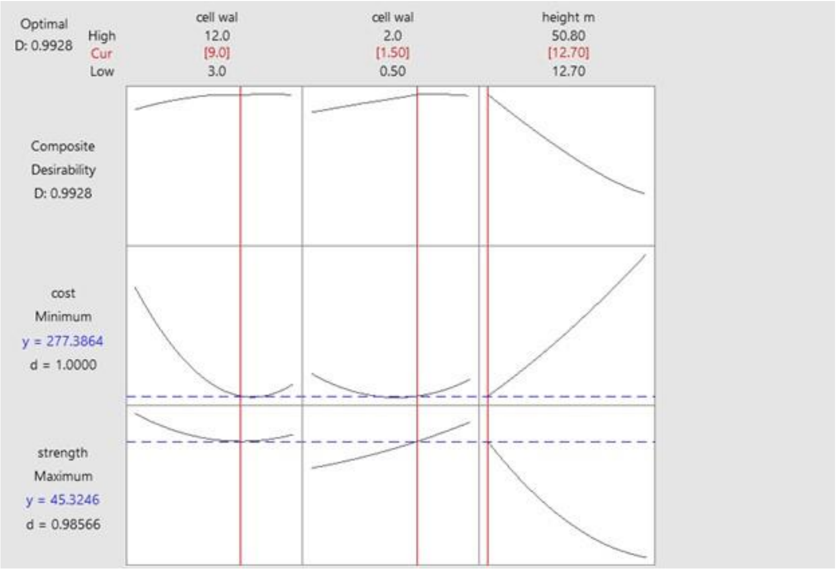
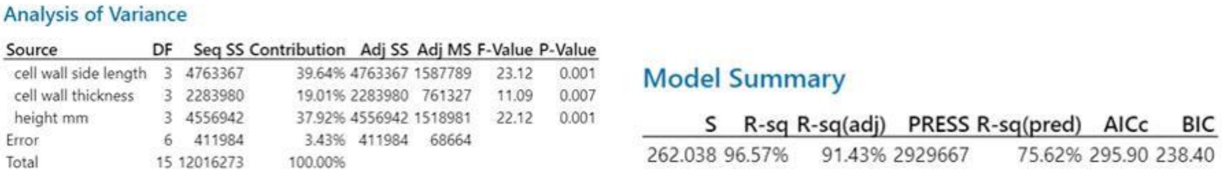


Figure 27: RSM of over-expanded hexagonal configuration



Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
cell wall side length	3	4763367	39.64%	4763367	1587789	23.12	0.001
cell wall thickness	3	2283980	19.01%	2283980	761327	11.09	0.007
height mm	3	4556942	37.92%	4556942	1518981	22.12	0.001
Error	6	411984	3.43%	411984	68664		
Total	15	12016273	100.00%				

Model Summary

S	R-sq	R-sq(adj)	PRESS	R-sq(pred)	AICc	BIC
262.038	96.57%	91.43%	2929667	75.62%	295.90	238.40

Figure 28: ANOVA general linear model for square shape

ANOVA and RSM results for all three tested configurations are displayed and elaborated here. These are the important analyses to find the most dominant factors that affect the results. These analyses are clearly showing the most dominant factors are the height of the core and cell wall length which affects the results most.

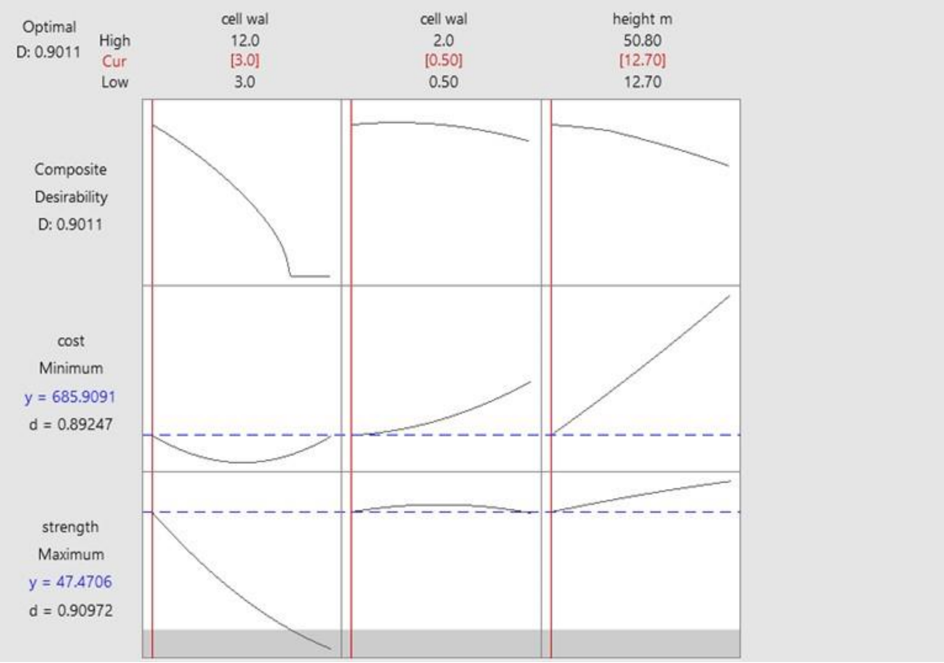


Figure 29: RSM of square shape

Fig 24-29 above depicts the importance of response surface methodology (RSM) as a statistical approach for the optimization of experimental conditions and systems cannot be overstated in so far as RSM examines the relationship between the many factors and the one output response. Accordingly, changes in the component features such as cell wall thickness, core structure, and material composition lead to changes in its quality parameters of strength-to-weight ratio and cost. Besides the ANOVA linear model, Graphs of RSM help visualize the relationship between several input factors and the response variable.

Chapter 5 Validation

Modified parameters were also recalculated and tested as experimental and numerical analyses which again compared with modified ones produced by ANOVA analysis. ANOVA is a statistical method for the task of finding out if the means of two or more groups differ from each other statistically. Here, the scope is to evaluate several parameters setting options or working designs. Through this ANOVA test done on the results of the test survey and numerical simulations verification, it is established if there could be a noticeable amelioration in performance subject to various scenarios of tested configurations. This statistical examination of parameter setting or tuning the design will give us an idea of which of the two made the better result. It offers a randomized test (which is also used during the optimization campaign) for assessing the effectiveness of the optimization process and the most critical factors affecting the composed system's performance. ANSYS is believed to be the most useful engineering simulation tool that lets the user visualize and solve complicated systems.

Table 7: Different parametric results of Hexagon, Overexpanded Hexagon, and Square

Cellular configuration	Hexagon	Overexpanded hexagon	Square
Experimental Max Load (N)	82036	83403.5	196725.9
Numerical Max Load (N)	77554	82900	202050
Experimental Deformation (mm)	5.62	4.81	3.64
Numerical Deformation (mm)	5.10	4.15	3.62
Experimental Strength-to-weight ratio (KNM/kg)	49.77	45.79	48.7
Numerical Strength-to-weight ratio (KNM/kg)	47.1	45.52	50
Difference between Numerical from Experimental	-2.67	-0.27	+1.3

In this case, we are using ANSYS to model the operation of the system under various scenarios. By entering designs' characteristics and geometry into ANSYS, we estimated how they would function in real-world settings without having to create physical prototypes. With these simulation capabilities, one can rapidly and efficiently examine a wide range of design choices. You may evaluate the performance of various forms (hexagonal, rectangle, square) and parameter settings, discover possible problems, and optimize your designs for greater performance and efficiency. ANSYS delivers useful insights into how different design decisions affect your system's behavior and performance, which will help guide your optimization efforts. Table 7 shows the comparison between the experimental and numerical analysis results. These numerical and experimental analysis results are of the three different honeycomb structures which were made at optimum geometrical analysis resulted by MOO.

Figure 30: Experimental testing result of hexagonal shape

Fig 30-34 shows the comparison of numerical and experimental testing of hexagonal configuration including stress-strain and displacement. Mesh density and solver settings extensively impact the accuracy of the numerical effects. Different loading eventualities, together with tensile, compressive, or bending hundreds, may be implemented in the hexagonal structure. Hexagonal systems are generally encountered in various engineering programs due to their inherent strength and balance. Understanding their behavior below one-of-a-kind loading situations is important for designing green and dependable systems. In this contrast study, we analyze the stress-strain courting and displacement conduct of a hexagonal shape via numerical simulation and experimental testing. Numerical analysis involves the use of computational methods to simulate the conduct of the hexagonal shape underneath exceptional loading situations. Finite Element Analysis (FEA) is a commonly used numerical approach for such simulations. In FEA, the hexagonal shape is discretized into smaller elements, and the governing equations of mechanics are solved iteratively to determine the strain, strain, and displacement distribution inside the shape. The hexagonal shape is modeled on the usage of appropriate cloth properties, geometric dimensions, and boundary situations. Its desired mechanical response is below numerous conditions. The numerical simulation presents designated insights into the stress-pressure courting and displacement conduct of the hexagonal shape. Key parameters which include most strain, pressure distribution, and deformation styles are analyzed to understand the structural reaction.

Experimental trying out includes body subjecting the hexagonal structure to controlled loading conditions and measuring its mechanical response through the use of specialized gadgets including load cells, strain gauges, and displacement sensors. A physical specimen of the hexagonal shape is fabricated using appropriate substances and production strategies. Care is taken to ensure dimensional accuracy and homogeneity of material properties. The specimen is mounted in testing equipment, and the favored loading situations are implemented step by step. Load-displacement facts are recorded all through the take a look at the use of load cells and displacement sensors. During the test, numerous parameters which include implemented load, displacement, and stress are constantly monitored and recorded. This record serves as the idea for studying the mechanical conduct of the hexagonal structure.

Once the numerical simulation and experimental testing are finished, a comprehensive comparison of the effects is conducted to assess the accuracy and reliability of the numerical model. The stress strain curves acquired from numerical simulation and experimental checking out are compared to assess their similarity. Any discrepancies or differences inside the tendencies are analyzed to become aware of capability resources of blunders. The displacement profiles acquired from numerical simulation and experimental checking out are compared to evaluate the agreement between the two. Factors that include structural stiffness, boundary situations, and fabric nonlinearity affect displacement behavior. If huge disparities exist in the various numerical and experimental consequences, the numerical version may also moreover require validation and calibration to beautify its accuracy. This method entails adjusting version parameters or refining the mesh to better shape the experimental information. The contrast between numerical simulation and experimental checking out presents treasured insights into the mechanical conduct of the hexagonal structure beneath unique loading conditions. By rigorously analyzing pressure-stress relationships and displacement conduct, engineers can refine their format methodologies and optimize the performance of hexagonal systems in realistic packages.

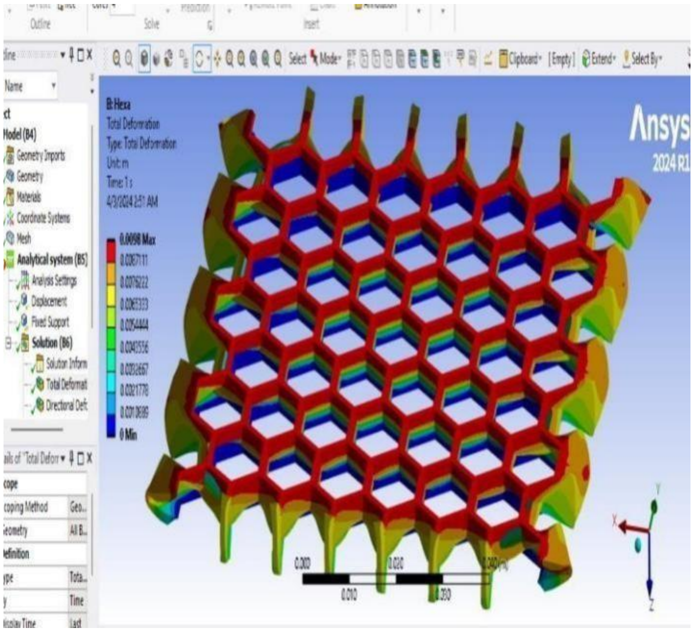


Figure 31: Numerical analysis result of hexagon shape

Figure 32 provides the strain-pressure curve graph for the hexagonal form, illustrating wonderful curves representing the outcomes obtained from numerical simulations and experimental checking out. This graphical example offers critical insights into the mechanical behavior of the hexagonal honeycomb form underneath loading conditions. The horizontal axis of the graph typically represents the stress, that is a degree of the deformation experienced by the fabric relative to its original size. Strain is expressed as a dimensionless quantity or percentage and indicates how an awful lot the cloth has stretched or compressed. The vertical axis, however, represents strain, that's the pressure carried out consistent with unit area. Stress is typically measured in gadgets of strain (which includes MPa or psi) and quantifies the internal forces within the material attributable to external masses. The stress-strain curve itself depicts the relationship between stress and strain as the structure undergoes deformation. As the cloth is subjected to growing levels of stress, it starts to deform, leading to a boom in stress. The preliminary part of the curve, known as the linear elastic region, demonstrates a linear courting between pressure and pressure. In this place, the cloth behaves elastically, meaning that it could go back to its original form as soon as the burden is eliminated without permanent deformation.

Beyond the linear elastic place, the curve enters the plastic deformation vicinity, where the fabric undergoes everlasting deformation. In this segment, the cloth also can showcase stress hardening or softening, depending on its unique houses. Strain hardening happens when the material becomes stronger and stiffer because it deforms, at the same time as stress softening entails a decrease in energy and stiffness. The factor at which the curve starts off evolved to deviate from linearity and input the plastic deformation location is referred to as the yield factor or yield power. This is a crucial parameter that suggests the onset of everlasting deformation within the fabric. Beyond the yield point, the fabric keeps deforming till it reaches its ultimate tensile strength, that is the maximum strain it can face up to earlier than failure takes place. The closing tensile power is represented by using the height of the stress-strain curve. The slope of the pressure-strain curve in the linear elastic vicinity is called the modulus of elasticity or Young's modulus. This parameter quantifies the material's stiffness and resistance to deformation underneath the load. A better Young's modulus suggests a stiffer fabric that requires higher tiers of strain to result in deformation. By evaluating the stress-pressure curves acquired from numerical simulations and experimental testing, engineers can validate the accuracy of the numerical version and verify its predictive abilities. Discrepancies between the two curves can also suggest areas where the numerical version desires refinement or calibration. Conversely, near settlement among the curves presents self-assurance in the accuracy of the numerical simulations and allows engineers to apply the version to discover the structural behavior of the hexagonal honeycomb shape below exceptional loading conditions and design situations. This graphical representation facilitates the validation of numerical results, evaluation of material conduct, and optimization of structural designs for greater performance.

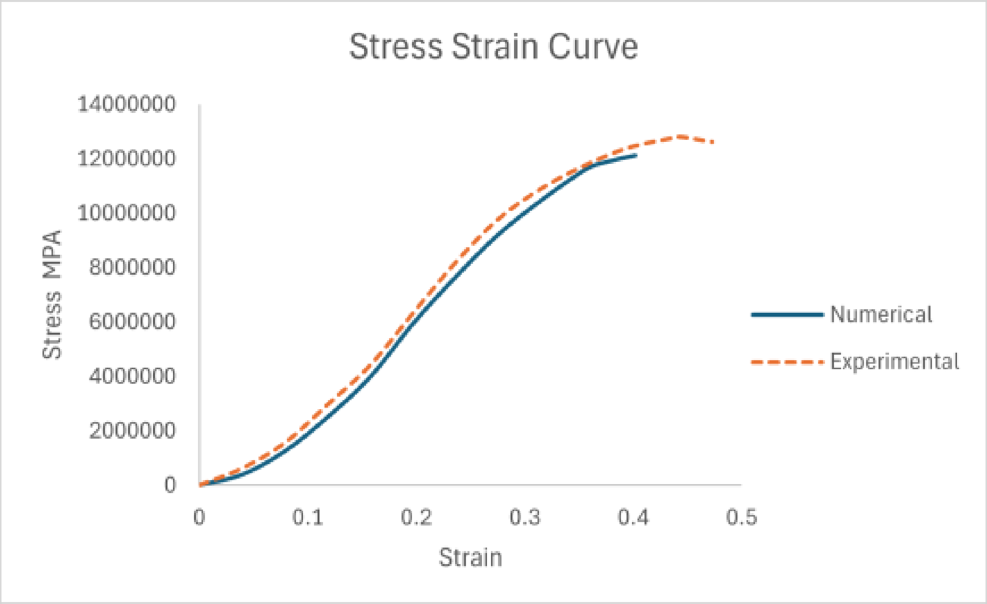


Figure 32: stress-strain curve of hexagon configuration

Figure 33 displays the load-deformation curve graph for the hexagonal shape, showcasing two wonderful curves representing the effects obtained from numerical simulations and experimental testing. This graphical representation gives precious insights into the mechanical reaction of the hexagonal honeycomb structure underneath applied hundreds. The horizontal axis of the graph normally represents deformation, which refers to the change in form or size of the shape in response to implemented loads. Deformation can arise in numerous forms, including stretching, compression, bending, or twisting, depending on the character of the loading situations. In the context of the hexagonal honeycomb structure, deformation frequently involves compression due to the loading scenario considered in the studies. The vertical axis of the graph represents the implemented load, which is the external pressure exerted on the shape. Load is generally measured in devices of pressure, such as Newtons (N) or pounds (lbs.), and quantifies the significance of the forces appearing at the shape. As the applied load increases, the structure reviews extra degrees of deformation. The load-deformation curve itself illustrates the connection between the carried-out load and the ensuing deformation of the structure. Initially, as the load is carried out, the structure undergoes elastic deformation, meaning that it deforms reversibly and returns to its authentic shape once the weight is eliminated. This elastic deformation segment is characterized using a linear relationship between load and deformation, with a steady slope representing the shape's stiffness.

Beyond a certain point, referred to as the yield point or yield load, the structure starts off evolving to go through plastic deformation, in which everlasting changes in shape arise. Plastic deformation is typically associated with the rearrangement of cloth microstructures and the onset of irreversible changes. The load-deformation curve inside the plastic deformation area can also exhibit nonlinear behavior, indicating the revolutionary deformation of the structure underneath increasing masses.

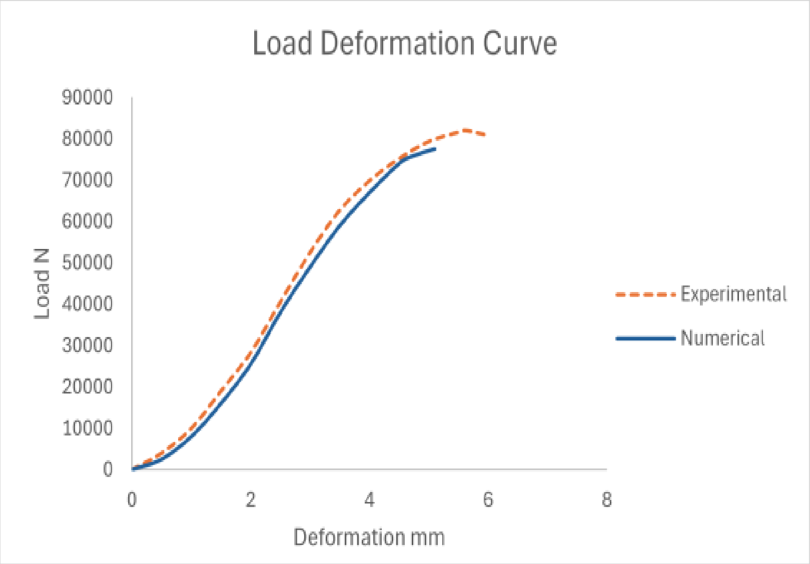


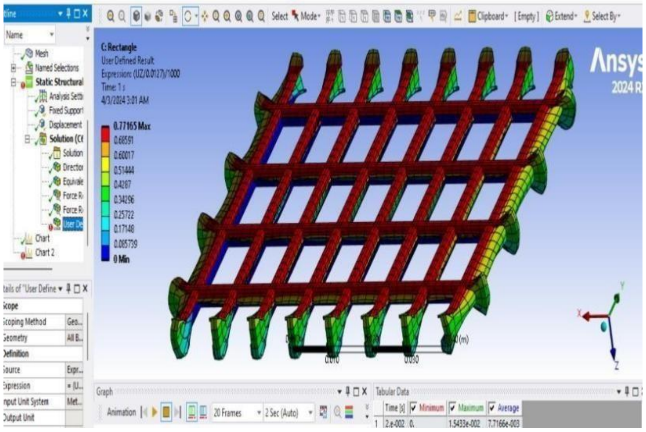
Figure 33: Load Deformation curve of hexagon configuration

The closing point at the load-deformation curve represents the maximum load that the structure can resist earlier than failure occurs. This is referred to as the final load or failure load and corresponds to the factor wherein the structure collapses or fractures underneath the implemented load. The load-deformation curve can also show off a sudden drop or plateau at this factor, indicating the failure of the shape. By comparing the weight-deformation curves obtained from numerical simulations and experimental experiments, engineers can examine the accuracy and reliability of the numerical model in predicting the structural response of the hexagonal honeycomb shape. Discrepancies between the two curves might also suggest regions in which the numerical version requires refinement or calibration to represent the actual conduct of the structure. Conversely, near settlement among the curves provides confidence in the predictive skills of the numerical simulations and allows engineers to apply the model for additional analysis and optimization. In summary, Figure 33 serves as an important tool for understanding the mechanical conduct of the hexagonal honeycomb structure using visually representing the connection among carried-out masses and resulting deformations. This graphical illustration allows validation of numerical fashions, assessment of structural overall performance, and optimization of design parameters for stronger reliability and performance.

Fig 34-37 shows the comparison of numerical and experimental testing of over expanded hexagon including the stress-strain curve and displacement curve. The study investigates the mechanical behavior of an over-extended hexagon through a comparative evaluation of numerical simulation and experimental trying out. Over-elevated hexagons are of precise interest due to their unique deformation characteristics, which may significantly affect structural integrity and overall performance below loading situations. In the numerical evaluation, Finite Element Analysis (FEA) is used to simulate the behavior of the over-multiplied hexagon. The hexagon is discretized into finite elements, and the governing equations of mechanics are solved iteratively to expect strain, pressure, and displacement distribution in the shape. Various loading scenarios, such as axial compression and lateral expansion, are simulated to assess the structural reaction under distinct situations. Experimental trying out involves physically subjecting the over-accelerated hexagon to managed loading situations in a laboratory place. A physical specimen of the hexagon is fabricated, and specialized devices such as load cells, stress gauges, and displacement sensors are used to measure its mechanical reaction. The specimen is step-by-step loaded, and statistics concerning carried out load, displacement, and pressure are recorded at some point in the test to assess the structural conduct. Upon finishing touch of each numerical simulation and experimental testing, a complete contrast of the consequences is conducted to assess their agreement and discover any discrepancies.

Figure 34: Experimental testing result of overexpanded hexagon shape

The Stress-strain curves obtained from numerical simulation and experimental testing are compared to assess their similarity, thinking about elements together with fabric residences and loading situations. Additionally, the displacement behavior of the over-elevated hexagon is analyzed, with a unique interest in deformation patterns and structural stability. If substantial disparities exist among the numerical and experimental consequences, similarly validation and calibration of the numerical model can be essential to enhance its accuracy. This manner might also additionally include adjusting version parameters, refining the mesh, or incorporating additional experimental records to better suit the determined behavior of the over-elevated hexagon. The motive is to extend a dependable numerical version that predicts the mechanical response of the structure beneath various loading conditions. In the quit, the assessment among numerical simulation and experimental testing gives valuable insights into the mechanical conduct of an over-extended hexagon. By carefully reading pressure-pressure relationships and displacement behavior, engineers can refine their statistics of the structural reaction and optimize the layout of over-increased hexagonal structures for specific programs. Further studies may additionally be interested in exploring the outcomes of various material houses, geometric configurations, and loading situations to beautify the overall performance and reliability of such structures in practical engineering applications.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Input Unit System | Met...
Output Unit |

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Figure 35: Numerical Testing result of over-expanded hexagon configuration

Figure 36 reveals the load-deformation curves especially tailor-made for the over-improved hexagonal shape, offering a comparative analysis of consequences derived from each numerical simulation and experimental testing. This graphical representation serves as a complete tool to dissect how the over-increased hexagonal honeycomb shape reacts to growing ranges of applied load in correlation with the resulting deformation. On the horizontal axis, the graph plots deformation, showcasing the structural adjustments placed below that have an impact on outside forces. This metric, crucial for understanding the material's reaction to loading conditions, encompasses modifications in form or period. Conversely, the vertical axis illustrates load, quantifying the importance of the door forces exerted at the form.

A load-deformation curve, additionally known as a stress-pressure curve or pressure-displacement curve, is a graphical illustration that illustrates the connection between the performed load (force) and the following deformation (displacement) of a fabric or shape. This curve is important in expertise on how materials respond to out of doors forces and is drastically applied in mechanical trying out and materials engineering. The horizontal axis of the curve represents deformation, which refers to the alternate shape or length of the fabric or shape under the influence of implemented hundreds. Deformation can arise in diverse forms which include stretching, compression, bending, or twisting. It is generally measured in devices of period (e.g., millimeters, inches) or displacement (e.g., micrometers, nanometers). Deformation is important for assessing the fabric's conduct and structural integrity under specific loading conditions. The vertical axis of the curve represents load, which quantifies the importance of the outside forces applied to the fabric or shape. Load is usually measured in devices of pressure together with Newtons (N) or pounds-pressure (lbf). It indicates the amount of force exerted on the cloth, inflicting deformation. Load performs a pivotal role in figuring out the cloth's reaction to outside forces and its capacity to face up to carry out hundreds without failure.

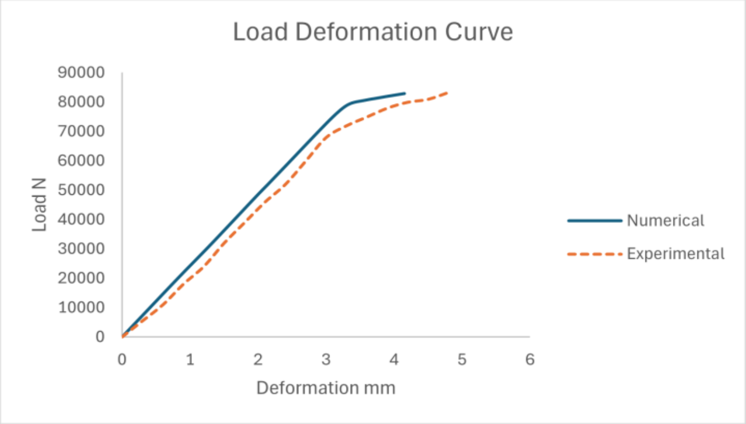

Figure 36: Load-deformation curve of over-expanded hexagon shape

The load-deformation curve is usually famous for numerous awesome areas, each like exceptional stages of structure behavior. At the beginning of the curve, the cloth undergoes elastic deformation, wherein it deforms reversibly under implemented loads connection between load and deformation is linear, consistent with Hooke's Law. Beyond a certain point, referred to as the yield point, the fabric starts to evolve to go through plastic deformation, where permanent changes in form occur even after the load is removed. The yield factor signifies the onset of plasticity in the fabric. In the plastic deformation vicinity, the fabric continues to deform plastically beneath growing masses, and the connection between load and deformation can also emerge as nonlinear. The load-deformation returns to its unique shape as soon as the weight is eliminated. In this area, the curve reaches its top on the ultimate load, representing the most load that the material can withstand before failure happens. Beyond this point, the material undergoes rapid deformation until failure. The curve ends at the fracture point, wherein the material fails catastrophically under the carried-out load, resulting in complete structural failure.

In Figure 37, we see stress-stress curves for the overextended hexagonal form, with separate traces representing results from numerical simulations and physical checking out. This visual resource enables us to recognize how the hexagonal honeycomb shape reacts to exceptional strain and pressure ranges. On the horizontal axis, stress measures the cloth's deformation relative to its authentic length underneath the carried-out load. It's an important indicator of elasticity and resilience to outside forces. The vertical axis shows strain, which quantifies pressure consistent with the unit area on the fabric. Stress gauges the structure's inner resistance in opposition to deformation, indicating its strength and capacity to resist outside pressures earlier than failure. The pressure-pressure curve illustrates the connection between strain and stress at some stage in deformation. Initially, in the elastic phase, the curve suggests a linear dating, signifying the cloth's ability to return to its authentic shape after load removal without permanent deformation. Stress-stress evaluation is a cornerstone in materials technology and engineering, particularly relevant to the exam of structures like the hexagonal honeycomb shapes referred to in the previous

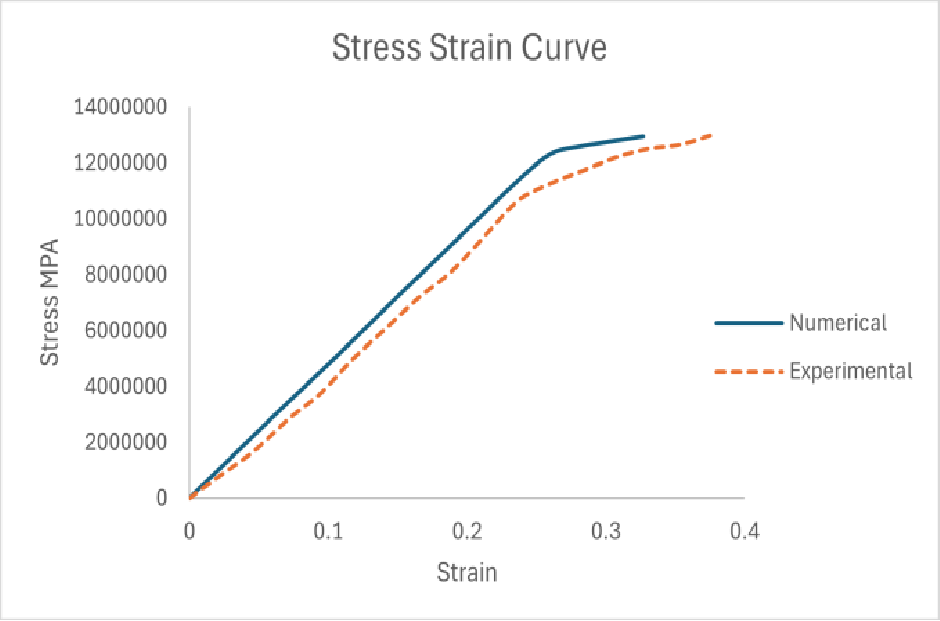

Figure 37: stress-strain curve Square of over-expanded hexagon shape

questions. Stress denoted using the symbol σ, represents the internal resistance within a material while subjected to outside forces, whilst strain, indicated by using ε, quantifies the cloth's deformation beneath such hundreds. These concepts are paramount in assessing how substances perform under numerous conditions. The closing tensile strength (UTS) indicates the most stress the cloth can undergo before failure. Additionally, parameters like the modulus of elasticity (Young's modulus) symbolize the cloth's stiffness, even as longevity and ductility denote its capability to take in power and undergo plastic deformation earlier than fracturing, respectively. By comprehensive knowledge of pressure and strain conduct via stress-strain analysis, engineers can optimize material designs and structural configurations for more suitable overall performance and reliability, as exemplified using the meticulous examination of strain-strain curves, aiding within the validation of numerical models and assessment of structural integrity under varying loading situations.

Fig 38-41 shows the comparison of numerical and experimental testing of squares including stress-strain and displacement. The comparative assessment supplied in Figures forty-four-forty-seven investigates the mechanical conduct of a square shape through each numerical simulation and experimental attempt. Square structures are essential elements in engineering layout, and understanding their response to diverse loading situations is essential for ensuring structural integrity and overall performance. The numerical evaluation uses Finite Element

Analysis (FEA) to simulate the conduct of the square shape underneath particular loading scenarios. Finite Element Analysis (FEA) is a complicated computational technique extensively applied in engineering to simulate and examine the structural behavior of complex systems subjected to numerous loading conditions. In the specific context of the studies mentioned above, FEA serves as a pivotal tool for comprehensively knowing the mechanical response of honeycomb structures produced via Fused Deposition Modelling (FDM). The process of FEA entails numerous complex steps, each contributing to in-depth data on the shape's overall performance. The preliminary segment of FEA encompasses the creation of a digital example of the honeycomb structure's geometry using specialized software. This digital model successfully captures the problematic statistics of the form, which include the form and dimensions of individual cells. Geometry has to be meticulously defined to make certain that it displays the real-global counterpart faithfully. Once the geometry is hooked up, the subsequent step involves mesh technology. Meshing is the system of dividing the shape into smaller, interconnected factors known as finite factors. This discretization is vital for accurately taking pictures of the structural behavior while retaining computational efficiency. The mesh density ought to strike stability between shooting geometric intricacies and minimizing computational sources.

After mesh generation, fabric properties are assigned to the finite elements in the shape. These material properties, consisting of Young's modulus, Poisson's ratio, and density, dictate how the fabric will deform and reply to outside hundreds. In the case of the studies concept, the material homes would be primarily based on the precise characteristics of PLA, the thermoplastic generally utilized in FDM processes. Accurate illustrations of fabric homes are essential for obtaining practical simulation outcomes. Once the material properties are assigned, boundary conditions are described. Boundary situations specify how the shape is restricted and the way external loads are applied. For the compression loading situation taken into consideration within the research, certain points of the shape would be fixed (which include the base), whilst compressive forces would be applied to different regions. With the model completely defined, the software program solves a set of mathematical equations that govern the conduct of the shape below the required loading and boundary situations. These equations usually arise from principles that include equilibrium, compatibility, and cloth constitutive behavior. The answer technique includes iteratively fixing the equations to obtain the displacement, strain, and pressure distributions at some stage in the structure. This analysis offers precious insights into how the honeycomb shape will deform and respond to external masses, allowing engineers to assess its structural integrity and overall performance. Post-processing is an essential step in FEA, wherein the consequences of the analysis are visualized and interpreted. Engineers can have a look at elements which include pressure concentrations, deformation styles, and failure modes to gain a deeper knowledge of the structure's behavior. Visualization equipment allows for the generation of exact plots and animations, assisting with the interpretation of outcomes. Engineers can find out important areas of the form experiencing immoderate stresses or deformations and investigate ability failure modes. FEA also can be used iteratively to optimize the design of the honeycomb systems. By systematically various design parameters and analyzing their outcomes on overall performance metrics along with strength-to weight ratio, engineers can identify the most efficient configurations. Optimization algorithms can be hired to routinely search for the most useful layout parameters, taking into consideration the exploration of a great design area. This iterative optimization process enables engineers to refine the design to meet performance objectives while minimizing cloth usage and manufacturing time.

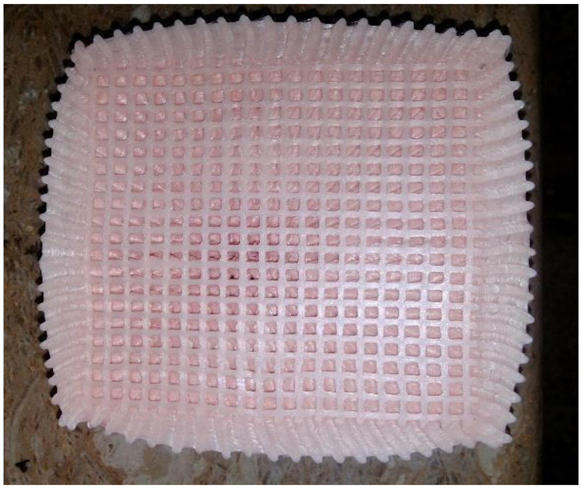

Figure 38: Experimental testing result of square shape

It plays an important role in the research proposal by imparting complete expertise of the mechanical behavior of honeycomb structures synthetic the use of FDM. Through specific modeling, evaluation, and optimization, FEA permits engineers to optimize the design of the systems to fulfill preferred overall performance standards effectively.

Figure 39 displays the numerical analysis results of a structure having a square shape configuration. Square geometry is discretized into finite elements, and the governing equations of mechanics are solved iteratively to expect stress, pressure, and displacement distribution in the shape. Various loading conditions, together with tensile, compressive, and bending masses, are implemented to evaluate the structural response. Experimental testing includes bodily subjecting a square specimen to managed loading situations in laboratory surroundings. A physical specimen of the rectangular shape is fabricated, and specialized gadgets along with load cells, strain gauges, and displacement sensors are used to degree its mechanical response. The specimen is step by step loaded, and records concerning applied load, displacement, and strain are recorded during the check to evaluate the structural conduct. Following the entirety of each numerical simulation and experimental checking out, a comprehensive comparison of the effects is carried out to assess their settlement and pick out any disparities. The stress-strain curves acquired from numerical simulation and experimental testing are compared to evaluate their consistency, thinking about factors at the side of cloth homes and loading conditions. Additionally, the displacement behavior of the square shape is analyzed, specializing in deformation patterns and structural stability. If vast differences exist in several of the numerical and experimental results, similarly validation and calibration of the numerical model can be required to beautify its accuracy. This technique may include adjusting model parameters, refining the mesh, or incorporating extra experimental data to better align with placed conduct. The goal is to develop a reliable numerical model that appropriately predicts the mechanical response of the rectangular shape beneath diverse loading situations. In quit, the evaluation among numerical simulation and experimental sorting out provides precious insights into the mechanical behavior of a square structure. By analyzing strain stress relationships and displacement behavior, engineers can refine their information on structural reactions and optimize the layout of square systems for precise programs. Further research may additionally discover the outcomes of numerous cloth houses, geometric configurations, and loading conditions to improve the performance and reliability of rectangular structures in practical engineering situations.

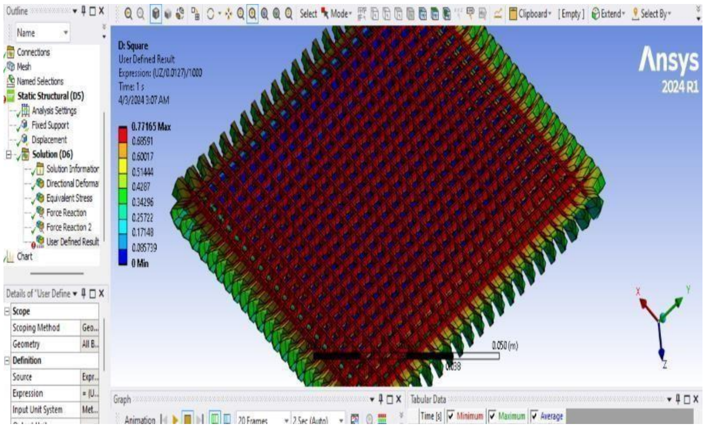

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Figure 39: Numerical analysis result of square shape

Figure 40 gives the load-deformation curves especially tailored for the square form, presenting a comparative assessment of effects received from each numerical simulation and experimental testing. This graphical illustration offers an in-depth notion of how the square honeycomb shape responds to increasing stages of implemented load alongside facet ensuing deformation. On the horizontal axis, the graph depicts deformation, showcasing the structural changes determined below that have an impact on outside forces. This metric is essential for information on how the cloth responds to loading situations, encompassing adjustments in form or length. Conversely, the vertical axis illustrates load, quantifying the fee of the outdoor forces exerted on the shape.

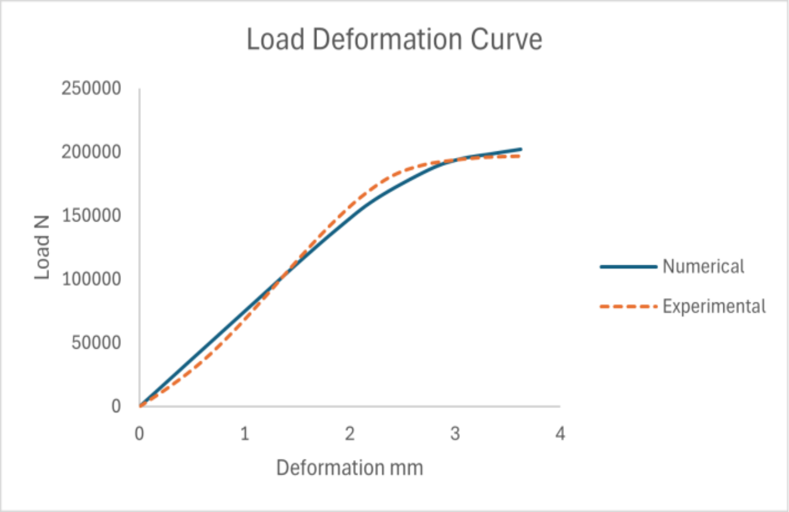

Figure 40: Load-deformation curve of over-expanded hexagon shape

Figure 41 illustrates the stress-strain curve for the rectangular honeycomb form, imparting wonderful curves representing consequences from numerical simulations and experimental checking out. This visible illustration gives a detailed expertise of the manner the rectangular honeycomb shape responds to special stages of applied stress, relative to the resulting stress. On the horizontal axis, stress is plotted, depicting the degree of deformation skilled via the fabric relative to its precise dimensions beneath the carried-out stress. Strain serves as a vital metric for evaluating the cloth's elasticity and its functionality to bear external forces without eternal deformation. Conversely, the vertical axis portrays stress, quantifying the force steady with the unit place exerted on the cloth. In summary, figure 41 serves as a pivotal visible beneficial resource for comprehending the mechanical conduct of the square honeycomb structure, supplying crucial insights into its electricity and deformation traits below numerous loading situations. This graphical illustration allows the validation of numerical models, assessment of material behavior, and optimization of structural designs for improved performance and reliability.

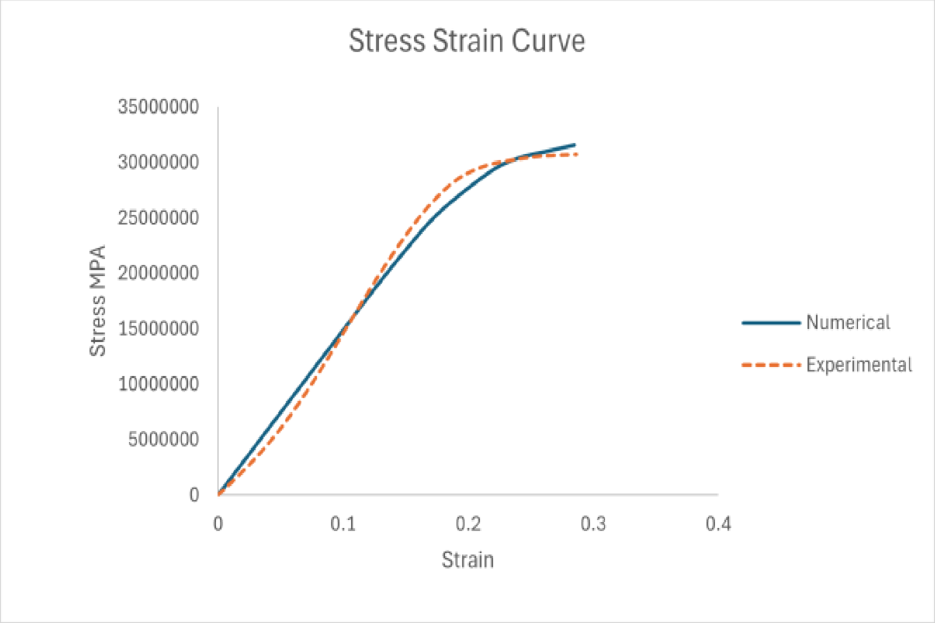

Figure 41: stress-strain curve of square shape

Experimental and numerical results comparison with optimized results by MOO and ANOVA. A careful study is required when comparing experimental and numerical findings for different geometries (hexagon, over-expanded hexagon, and square). To begin, experimental data is derived from real-world observations, which are frequently obtained by physical testing or measurements.

ANOVA provides a statistical layer to this research, allowing for the measurement of performance differences across improved geometries. ANOVA allows researchers to assess whether observed differences are statistically significant or may be attributable to random chance.

Table 8: Comparison of experimental, numerical, and optimized strength-to-weight ratios

Cell shapes	Hexagon	Over-expanded hexagon	Square
Experimental Strength-to ratio (MNM/Kg)	49.77	45.79	48.7
Numerical Strength to-ratio (MNM/Kg)	47.1	45.52	50
Optimized Strength to weight ratio (MNM/Kg)	51.29	47.3235	48.17

Hence, in addition to numerical results, the data provides exact information to decipher the real performances of these geometries. Unlike sound systems, numerical simulations employ computational models to calculate how such structures will evolve. However, the assumption of the simulations and the simplifications that it takes before reaching an answer, make it less credible even if such situations can be tested and simulated. Such information is important as it helps determine how closely the numerical models represent the real-world situations they are intended to model, which is why experiments and numerical data comparisons are important. Said comparison helps in the evaluation of the reliability of the simulation models by establishing whether they faithfully depict the real-world phenomena of interest. The second MOO methodology is to determine this type of gradual ideal solution for all objective functions (which are for most of the time conflict with each other). This involves the establishment of several selection/objection criteria such as efficiency, as well as loss minimization, and then the use of MOS methodologies to investigate any trade-offs that may emerge. Researchers are particularly interested in challenging geometries requiring the best performance and efficiency optimizing them for a specific use.

Chapter 6 Conclusion & Recommendations

6.1 Comparisons

Figures 42& 43 also help us to conclude. The conclusion drawn from the cost comparison is explained below.

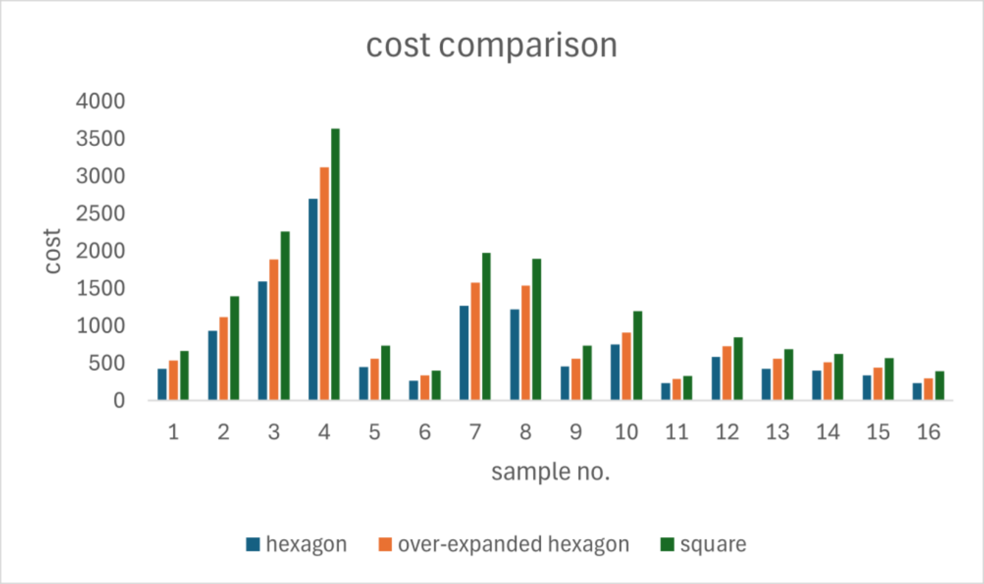

Figure 42: Manufacturing cost comparison of hexagon, over expanded hexagon and square shape structures

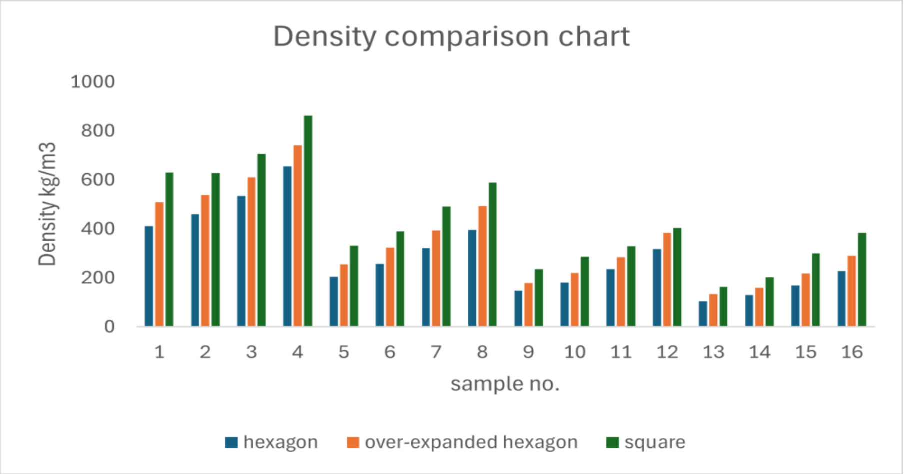

Figure 43: Density comparison chart

Figure 43 shows the density comparison of all 48 printed structures which clearly shows that hexagonal shape structures have low densities, and this is one of the reasons that the manufacturing cost of hexagon shape honeycomb structures was less as compared to the other two (over-expanded hexagon and square shape) configurations. Choosing the best cellular configuration based on less manufacturing cost was one of our main objectives therefore the comparisons which are shown in Figures 42& 43 help us to choose the best cellular configuration based on less manufacturing cost which is hexagon shape.

6.2 Conclusion

Finally, our study sought to compare the strength-to-weight ratios of three distinct cellular shapes: hexagonal, square, and over-expanded hexagon. These results, however, fall in line with contemporary studies, stressing consensus on contending the lessening of subsidies as the best approach to stimulating agricultural production. The hexagonal structures are creative designs that can be used for basic experiments, validations, and testing as they are the most simple and efficient structures. The best feature of these structures is a combination of low cost, low weight, and high ratios strength-to-weight. This property makes these materials perfect for practical use. Through our work, we identified parameters under fluctuations of strength-to-weight ratios and cost decreases contributing to general commercialization efforts which hopefully will help future studies and industrial applications. While the hexagonal structures proved the most reliable means of survival under our conditions, it is necessary to admit that the square and over-expanded hexagon designs might also deliver beneficial outcomes in some cases. Such a design might yield advantages in some areas and should be critically assessed to see whether it is ready for implementation in future experiments. Thus, summing up, our investigation reveals the main feature of the cellular pattern selection aimed at achieving the twofold effect: to enhance the ratio of strength to weight and to reduce production expenses. Not only do they pick hexagonal designs, but they give facts and analysis to back their standard up so their only potential to be better is to improve their performance.

The conclusions drawn from this investigation are described below:

- Our results show that increasing cell size and core height decreases the strength of honeycomb structures while increasing cell wall thickness enhances strength.
- Hexagonal structures outperform square and over-expanded hexagonal designs in terms of strength-to-weight ratio.

- In addition to performance, our analysis considered production time and costs. Hexagonal designs not only have a better strength-to-weight ratio but are also quicker and cheaper to produce than square and over-expanded hexagonal forms.
- Optimized geometrical parameters for strength-to-weight ratio and cost were identified: hexagonal (6mm cell wall length, 1mm thickness), over-expanded hexagon (9mm length, 1.5mm thickness), square (3mm length, 0.5mm thickness), all with a core height of 12.7mm.
- Optimized results were validated through experimental and numerical analysis with a 2 to 3 percent variation in results.

6.3 Recommendations

- While we operated on these forms such as hexagonal, square, as well, and over-expanded hexagon ones, future investigation could also look in the direction of the larger comprehensive collaboration of cellular arrangement Struggling with the not-so-standard forms and shapes could result in finding a superior building design that is, of course, way better in terms of its efficiency.
- Our study used PLA material to make honeycombs using the FDM printing technology. With dynamic analysis, we investigated the effect of the honeycomb structures on the deflection and natural frequency of the printed string. Tomorrow's research may consider instead the use of other materials with better mechanical performance. Such materials may include carbon fiber-reinforced plastics or metal mixtures, and they will help to improve strength and lifetime.
- We established proper conditions for increasing strength-to-weight ratios and lowering production costs. Nevertheless, there is still much room for improving these circumstances and it is possible to render them even more effective. Tuning in variables like layer thickness, infill density, and printing speed prevents production’s downside (e.g. more complex structural performance and savings of $).

- Making computer simulations with tools such as finite element analysis (FEA) or CFD for implementation of the design items is the best solution to get more specific info about the mechanical behavior and performance of honeycomb structures. They can assist in the achievement of design improvement connected with the answer to the question of how the body will behave under various stresses.

- The growing significance of sustainability justifies future research into the role of additive manufacturing methods and materials in the solution of environmental and ecological problems. It is vital to study eco-friendly materials and enhance processes to minimize energy use and waste production that can help achieve robust green practices in manufacturing.

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