ISSN: 2583-5688 Volume: 003 (2024), pp. 21-30

Design and analysis of a honeycomb structure

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Abstract

Honeycomb structures have long been recognized for their exceptional mechanical efficiency, offering a high strength-to-weight ratio, effective energy absorption, and structural versatility. With the rise of additive manufacturing, particularly 3D printing, the potential to design and fabricate intricate honeycomb geometries has expanded significantly. This study investigates the mechanical performance of honeycomb panels constructed using three distinct materials: Poly lactic Acid (PLA), Stainless Steel 316L, and Titanium Alloy Ti6Al4V. Through Finite Element Analysis (FEA), each material's behavior under compressive loading was simulated and analyzed to understand their deformation characteristics, stress distribution, and overall structural integrity. The findings reveal that PLA, while eco-friendly and lightweight, is best suited for low-load applications, whereas Titanium Alloy Ti6Al4V offers the highest performance under demanding mechanical conditions. Stainless Steel 316L strikes a balance between strength and cost but introduces significant weight. This research underscores the importance of material selection in honeycomb design and highlights promising directions for future exploration, including hybrid material systems, functionally graded lattices, and AI-assisted topology optimization.
Keywords: *Honeycomb Structure, Additive Manufacturing, PLA, Titanium Alloy, Stainless Steel 316L, FEA, Mechanical Performance.*

1. Introduction

Nature has long served as a source of inspiration for engineering solutions, and one of the most striking examples is the honeycomb structure. Characterized by its repeating hexagonal pattern, this geometry is remarkably efficient—it provides high strength and stiffness while using minimal material. This makes it especially attractive in fields such as aerospace, automotive, and civil engineering, where optimizing the strength-to-weight ratio is critical. Honeycomb structures are often employed in components that need to bear loads or absorb energy during impact, such as aircraft panels, car crumple zones, and structural reinforcements in buildings.

With the rise of additive manufacturing technologies, particularly 3D printing, it has become increasingly feasible to fabricate these intricate geometries with great precision. Unlike traditional manufacturing methods, 3D printing allows for more complex designs and the use of a wide range of materials, including polymers, metals, and composites. This technological advancement opens up new possibilities for tailoring the mechanical properties of honeycomb structures to suit specific applications.

In this study, the focus is on evaluating how different materials influence the mechanical behavior of a honeycomb structure under compressive loading. To ensure a fair comparison, the geometry of the honeycomb is kept constant while only the material properties are varied. Using simulation tools such as finite element analysis (FEA), the structures are subjected to compressive forces, and their responses—such as deformation patterns, stress distribution, and failure modes—are analyzed. This approach allows for a detailed understanding of how material selection impacts the structural performance of honeycomb designs and helps guide engineering decisions in real-world applications.

2. Materials and Methods

The simulation approach used in this study is inspired by the methodology outlined by Alwattar and Mian (2019). To understand the mechanical behavior of the honeycomb design more accurately, two models were created and compared: one representing the actual honeycomb lattice geometry and the other a simplified equivalent solid block. Both models shared the same outer dimensions to ensure a fair comparison.

The honeycomb structure model reflects the real structure with its repeating hexagonal cells and thin walls, closely matching the geometry of the 3D-printed PLA samples used in this project. In contrast, the equivalent elastic model replaces the cellular geometry with a uniform solid material that mimics the overall mechanical response of the honeycomb structure. In other words, even though this equivalent model doesn't include the detailed lattice design, it is expected to show similar stress–strain behavior under identical loading conditions. This comparison helps validate the mechanical efficiency of the honeycomb structure and supports the idea that its unique geometry, rather than just the material, plays a significant role in achieving strength with reduced weight.

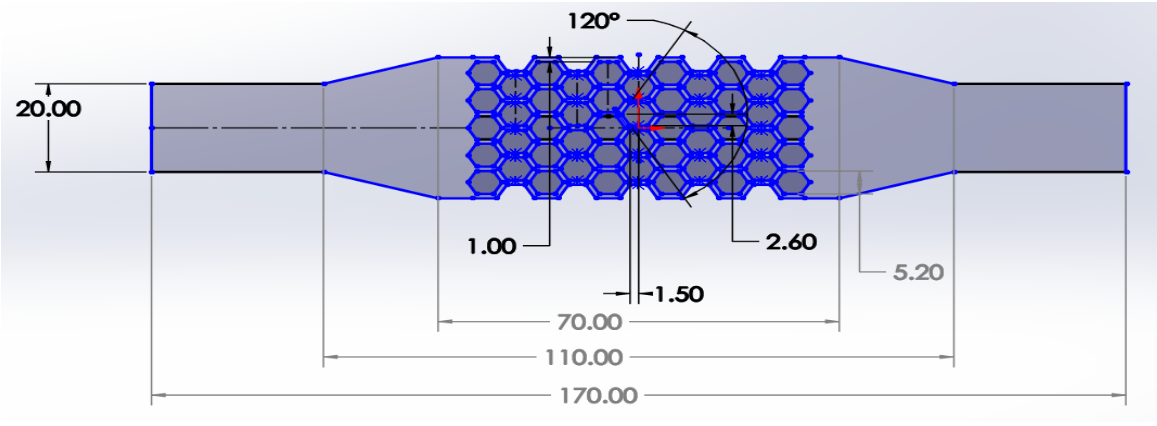

Fig 1. Material Comparison: PLA vs. Stainless Steel 316L vs. Titanium Alloy Ti6Al4V

Table 1. **PLA** is ideal for low-cost, low-stress, environmentally sustainable applications.

Aspect	PLA (Polylactic Acid)	Stainless Steel 316L	Titanium Alloy Ti6Al4V
Origin	Bio-based (renewable)	Industrial alloy (iron, chromium, nickel)	Aerospace-grade metal (titanium, aluminum, vanadium)
Weight	Very lightweight	Heavy	Lightweight
Strength	Low to moderate	High	Very high
Elastic Modulus	~3.5 GPa	~200 GPa	~110 GPa
Ductility	Brittle	High	Moderate
Thermal Resistance	Poor (softens ~60°C)	Excellent	Excellent
Corrosion Resistance	Low	Very high	Very high
Durability	Low (limited outdoor use)	Long-lasting	Extremely durable
Biodegradability	Yes	No	No
Recyclability	Limited	High	High
Ease of 3D Printing	Very easy (low temp)	Moderate	Complex (requires inert atmosphere)
Post-processing Needs	Minimal	Moderate (finishing, stress relief)	High (machining, heat treatment)
Cost	Low	Moderate	High
Sustainability	Excellent (eco-friendly origin)	Good (recyclable, durable)	Good (long service life offsets production energy)

Aspect	PLA (Polylactic Acid)	Stainless Steel 316L	Titanium Alloy Ti6Al4V
Best Use Cases	Prototyping, packaging, temporary structures	Structural supports, industrial components	Aerospace, medical implants, high-performance structures

Stainless Steel 316L balances strength and durability with relatively manageable production complexity, suitable for long-term structural use.

Titanium Alloy Ti6Al4V is unmatched in strength-to-weight performance but requires high-cost, precise manufacturing environments, best suited for critical applications.

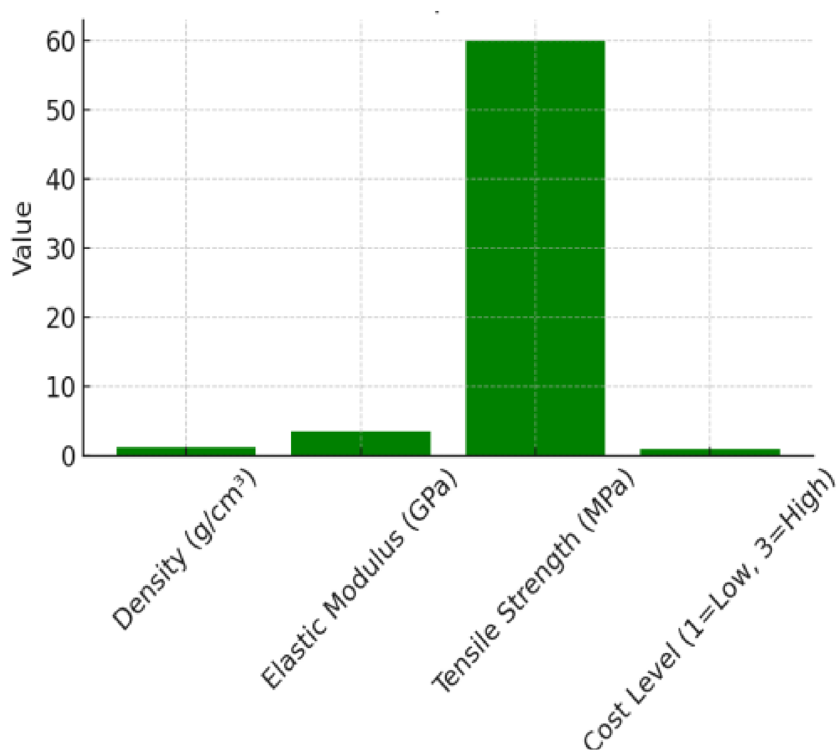

Fig 2. Material Properties of PLA

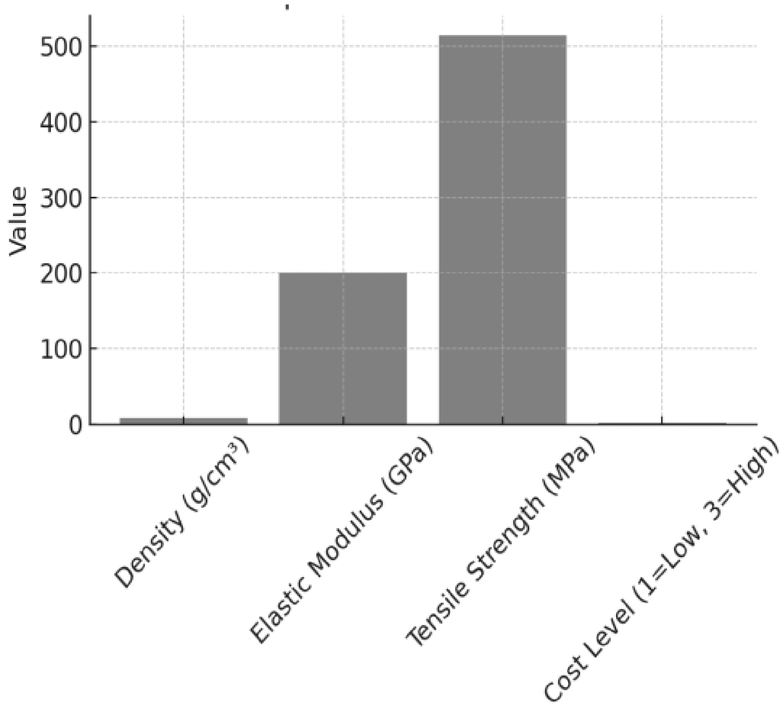

Fig 3.Material Properties of Stainless Steel 316L

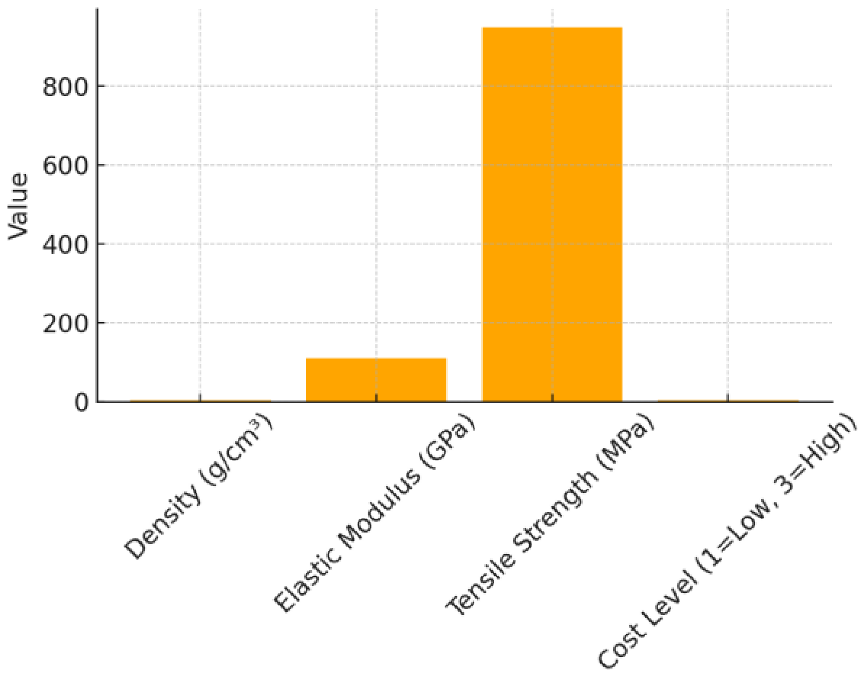

Fig 4.Material Properties of Titanium Alloy II6AI4V

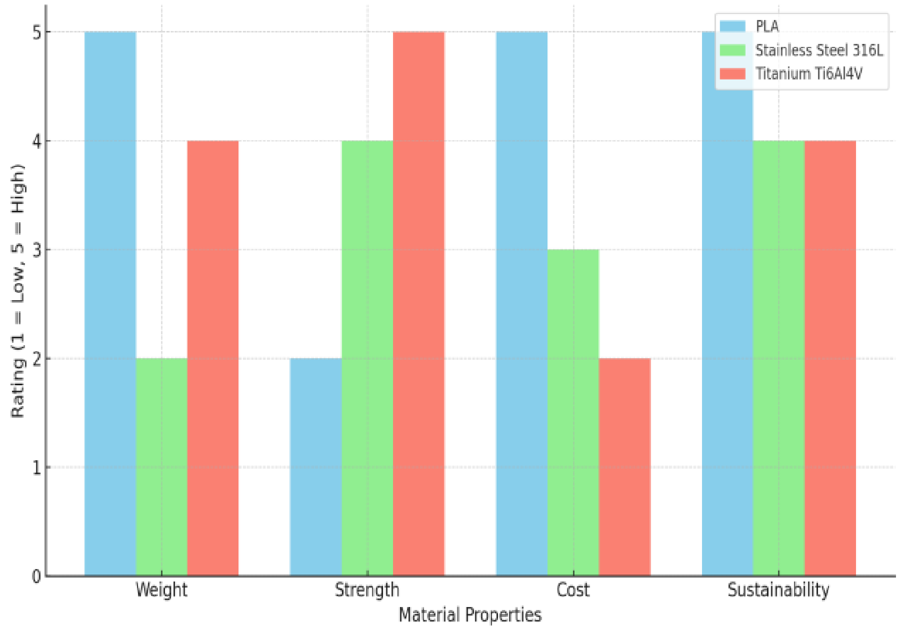

Fig 5. Comparison Material Performance for Honeycomb Structures

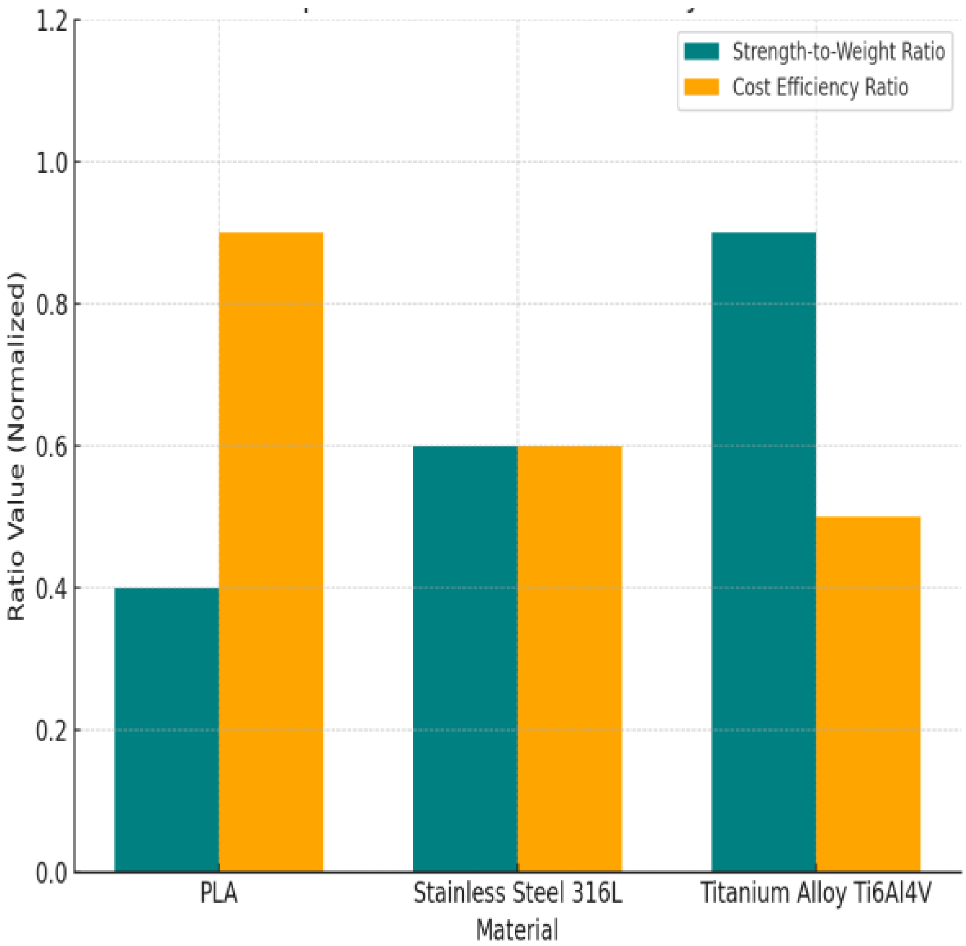

Fig 6.Comparison of Material efficiency Ratios.

3. Environmental and Economic Benefits

3.1 Benefits of Using PLA in Honeycomb Structures

Eco-Friendliness and Sustainability

PLA (Polylactic Acid) is derived from renewable sources like corn starch and sugarcane, making it one of the most environmentally friendly materials used in additive manufacturing. Its biodegradable nature ensures that it decomposes naturally, reducing plastic waste and supporting sustainable product life cycles.

Low Manufacturing Waste

In 3D printing, PLA is used with precision, generating minimal waste. Combined with the naturally efficient honeycomb geometry, PLA structures are both lightweight and resource-conscious.

Cost-Effective Prototyping

PLA is relatively inexpensive and easy to work with, which makes it ideal for rapid prototyping and low-load structural applications. It allows for quick iterations in design without significant material costs, enabling faster product development.

3.2 Benefits of Using Titanium Alloy in Honeycomb Structures

High Strength-to-Weight Ratio

Titanium Alloy Ti6Al4V is prized for delivering high mechanical strength while remaining lightweight. This makes it ideal for aerospace and biomedical applications, where performance must not come at the cost of added mass.

Long-Term Durability and Reduced Maintenance

Due to its exceptional corrosion and fatigue resistance, titanium structures last significantly longer than many other materials. This reduces the need for frequent replacements, lowering overall lifecycle costs.

Energy Efficiency through Lightweight Design

In transportation and aerospace, titanium's lightness contributes to improved fuel efficiency. Lighter components reduce energy consumption over time, helping lower environmental impact.

3.3 Benefits of Using Stainless Steel 316L in Honeycomb Structures

Structural Reliability in Harsh Conditions

Stainless Steel 316L is well known for its corrosion resistance and mechanical strength, making it suitable for demanding environments such as marine, chemical, or high-load mechanical systems.

Wide Availability and Manufacturing Ease

The material is widely available and compatible with most conventional and additive manufacturing techniques. This accessibility lowers production costs and simplifies supply chain management.

Recyclability and Material Reuse

One of the key environmental advantages of stainless steel is its recyclability. It can be reused without significant degradation in quality, supporting circular economy practices in engineering and construction.

4. Problems and Limitations of Using PLA, Titanium Alloy and Stainless Steel in Honeycomb Structures

4.1 Polylactic Acid (PLA): Challenges in Strength and Durability

While PLA is widely celebrated for being biodegradable and easy to print using additive manufacturing, its limitations are significant when structural performance is critical. One of the main drawbacks is its brittle nature, which makes it prone to cracking under high stress or impact. PLA also suffers from low thermal resistance; when exposed to elevated temperatures, it tends to soften or deform, which limits its application in environments where heat or mechanical loads are present. Additionally, PLA exhibits limited long-term durability, especially in outdoor settings where moisture and UV exposure can degrade its integrity over time. Although ideal for prototypes or lightweight components, PLA may not be suitable for load-bearing or high-performance honeycomb structures without reinforcement.

4.2 Titanium Alloy (Ti6Al4V): Cost and Printability Constraints

Titanium Alloy Ti6Al4V is recognized for its exceptional strength-to-weight ratio, corrosion resistance, and compatibility with biomedical and aerospace applications. However, these benefits come at a cost—literally. Titanium is expensive to procure and process, which can make large-scale or commercial applications less economically viable. Furthermore, additive manufacturing of titanium demands highly controlled environments due to its reactivity at high temperatures. This makes the printing process complex, requiring specialized equipment such as inert gas chambers and advanced powder handling systems. Post-processing, including heat treatment and surface finishing, also adds to the time and expense. These challenges can limit its use where budget constraints or rapid prototyping are priorities.

4.3 Stainless Steel 316L: High Density and Weight Concerns

Stainless Steel 316L offers outstanding strength, corrosion resistance, and ease of manufacturing, making it a popular choice for industrial honeycomb structures. However, its high density and overall weight pose a challenge, especially in applications where weight savings are essential, such as aerospace and electric vehicles. While it provides mechanical reliability, the trade-off is reduced fuel efficiency and increased structural mass. In terms of 3D printing, stainless steel generally prints well, but it may still require post-processing (e.g., stress relief annealing or machining) to achieve optimal surface finish and precision. Additionally, stainless steel lacks the biocompatibility of titanium and the environmental friendliness of PLA, placing it in a middle ground where performance is excellent, but sustainability and weight reduction are less ideal.

5. Conclusions

5.1 Stress Distribution and Deformation Behaviour

The SolidWorks simulation of the PLA honeycomb structure revealed a relatively even distribution of stress across the hexagonal cells under compressive load. However, higher stress concentrations were observed at the joints where the cell walls intersect. These junctions became focal points for strain accumulation, making them the most likely areas for initial deformation or failure. As the load increased, plastic deformation occurred earlier than in metal-based structures, confirming PLA's limited ductility.

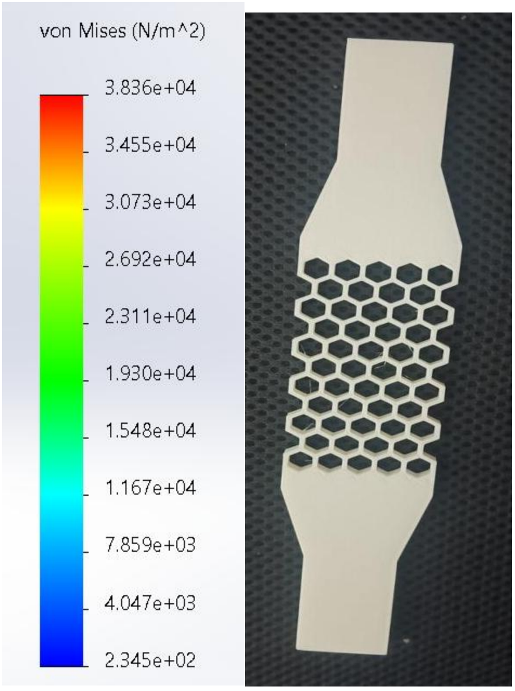

Fig 7. Honey Comb Structure.

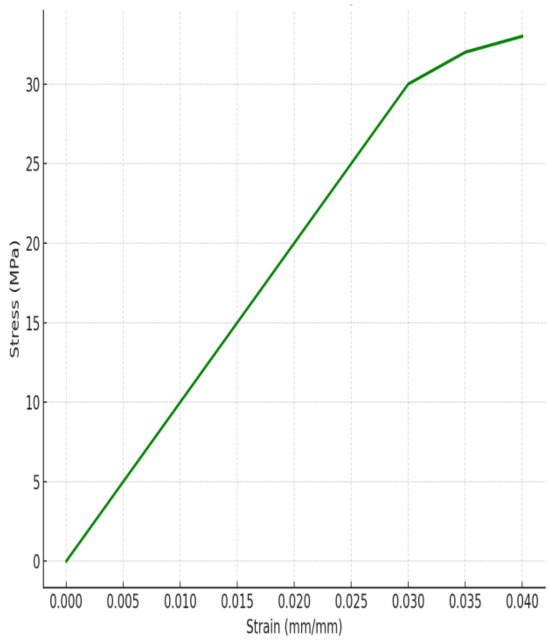

Fig 8. Stress Strain Curve for PLA Honeycomb structure.

5.2 Mechanical Performance Under Compression

The stress-strain chart generated from the simulation showed that PLA maintained a linear elastic response up to a moderate load before yielding. Beyond this point, the material exhibited a sudden drop in stiffness, indicating brittle fracture characteristics. The structure's ability to withstand compressive loads without significant displacement was effective up to a threshold, beyond which wall buckling and micro-cracking initiated.

5.3 Material Suitability and Application Insights

The simulation results reinforce PLA's suitability for non-critical structural applications where lightweight design, low cost, and environmental sustainability are prioritized. It is especially appropriate for prototyping, custom packaging, and temporary structural components. However, its mechanical limitations—especially under higher stress—highlight the need for design reinforcement, either through geometry optimization or material blending with tougher polymers or fibers.

5.4 Design Considerations from FEA Analysis

To improve performance, the simulation suggests that wall thickness, infill density, and cell size should be carefully optimized. Even minor adjustments in these parameters can significantly impact stress distribution and delay the onset of failure. Additionally, reinforcing high-stress regions (e.g., cell junctions) or integrating support ribs could enhance durability.

6. Future Scope

Looking ahead, honeycomb structures offer a wealth of opportunities for continued innovation, particularly as new materials and design technologies mature. One of the most promising directions is the development of hybrid honeycomb systems that blend polymers and metals to combine the advantages of both material types. For example, a titanium shell with a PLA or carbon-fiber-reinforced core could deliver high mechanical strength while significantly reducing overall weight and material costs. Additionally, the concept of functionally graded honeycomb structures is gaining traction. These are designed to gradually change in density, cell size, or wall thickness across the structure. Such customization allows engineers to tailor stiffness, energy absorption, and thermal behavior according to specific performance requirements—ideal for components exposed to variable loads or thermal gradients, such as aerospace panels or medical implants. The future of honeycomb design is also closely tied to smart and responsive materials. By embedding strain sensors, conductive filaments, or piezoelectric materials directly into the honeycomb lattice during 3D printing, structures could become self-monitoring. This would enable real-time feedback on stress, damage, or environmental conditions, leading to safer and more adaptive systems in aerospace, automotive, and civil infrastructure. Artificial intelligence (AI) and topology optimization algorithms are revolutionizing structural design by enabling engineers to create forms that are not just efficient, but intelligently shaped for the exact forces they will experience. In honeycomb structures, AI can be used to automatically optimize the geometry and distribution of cells based on simulations or real-time performance data, significantly improving both durability and material efficiency. Furthermore, as sustainability becomes a global engineering priority, biodegradable and recycled materials will play a larger role in the design of temporary or modular honeycomb structures. These could be used in disaster-relief shelters, packaging, or even 3D-printed construction components that are both strong and environmentally responsible.

References

1. Gibson, L. J., & Ashby, M. F. (1997). Cellular Solids: Structure and Properties (2nd ed.). Cambridge University Press.
2. Du Plessis, A., et al. (2018). Beautiful and Strong: The Complex Microarchitecture of Nature-Inspired Cellular Materials. Nature Reviews Materials, 3(12), 440–456.
3. Fang, D., & Wang, Y. (2018). Mechanics of Metamaterials with Negative Poisson's Ratio Based on Re-Entrant Honeycomb. International Journal of Solids and Structures, 146, 1–13.
4. Wannarong, W., & Singhanart, P. (2019). A Review of Sandwich Composite Structures with 3D Printed Honeycomb Cores. Procedia Manufacturing, 30, 156–163.
5. Là, L. T., et al. (2020). The 3D Printing of Novel Honeycomb–Hollow Pyramid Sandwich Structures for Microwave and Mechanical Energy Absorption. Additive Manufacturing, 36, 101565.
6. Zhao, Y., et al. (2018). Design and 3D Printing of Honeycomb Structures with Graded Densities for Energy Absorption. Materials & Design, 137, 394–404.

7. Yang, X., et al. (2020). Experimental Study on the Compression Properties of 3D Printed Honeycomb Structures with Different Cell Shapes. Composite Structures, 248, 112533.
8. Rad, M. S., et al. (2021). Mechanical Properties and Energy Absorption of Additively Manufactured Honeycomb Structures: A Review. Additive Manufacturing, 39, 101701.
9. Ali, A., et al. (2021). Optimizing Impact Toughness in 3D-Printed PLA Structures Using Hilbert Curve and Honeycomb Infill Patterns. Materials Today: Proceedings, 47(9), 3775–3780.
10. Yang, L., et al. (2019). Mechanical Behavior and Energy Absorption of Additively Manufactured Lattice Structures: A Review. Engineering Structures, 188, 437–455.
11. Song, Y., et al. (2017). Measurements of the Mechanical Response of Unidirectional 3D-Printed PLA. Journal of Materials Research, 32(10), 1826–1834.
12. Springer, T., et al. (2023). Numerical and Experimental Study of Energy Absorption of PLA Calibrated Honeycomb Structures. Journal of Polymer Engineering, 43(2), 102–115.
13. Zhang, Z., et al. (2019). Review of Lightweight Sandwich Structures with Lattice Cores Fabricated by Additive Manufacturing. International Journal of Lightweight Materials and Manufacture, 2(3), 103–113.
14. Maskery, I., et al. (2017). Mechanical Properties of Ti-6Al-4V Selectively Laser Melted Lattice Structures. Additive Manufacturing, 16, 24–29.
15. Wu, J., et al. (2017). Mechanical Properties of Architected Lattice Structures Manufactured Using Selective Laser Melting. Materials & Design, 117, 121–131.
16. Yan, C., et al. (2014). Evaluations of Cellular Lattice Structures Manufactured Using Selective Laser Melting. International Journal of Machine Tools and Manufacture, 88, 47–56.
17. Liu, Y., et al. (2020). Mechanical Behavior of Multi-Material Lattice Structures under Quasi-Static Load. Materials Science and Engineering A, 781, 139170.
18. Mohammed, I. Y., et al. (2022). Advances in 3D Printing of Functionally Graded Materials for Lightweight Structures. Journal of Manufacturing Processes, 74, 410–421.
19. Alomarah, A., et al. (2020). Additive Manufacturing of Lightweight Structures: Performance and Prospects. Journal of Manufacturing Science and Engineering, 142(9), 090801.
20. Mirzaali, M. J., et al. (2018). Multiscale Mechanical Characterization of 3D Printed Auxetic Structures Made of PLA. Materials & Design, 151, 81–89.
21. Banerjee, A., & Kumar, S. (2020). Comparative Assessment of 3D Printed and Molded Polymer Lattice Structures under Mechanical Load. Polymer Testing, 90, 106711.
22. Cheng, L., et al. (2017). Efficient Design of Cellular Structures Using Topology Optimization: Application to Additive Manufacturing. Structural and Multidisciplinary Optimization, 55(3), 1045–1060.
23. Zegard, T., & Paulino, G. H. (2016). Bridging Topology Optimization and Additive Manufacturing. Structural and Multidisciplinary Optimization, 53, 175–192.
24. Mirzendehdel, A. M., & Suresh, K. (2016). Support Structure-Constrained Topology Optimization for Additive Manufacturing. Computer-Aided Design, 81, 1–13.
25. Wang, C. C. L., et al. (2018). Design and Optimization of Reconfigurable Honeycomb Structures for Impact Energy Absorption. Engineering Structures, 177, 303–317.
26. Ngo, T. D., et al. (2018). Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges. Composites Part B: Engineering, 143, 172–196.
27. Kumar, R., & Singh, R. (2020). Investigations on Mechanical Properties of 3D Printed Thermoplastic Composites Using Fused Filament Fabrication Process. Materials Today: Proceedings, 28, 744–750.
28. Chen, Y., et al. (2017). Crashworthiness Design of Automotive Structures with Advanced High-Strength Steels and Cellular Materials. Thin-Walled Structures, 119, 48–56.
29. Zhang, Y., & Xu, S. (2021). Numerical and Experimental Study of Hexagonal Honeycomb Structures Under Different Loading Conditions. International Journal of Mechanical Sciences, 190, 106031.
30. Tsuji, H., & Ikada, Y. (2000). Properties and Morphology of Poly(l-lactide): 1. Annealing Condition Effects on Properties and Morphology of Poly(l-lactide). Polymer, 41(10), 3621–3630.
31. Anderson, K. S., Schreck, K. M., & Hillmyer, M. A. (2008). Toughening Polylactide. Polymer Reviews, 48(1), 85–108.
32. Shen, L., Haufe, J., & Patel, M. K. (2009). Product Overview and Market Projection of Emerging Bio-Based Plastics: PRO-BIP 2009. Utrecht University, The Netherlands.

33. European Bioplastics (2022). Bioplastics Market Development Update 2022. Retrieved from www.european-bioplastics.org

Appendix A: *FEA Simulation Parameters*

Mesh type: *Tetrahedral Element size: 1 mm Solver type: Static structural*

Appendix B: *Material Properties Used in Simulation*

PLA: Young's Modulus = 3.5 GPa, Poisson's Ratio = 0.36 Stainless Steel 316L: Young's Modulus = 200 GPa, Poisson's Ratio = 0.30 Titanium Ti6Al4V: Young's Modulus = 110 GPa, Poisson's Ratio = 0.34

Nomenclature:

σ: Stress (MPa) ε: Strain (unitless) E: Young's Modulus (GPa) FEA: Finite Element Analysis PLA: Polylactic Acid Ti6Al4V: Titanium Alloy (6% Aluminum, 4% Vanadium)