Investigation Of Energy Absorption Characteristic of Origami Inspired 3D-Printed Sandwich Honeycomb Structures

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Thesis Supervisor:

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Abstract

The energy absorption characteristics of origami inspired honeycomb structures under low velocity impact and quasi static compression loading conditions are investigated in this study. Three configurations were examined: Origami inspired Honeycomb (OH) and Modified Origami inspired Honeycomb (MOH) with smoothed corners. Fused deposition modeling with PETG material was used to fabricate the structures and they were subjected to drop weight impact testing according to ASTM D7136 standard and compression testing according to ASTM C365 standard.

Finite element analysis using Abaqus/Explicit and experimental testing revealed that the Modified Origami-inspired Honeycomb demonstrated superior energy absorption characteristics compared to traditional and conventional origami designs. The MOH structure exhibited a 45.9% longer impact duration (0.0410 seconds) compared to the Traditional Honeycomb (0.0281 seconds), indicating more efficient energy distribution. While the MOH showed a lower peak load of 15,000 N compared to TH's 33,500 N under compression, it maintained a more stable plateau load of 13,000 N versus OH's 6,500 N, suggesting improved energy absorption sustainability.

The incorporation of smoothed corners in the MOH design effectively reduced stress concentrations and promoted more uniform deformation patterns, resulting in a 42.3% increase in maximum deformation capacity compared to the traditional design. The study demonstrates that geometric modifications in origami-inspired honeycomb structures can significantly enhance their energy absorption efficiency and structural stability, although these improvements come with increased manufacturing complexity.

These findings contribute to the development of improved impact-resistant structures and provide insights into the relationship between geometric design parameters and energy absorption characteristics in honeycomb structures. The research has implications for applications in aerospace, automotive, and other industries where efficient energy absorption and impact protection are crucial.

Keywords: Origami-inspired structures, Honeycomb sandwich structures, Energy absorption, Impact resistance, Finite element analysis, Drop-weight impact testing

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Chapter 1. Introduction

1.1 Background and Motivation

1.1.1 Overview of Origami-Inspired Engineering

The ancient art of origami, with its intricate folds and mesmerizing transformations, has transcended its artistic origins to inspire a growing field of engineering known as origami-inspired engineering. This young science makes use of geometric patterns and folding techniques utilizing the art of origami to develop and construct new materials with unique characteristics. Precision in folding has expanded new horizons in engineering since flat materials can be easily molded into 3D structures to solve problems in various areas of application. (J. Qi et al., 2021).

The idea behind origami-inspired engineering is as old as the origami itself and was initiated by the early researchers in the late 1970s when K.O. Miura created the Miura-ori fold – tessellated pattern with high deployability and compactness. This laid the basis for the future research on the prospects of using origami in engineering (J. Ma & You, 2013). Subsequent years saw researchers focusing more on the mathematical, specifically geometric and mechanical, concepts of origami and creating more complex models and computational methods to study and design structures with origami concepts.

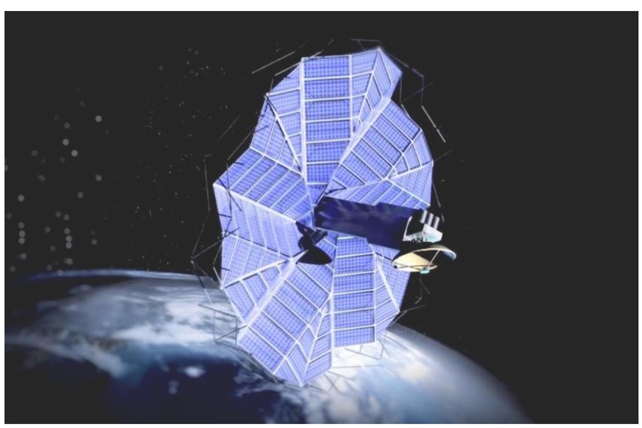

Figure 1: Miura-Ori fold application in space industry.

The matter is that work of origami-inspired engineering is based on the principles of light structures, easy to deploy and multifunctional. The folding process also permits compact stowage and easy readiness for use which makes these structures ideal for applications in aerospace particularly in space where space and mass are critical success factors. In addition, the geometric transformability of the structures derived from origami allows the structures to have multifunctional use in response to their environment and in addition to their mechanical functionality. (Zhou et al., 2017).

Although the idea of applying origami engineering in different fields has attracted a lot of attention in the recent past, the field is relatively new and offers numerous opportunities for research. In aerospace application, origami has been used in solar panels, antennas and spacecraft structures with applications in space missions especially where compactness during launch is desirable but expandable structures are needed once in space. In the automotive field, the use of origami in designs has been studied in terms of energy management parts and crashworthiness, with a view of improving safety and minimizing the weight of automobiles. The medical sector has also soon various origami like stents and surgical instruments that can be manipulated and placed with a lot of control inside the human body.

The applications and possibilities inherent in origami-inspired engineering have motivated a number of studies; researchers and engineers continue to explore new possibilities. The use of origami inspired structures are becoming more and more diverse from self-folding robots to adaptive building facades. With these developments in the future, the field is promising to change how engineering design is done and allow for the construction of a new wave of foldable, portable, and versatile structures. (Ingrole et al., 2017).

1.1.2 Potential Applications in Impact Absorption

The practical uses of the structures based on the origami engineering principles for impact and energy management are found in many industries and engineering systems. These structures can deform in a controlled and predictable manner when subjected to impact loading which is desirable in many applications where weight is a factor, and where structures need to be particularly strong to protect against impact loads.

In aerospace applications, the foldability and lightweight of origami structures render it appropriate for use in impact mitigation systems in space vehicles, and satellites. The extraterrestrial conditions that include risk of micrometeoroid and orbital debris impacts require the establishment of efficient and reliable protective mechanisms. By adapting the principles of origami, the structures can be built in such a way that energy from these impacts is absorbed and safely dispersed to protect such components hence enhancing the success of the mission as shown in Figure 2 (J. Qi et al., 2021).

Figure 2: Energy absorption application in aerospace industry.

The automotive industry is also set to gain greatly from the incorporation of origami type structures in impact management systems. The desire to enhance the fuel economy and minimize emissions has led to the need to find lightweight materials and structures that do not compromise or even add to the crashworthiness of vehicles. Crash boxes and energy-absorbing parts, motivated by origami, can be an effective one, which gives vehicle occupants more safety, better impact protection, and lighter weight as shown in Figure 3. (Zhou et al., 2017).

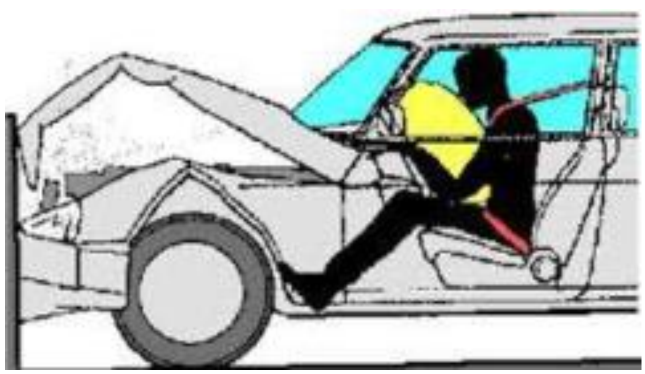

Figure 3: Energy absorption application in automotive industry.

Besides aerospace and automotive industries, application of origami based structures may have further implications for vibration damping in other contexts. In helmets and body armor for example, these structures can be built-in to improve the helmet’s ability to absorb impact force and thus minimize harm on the wearer. In packaging, ideas based on origami would be useful in giving the best form of cushioning and protection to sensitive products during transportation and handling. This makes it possible to design structures with desired mechanical response characteristics based on geometry and the choice of material, and this makes it possible to develop solutions to impact protection problems for given applications.

The application of origami structures for impact energy dissipation is not limited to their lightweight and stowage characteristics alone. Due to the ability of these structures to fold and change their geometry in a precise way they can also be made to show specific mechanical characteristics such as stiffness and energy absorptivity. This tunability enables one to design a structure that can perform better in different impact situations and loading conditions in order to offer the best protection in many different scenarios. In addition, the unique and highly predictable deformation of origami-inspired structures under impact loading can also be used effectively to reduce damages to the protected structure and likelihood of failure.

1.1.3 Need for Comprehensive Understanding

Investigation of the performance of such honeycomb sandwich structures based on origami designs under different loads is also required for their application to impact applications. It is found that the effects of folding geometry, material properties and impact parameters on energy absorption of the origami structures are strongly coupled. Though many studies have mentioned some of the peculiarities of their behaviour, a thorough and detailed study of these properties is necessary for practical applications to make full use of their possibilities.

The research studies of origami-inspired honeycomb sandwich structures are mainly limited to quasi static compressive performance and energy management characteristics (J. Qi et al., 2021). Response of these structures during impact loading especially at low velocities is still relatively poorly understood however. Deformation processes and failure behavior in the impact loading regime can be very different from that in the quasi-static one, and therefore should be studied separately. The behavior of materials under dynamic loading is often very different from that of their quasi static counterpart, and this is particularly true for cellular materials such as honeycombs (Foo et al., 2006). Due to the strain rate sensitivity of these materials, stiffness, strength and energy absorption capacity changes must be considered in the design and analysis of impact resistant structures.

Further, the energy absorption capability of the structure should be studied in depth in terms of the different geometric characteristics of the honeycomb sandwich structures based on origami, such as cell size, wall thickness, and folding angle. The fact that the geometry of the structures controls the mechanical response of such structures offers a powerful means for increasing the energy absorbing properties of the structures (Ingrole et al., 2017). However, there is no organized work that shows the correlation between geometric parameters and energy absorption performance for different impacts, which this study will provide the engineers with the knowledge of how to design structures for various impacts. Folding honeycombs according to origami principles create new geometries, which impose additional geometrical constraints on honeycombs' deformation and failure behaviour under impact. The modeling and design rules can be developed by identifying these geometric parameters.

In addition to geometries, face sheet and core material properties are important to determining the energy absorption capability of origami-inspired honeycomb sandwich structures. The deformation and failure of structure under impact loading strongly depend on the characteristics of the material such as strength, stiffness and ductility (Nunes & Silva, 2016). These aspects allow to choose the right material, and to calculate the efficiency of the entire sandwich structure. The material also had to be selected to be able to manufacture the material, to be cheap and to have no impact on the environment.

The last (but not least) point of future investigation is the creation of reliable models for assessment of the energy absorption capacity of origami honeycomb sandwiches at different conditions. These models would enable engineers to predesign and predetermine the performance of these structures for the intended applications, with confidence in their ability to overcome the effects of low velocity impacts. The models developed here are based on detailed understanding of the underlying energy absorption mechanisms and the effect of various geometric, material and impact parameters. Previous studies have proposed theoretically based models of energy absorption for conventional honeycomb structures, but such models may not apply directly to origami inspired honeycombs due to their unique geometric configuration and deformation mechanisms (D. Wang & Bai, 2015).

The successful use of origami inspired honeycomb sandwich structures in real world applications requires a global understanding of the energy absorption characteristics under low velocity impact loading. The aim of this thesis is to fill this need by conducting a systematic study of deformation mechanisms, failure modes and energy absorption capability of these structures, and to contribute to the development of new types of advanced impact mitigation solutions.

1.1.4 Research Gap and Thesis Contribution

Although the origami inspired honeycomb sandwich structures have attracted increasing interest and hold great potential for impact absorption, a significant research gap remains that this thesis attempts to fill. Previous studies have investigated the quasi-static compressive behavior and energy absorption of these structures, but the response to low velocity impact loading is relatively unexplored (J. Qi et al., 2021). Impact events inherently have a dynamic nature which may not fully be represented by quasi static analyses, therefore a separate study of the deformation mechanisms, failure modes and energy absorption behavior under impact loading conditions is required. Often, materials will exhibit quite different behavior under dynamic loading than their quasi static response, and this is especially true of cellular materials such as honeycombs (Foo et al., 2006). Changes in stiffness, strength, and energy absorption capacity of these materials as a function of strain rate sensitivity have to be carefully considered in the design and analysis of impact resistant structures.

It also provides further explanation for the influence of different geometric parameters on the energy absorption performance of origami inspired honeycomb sandwich structures. Geometric design of these structures provides a powerful tool for the optimization of their impact absorption capabilities through the ability to tailor the mechanical response of these structures (Ingrole et al., 2017). Nevertheless, a systematic study is needed to establish the relationship between geometric parameters and energy absorption performance for the purpose of engineering structures that are specifically designed for specific impact situations. A lack of an understanding of how variations in cell size, wall thickness, and folding angle influence the energy absorption behavior of these structures under impact loading exists in the existing literature. Origami inspired honeycombs display additional geometric complexities in the folding patterns that can affect their deformation and failure mechanisms under impact. Quantitative understanding of the roles of these geometric parameters is necessary for developing predictive models and design guidelines.

The choice of materials for face sheets and core also greatly influence the energy absorption characteristics of origami inspired honeycomb sandwich structures. Although some studies have attempted to find the best material for energy absorption by using different ones, there is still a lack of systematic investigation into the material structure interaction and its effect on the energy absorption under low velocity impact. Understanding these interactions with the mechanical properties of the materials (strength, stiffness and ductility), can significantly influence the deformation and failure modes of the structure and are important to optimize the overall performance (Nunes & Silva, 2016). In addition to meeting manufacturing feasibility, cost and environmental impact, appropriate materials should be selected.

The development of predictive models able to accurately predict the energy absorption characteristics of origami inspired honeycomb sandwich structures under different impact conditions is still in its infancy. These structures respond dynamically to these complex interplays between geometric parameters, material properties, and impact conditions, making sophisticated models of the dynamic response required. Theoretical models for conventional honeycomb structures exist but their applicability to origami-inspired honeycombs with their unique geometric configurations and deformation mechanisms requires careful evaluation, and possibly refinement (D. Wang & Bai, 2015). The energy absorption behavior of origami-inspired honeycombs may not be well predicted by existing models as they do not take into account the specific folding patterns and deformation modes observed in these honeycombs.

The purpose of this thesis is to bridge these research gaps by investigating the energy absorption mechanisms of origami inspired honeycomb sandwich structures under low velocity impact loading. The energy absorption performance will be analyzed using a combination of experimental testing and numerical simulations to study the influence of geometric parameters, material properties and impact conditions. This research will contribute to the development of advanced impact mitigation solutions and gain valuable insights for the design and optimization of origami inspired honeycomb sandwich structures for a variety of applications.

1.2 Research Objectives

The main goal of this work is to study the mechanism of energy absorption of origami inspired honeycomb sandwich structures subjected to low velocity impact loading in a comprehensive manner. Specifically, the goals of this research are to:

- In the study, the geometric parameters of the origami-inspired honeycomb core will be systematically varied to analyze how its energy absorption capabilities vary. Subsequently, a series of honeycomb sandwich structures inspired by origami will be designed and fabricated with varying geometric parameters, and experimentally tested and numerically simulated to characterize their impact response. Our aim is to develop quantitative relationships between geometric parameters and energy absorption performance, with the goal of understanding design and optimization of such structures. Previous work has explored the effect of geometrical parameters on the energy absorption of origami structures, noting the role of number of modules, dihedral angle, and cell wall thickness (J. Ma & You, 2013; J. Qi et al., 2021). These findings will be extended to a broader range of geometric parameters and impact conditions in this research.

- Experimental testing and numerical simulations will be used in concert to determine the dominant deformation modes and failure mechanisms in origami inspired honeycomb sandwich structures subjected to low velocity impact loading. The deformation process during impact will be captured using high speed imaging and digital image correlation techniques and numerical simulations will provide detailed stress and strain distributions in the structure. It is hoped that by understanding how these structures deform and fail under impact, critical failure points can be identified and strategies to improve their energy absorption capabilities can be developed. Deformation and failure modes of conventional honeycomb structures subjected to impact loading have been extensively studied (Foo et al., 2006), b However, the geometry of the origami inspired honeycombs may result in different, and potentially more efficient, energy absorption mechanisms.
- The influence of the choice of materials for face sheets and the core on the energy absorption performance of the sandwich structure will be studied. Strength, stiffness, ductility and strain rate sensitivity will be considered in different material combinations. It is desired to find material combinations that can provide the best energy absorption performance under low velocity impact loading. The deformation and failure modes of sandwich structures under impact are very sensitive to the mechanical properties of the materials used (Nunes & Silva, 2016). This research will investigate the interplay between material properties and structural response, providing insights for material selection and optimization.
- The research will develop predictive models to accurately predict the energy absorption characteristics of origami inspired honeycomb sandwich structures under different impact

conditions using experimental and numerical results to guide. Geometric parameters, material properties, and impact parameters will be included in these models to afford valuable tool for designing and optimizing these structures. So to develop such models, you need to have a good understanding of the underlying energy absorption mechanisms and the complex deformation and failure modes observed in these structures. Previous theoretical models have been suggested for predicting the energy absorption of conventional honeycomb structures, but these may not be directly applicable to origami inspired honeycombs, as they have unique geometric configurations and deformation mechanisms (D. Wang & Bai, 2015). This research will aim to develop new or adapt existing models to accurately predict the energy absorption of origami-inspired honeycomb sandwich structures.

1.2.1 Impact Scenarios and Loading Conditions

Low velocity impact, which has been characterized by impact velocities less than 20 m/s, will be the focus of the investigation into the energy absorption mechanisms of origami inspired honeycomb sandwich structures (J. Ma & You, 2013). This range of velocities is of interest for automotive crashes, dropped objects, and sporting impacts. Low velocity impact is chosen as the primary focus since it is common in real world situations and has the potential to cause large amounts of damage to structures and components.

The specific drop-weight impact test is the impact scenario to be investigated. In this scenario we simulate the impact of a falling object by dropping a known mass from known height onto the sandwich structure. Varying mass and drop height control the impact energy and allows for investigation of the structure's response under a range of impact severities. Previous studies have widely used this method to evaluate the impact resistance of honeycomb sandwich structures (Foo et al., 2006; J. Qi et al., 2021). Drop-weight impact testing is advantageous because it is simple and produces controlled impact energies. To constrain impact energies within the range of interest for low velocity impact, the choice of impactor mass and drop height will be made carefully. The fundamental response of the structure under this loading condition will be studied focusing on the central impact where the impactor hits the center of the panel.

1.3 Research Questions

This research focuses on the following key questions, the answers to which will lead to investigation of the energy absorption mechanisms of origami inspired honeycomb sandwich structures under low velocity impact loading:

1. What is the influence of the geometry of the origami inspired honeycomb sandwich structure on its energy absorption capabilities? The purpose of this question is to investigate how the geometric parameters of the origami core, including cell size, wall thickness, and folding angle, relate to its capability to absorb and dissipate impact energy. The objective is to determine the best geometric configurations for energy absorption and minimum peak impact force.

2. Under low velocity impact loading, what are the key deformation modes and failure mechanisms? The objective of this question is to discover the particular ways in which origami inspired honeycomb sandwich structures deform and fail in impact. The aim of the investigation is to identify the dominant deformation modes (e.g. buckling, folding, crushing) and the failure mechanisms that govern the ultimate collapse of the structure. It is important to understand these modes and mechanisms so strategies can be developed to improve the energy absorption capabilities for these structures.

3. What effect do material properties and structural configurations have on the energy absorption performance? This question investigates the interaction between the material properties of the face sheets and core, and the overall configuration, and their effect on the energy absorption behavior of the sandwich structure. Different material combinations and structural configurations are to be investigated in the investigation such that energy absorption performance under low velocity impact loading is identified. Previous studies have shown that the energy absorption of honeycomb structures is influenced by material properties and particularly the strength, stiffness, and ductility (Foo et al., 2006; Nunes & Silva, 2016).

4. Whether it is possible to create accurate predictive models to estimate energy absorption of honeycomb sandwich structures under different impact conditions if they were designed using origami principles? This question will endeavor to produce mathematical or computational algorithms to predict the energy absorption behaviour of such structures in

terms of their geometrical dimensions, material properties, and oblique loading conditions. Such models would allow engineers to design and optimize origami inspired honeycomb sandwich structures for specific applications without the need for extensive experimental testing. With experimental results compared to these models, the accuracy and reliability of these models will be evaluated.

By answering these research questions, this thesis aims to gain a complete understanding of the energy absorption mechanisms of origami inspired honeycomb sandwich structures under low velocity impact loading. The results will help in the design of more advanced impact mitigation solutions and will aid the wider application of these structures in engineering.

1.4 Thesis Outline

Chapters of the thesis are organized to provide a structured and holistic investigation of the energy absorption characteristics of origami inspired honeycomb sandwich structures under low velocity impact loading:

- Chapter 1: Introduction This is the introductory chapter that sets up the rest of the thesis by giving some background on origami inspired engineering and some applications of this in impact absorption. It also helps fill a gap in the research, objectives and questions that will drive the investigation.
- Chapter 2: Literature Review In this chapter, the relevant literature is presented in a comprehensive review including origami engineering, honeycomb sandwich structures, and experimental and numerical studies on energy absorption. The knowledge gaps will be identified and a theoretical foundation will be provided through a critical review of existing research.
- Chapter 3: Methodology Detailed in this chapter are the research methodology including the design and fabrication of origami inspired honeycomb sandwich structures, experimental setup and testing procedure, numerical modeling and simulation methods, and data analysis methods. The approaches chosen will be explained in terms of rationale, and the validity and reliability of the methods will be discussed.
- Chapter 4: Results and Discussions The results from the experimental and numerical investigation are presented in this chapter. The energy absorption performance of the

origami-inspired honeycomb sandwich structures will be analyzed and discussed in detail with the influence of geometric parameters, material properties, and impact conditions. The low velocity impact loading will be used to identify and characterize the key deformation modes and failure mechanisms.

- Chapter 5: Conclusion and Recommendations The final chapter concludes by summarizing the main findings of this work with contributions to origami inspired engineering and impact absorption. The study limitations will be acknowledged, and future research directions will be suggested. The chapter ends by highlighting the practical implications of the research and its potential to influence the design and development of future advanced impact mitigation solutions.

The thesis will first provide a general overview of the field, then dive into the topics in a more and more focused way, until it reaches the questions investigated in the study. Experimental and numerical methods are combined to gain a robust and holistic understanding of the energy absorption mechanisms of origami inspired honeycomb sandwich structures under low velocity impact loading. This research will have implications on the advancement of origami inspired engineering and applications in impact absorption to realize safer and more efficient engineering systems.

Chapter 2. Literature Review

2.1 Historical Development of Origami Engineering

Origami engineering's historical journey traces its roots back to the ancient art of origami, which, for the most part, has always been practiced for its artistic expression and cultural tradition. The Japanese word "origami" is actually made up of the word "oru" (to fold) and the word "kami" (paper). Traditional origami involved folding paper into intricate shapes and figures but the principles and techniques have slowly been introduced to many engineering and technological applications.

Table 1: Literature review findings

Author's & Year	Study Focus	Methodology	Key Findings
J. Ma & You (2013)	Energy absorption of thin-walled square tubes with pre-folded origami pattern	Numerical simulation and theoretical analysis	Optimal design increased energy absorption by up to 29.2% Initial peak force reduced by 56.5%
Zhou et al. (2017)	Crashworthiness design for trapezoid origami crash boxes	Experimental and numerical study	Origami patterns enhanced energy absorption in crash boxes
J. Qi et al. (2021)	Energy absorption of origami-inspired honeycomb sandwich structures under low-velocity impact.	Experimental testing and numerical simulation.	Origami-inspired honeycombs showed superior energy absorption compared to traditional designs Geometric parameters significantly influenced energy absorption performance.

Du et al. (2019)	Fabrication and mechanical behavior of carbon fiber reinforced composite fold core.	Experimental testing and numerical analysis	Analytical models accurately predicted damage modes and mechanical performance of origami core
Foo et al. (2006)	Quasi-static and low-velocity impact failure of aluminum honeycomb sandwich panels	Experimental study	Identified various failure modes in honeycomb sandwich panels under impact loading
Zhang et al. (2016)	Indentation and energy absorption of honeycomb sandwich panel under low-velocity impact	Experimental and numerical investigation	Demonstrated the influence of core height and face sheet thickness on energy absorption
Li et al. (2020)	Bending behavior of sandwich beam with tailored hierarchical honeycomb cores	Experimental and numerical study	Hierarchical honeycomb cores showed improved bending performance compared to traditional honeycombs
Wickeler & Naguib (2022)	3D printed multi-material origami-inspired structures for quasi-static and impact applications	Experimental study using 3D printing	Demonstrated potential of 3D printing for fabricating origami-inspired structures with tailored properties
Yang et al. (2023)	Compressive mechanical properties and dynamic behavior of origami-inspired tri-directional auxetic meta structure	Experimental and numerical study	Tri-directional auxetic structures showed excellent compressive properties and dynamic behavior

Lam et al. (2024)	Dynamic crushing and energy absorption of bio-inspired shear thickening fluid-filled origami meta structure	Experimental and numerical study	Shear thickening fluid-filled origami structures showed enhanced energy absorption under dynamic crushing
Lan et al. (2023)	Impact resistance of foam-filled hybrid-chiral honeycomb beam under localized impulse loading	Experimental and numerical study	Foam-filled hybrid-chiral honeycomb beams demonstrated improved impact resistance under localized impulse loading

We attribute the transition from traditional origami to origami engineering to the exploration of the mathematical and geometrical aspects of origami in the mid 20th century. Some pioneers, known as the grandmaster of origami such as Akira Yoshizawa helped develop a system of symbols and diagrams showing origami folding patterns, so that they could be easier understood and shared (C. Qi et al., 2021). It was this standardization that allowed origami principles to be used to solve engineering problems.

Work in the historical development of origami engineering was also accomplished in Koryo Miura's 1970 introduction of the Miura-ori fold a 2D tessellated pattern that exhibits exceptional unrecoverable folding and unfolding properties. Since, the Miura-ori fold has become a cornerstone in origami engineering, and has been used for deployable structures, solar panels and even as medical devices. The high strength to weight ratio of origami structures along with their ability to undergo transformations from compact to deployed configurations, make them attractive for a large number of applications (J. Ma & You, 2013).

Computational tools and manufacturing techniques for advanced manufacturing also accelerated the development of origami engineering. Computer simulations were then used by researchers to study the folding behavior of origami structures and to optimize their designs for particular applications. Inexpensive 3D printing has permitted the fabrication of complex origami structures from a broad range of materials, and has greatly expanded the range of possibilities beyond the 'mechanical' paper-based origami. By integrating origami principles with 3D printing, we demonstrate new ways to create innovative and functional structures with tailored properties (J. Qi et al., 2021).

Over the past several years origami engineering has become a focus of research and development in the fields of aerospace, biomedical engineering, and robotics. The unique characteristics of origami structures, including the ability to fold and unfold in a controlled manner, compact storage, and the possibility of multi-functionality, have attracted origami structures to engineering design. Origami inspired designs have been used in engineering to develop new solutions to problems ranging from the development of deployable structures for space exploration, flexible robots for medical applications, to energy absorbing materials to protect against impact.

The evolution of origami engineering as a journey from an ancient art form into a high technology engineering discipline may be traced historically. Thanks to Yoshizawa and Miura, the origami principles began to be contributed, as well as advancements in computational tools and manufacturing techniques which opened the door for the mass use of the origami principles in technology and engineering. With more and more research going in this field, we can only expect even more innovating, and impactful applications of origami engineering in the coming years.

2.2 Application of Origami Engineering in Various Industries

Origami inspired structures have unique properties including the ability to fold and unfold in a controlled manner, their compact storage capabilities and their potential for multi functionality that have seen them adopted in many industries. We will show some of the key applications of origami engineering in a number of sectors in the following sections, highlighting how it can lead to the revolution of design and engineering practices.

2.2.1 Aerospace

The need for lightweight and deployable structures has resulted in the exploration of origami inspired designs in the aerospace industry. For instance, satellite and spacecraft solar panels must be small for launch, and become large on orbit. A solution to this challenge is provided by folding patterns based on origami, which allow for the efficient stowing and deployment of solar arrays. Extensive study has been directed towards the Miura-ori fold, a fold that can be folded flat and deployed smoothly, for the use in solar array design. (J. Qi et al., 2021).

Additionally, origami engineering has been investigated for deployable antenna and other space structure development. Folding from a flat sheet allows for the creation of complex 3D shapes with reduced costs due to reduced launch volume and weight. Origami-inspired designs are being introduced to aerospace, and the promise is to promote the development of more efficient and less costly space missions.

2.2.2 Automotive

Origami engineering has been applied in automotive industry for developing energy absorbing structures for crashworthiness. The ability to control deformation behavior of origami structures can be used to dissipate impact energy during collisions to improve passenger safety. Origami inspired patterns have been investigated as a means for designing car bumpers, or crash boxes, and other impact resistant components (Zhou et al., 2017).

In addition, origami engineering has been explored for designing adaptive and reconfigurable structures in automobiles. For instance, origami based folding mechanism can be incorporated within the seat, sunroof, other interior components to provide greater flexibility and customization of the interior components. Integration of origami principles into automotive design may result in more innovative and user friendly vehicles.

2.2.3 Robotics

Origami engineering has also been making itself felt in the field of robotics. Origami structures capable of folding and unfolding in a controlled manner induced the development of soft robots capable of navigating and performing detailed tasks in complex environments. Folding patterns built from origami have been used to build robotic grippers, manipulators, and even locomotion systems. (Li et al., 2020).

Additionally, the origami engineering has been utilized to design self folding robots that can assemble themselves from flat sheets. The manufacturing and deployment advantages of this approach are enormous, as they simplify the assembly processes. Origami inspired designs in robotics are set to create more versatile and adaptable robots to perform more tasks.

2.2.4 Biomedical

Origami engineering has been used in the area of biomedical field for design of drug delivery systems, tissue engineering scaffolds, and medical devices. Orfigami structures exhibit ability to encapsulate and release drugs in a controlled manner, which makes them attractive for targeted drug delivery. Additionally, scaffolds that can guide tissue growth and regeneration have also been created using origami based folding patterns (Zhang et al., 2020).

In addition, origami engineering was explored for the development of minimally invasive surgical tools and implants. Original structures are compact, flexible, and are suitable for moving through narrow passage and conforming to complex anatomical shapes. Introduction of the origami principles into biomedical engineering could be the beginning of more effective and less invasive biomedical treatments.

2.2.5 Architecture

Origami engineering has been previously applied in architecture to produce inventive and beautiful structures. New possibilities for architectural design are offered by the ability to design complex 3D shapes from flat sheets by folding. Facades, roofs and entire buildings have been designed with origami inspired patterns (J. Qi et al., 2021).

Additionally, origami engineering has been used in the development of adaptive and reconfigurable structures in architecture. Take origami based folding mechanisms, which are appropriate for buildable retractable roofs, movable walls and other dynamic elements, to increase flexibility and adaptability in buildings. Architectural application of origami principles is envisioned to result in a more sustainable and reactive architecture, capable of responding to changing environmental conditions and the ever changing needs of the user.

Origami engineering's potential for transformative application across different industries is the focus of these applications. Origami inspired structures provide unique properties that can be leveraged by engineers and designers to develop novel solutions, enhance existing technologies, and solve particular problems in their respective fields. As first introduced, origami engineering has changed the way we build more efficient, lighter, and more flexible structures, devices, and systems.

Origami engineering has multifold impact on these industries. It has been used in aerospace for the development of compact and deployable space exploration borne structures. In the automotive field, it has increased the crashworthiness and lead to the creation of adaptive interior parts. It has inspired design of soft robots and self folding robots in robotics. In application in the biomedical field, it has shown applications in drug delivery, tissue engineering and medical devices. In architecture, it has given birth to new and flexible structures.

The applications of origami engineering will continue to become more and more groundbreaking with the advancement of research in origami engineering. Through the integration of origami principles with advanced 4D printing and smart materials technologies, novel structures and devices of unparallel capabilities will be created. The adaptability and versatility of origami inspired design means that they are ideally suited to meet the ever changing needs and challenges of a number of different industries.

2.3 Honeycomb Sandwich Structures

2.3.1 Overview and Advantages

Composite materials, and in particular honeycomb sandwich structures, are a class of materials known for their excellent mechanical properties and versatility, and are often indispensable in many engineering applications. Typically, these structures are constructed with two thin, but rigid, face sheets that are tightly bonded to a lightweight honeycomb core. The honeycomb core has a hexagonal cell structure that reminds one of a beehive and gives the structure its famous high strength to weight ratio and stiffness. Fabricated from materials such as aluminum, carbon fiber, fiberglass, etc., the face sheets are important to help the overall bending and in-plane stiffness of the sandwich structure. The face sheets and core are separated by the critical interposed adhesive layer that acts as a link between them to maintain composite structural integrity and efficient load transfer (Foo et al., 2006).

The honeycomb sandwich structures have a distinctive configuration that provide several advantages making them attractive for a wide range of applications. The high strength to weight ratio of the honeycomb core engenders cells of low mass but high strength that can withstand large loads. The hexagonal cells distribute the applied load very well and effectively reduce the stress concentration and enhance the structural integrity of the whole. Additionally, the stiffness provided by the honeycomb core is extraordinary, resisting bending and deformation under a wide range of loading conditions. Since high strength, low weight, and stiffness are concomitant, honeycomb sandwich structures provide an optimal choice for those applications where weight reduction and structural performance in the same ratio are critical (Li et al., 2020).

Their remarkable energy absorption capabilities, however, makes the honeycomb sandwich structures a particularly noteworthy advantage. Because the honeycomb core is profuse with cells that can be controlled to deform and collapse upon impact, it can dissipate a lot of energy. Honeycomb sandwich structures possess this energy absorption attribute, particularly suited to applications where impact resistance and crashworthiness are key requirements, e.g. in the automotive and aerospace sector (J. Qi et al., 2021). With controlled deformation, impact energy is able to disperse through the structure and is able to protect underlying structure and occupants from deleterious collision effects. Studies have further explored the efficacy of honeycomb structures in energy absorption utilizing foam filled hybrid chiral honeycomb beams, which demonstrate their robustness under localized impulse loading (Lan et al., 2023).

Honeycomb sandwich structures also provide excellent thermal and acoustic insulation in addition to their structural and energy absorption merits. The honeycomb cells' snare of the air serves as an insulator, limiting, respectively, heat transfer and sound transfer. These structures are particularly suited to applications in which thermal and acoustic management are critical, for example, in building construction or transportation (Obadimu & Kourousis, 2022). Honeycomb sandwich structures are a versatile and compelling solution for engineering challenges due to the amalgamation of structural performance, energy absorption and insulation properties.

Honeycomb sandwich structures require the selection of materials that depend on the particular requirements of the applications. As the strength and stiffness of the face sheets are typically desired, the core material is chosen for its density, mechanical properties, and cost. Face sheet materials which are commonly used include aluminum alloys, carbon fiber composites, and fiberglass composites. In addition to the materials of choice for honeycomb sandwich cores, aluminum, Nomex, and even paper are all viable candidates for making the honeycomb cores. The overall weight, stiffness, and energy absorption characteristics of the sandwich structure are determined by the choice of core material. Additive manufacturing has also enabled making of honeycomb cores with intricate geometries and tunable properties, which further broadens the design space of these structures (J. Qi et al., 2021). In this thesis, the 3D printing of multi material origami inspired structures for quasi static and impact applications is explored and the potential of additive manufacturing in tailoring the mechanical behavior of these structures is underscored (Wickeler & Naguib, 2022).

Aerospace, automotive, marine and construction are among the diverse range of industries where Honeycomb sandwich structures are used. They find wide application in aerospace in the structures of aircraft, satellite panels, and launch vehicles where weight reduction and structural efficiency are of critical consideration. In the automotive industry they are used in body panels, bumpers and interior components with a synergistic combination of lightweight, stiffness and impact resistance. In the marine sector, they are molded into hulls and deck of ships for buoyancy, strength and corrosion resistance. They are used in walls, roofs and floors in construction as thermal insulation, soundproofing and structural support. Honeycomb sandwich structures have established themselves as integral parts of contemporary engineering design and construction in virtue of their versatility and performance advantages.

2.3.2 Limitations and the Need for Innovation

Despite the many advantages of traditional honeycomb sandwich structures, there are some limitations in these structures that require investigation of new designs. Their susceptibility to face sheet wrinkling and core crushing under particular loading conditions is one of the primary limitations. Although contributing to the lightweight nature of the structure, the thin face sheets can buckle or wrinkle under compressive or bending loads, resulting in loss of structural integrity (Foo et al., 2006). Similarly, the honeycomb core provides efficient energy absorption, but can collapse under excessive loads resulting in loss of stiffness and load bearing capacity. Honeycomb sandwich panels have been extensively studied under various loading conditions in order to understand their deformation and failure modes, which indicate their vulnerabilities and the need for improved designs that can withstand broader loading scenarios (C. Qi et al., 2021). In order to achieve enhanced energy absorption, novel configurations, e.g. foam filled hybrid chiral honeycomb beams, have also been investigated and shown to provide improved impact resistance under localized impulse loading (Lan et al., 2023).

One limitation of traditional honeycomb structures is that it is hard to achieve multi functionality. Although they excel in structural support, energy absorption and insulation, integration of further functionalities, such as sensing, actuation or self healing, can be problematic (C. Qi et al., 2021). The honeycomb geometry is inherently simple, and thus the possibilities for doing things complex or functional within the structure are inherently limited. Honeycomb designs that combine multiple functionalities are needed to meet the demands for multifunctional materials in diverse applications, e.g. aerospace and robotics. 3D printed multi material origami inspired structures are explored as a method to create structures with tailored properties for quasi static and impact applications, suggesting the possibility of multi functionalty in future designs (Wickeler & Naguib, 2022).

Additionally, the mechanical properties of such traditional honeycomb structures are limited. The geometry of the honeycomb core and the materials used for the face sheets and core determine to a large extent the properties of these structures. Certain degree of customization can be achieved by changing the cell size, wall thickness and material properties, but precision control over the mechanical response is often difficult. However, there is a need for structures with tailored stiffness, strength and energy absorption characteristics and the need for developing innovative honeycomb designs that allow greater tunability in property (C. Qi et al., 2021). The ongoing efforts to enhance and tailor the mechanical properties of these structures are demonstrated through research into advanced honeycomb designs such as gradient negative stiffness or assembled auxetic structures (Lan et al., 2023).

Innovations in design and materials are needed because traditional honeycomb sandwich structures are limited. One promising avenue to overcome these challenges is the emergence of origami engineering that allows the creation of complex and reconfigurable structures. Potential for energy absorption, multi function, and better control over mechanical properties can be gained by origami inspired honeycomb designs such as incorporating Miura ori or other folding patterns. Additional possibilities for the creation of innovative honeycomb structures with tailored functionalities are enabled through the integration of origami principles with advanced manufacturing techniques, such as 3D printing.

Encouraged by the ever increasing demands of different industries, the honeycomb designs are pursued for innovations. The need of lightweight and deployable structures with improved energy absorbing capability is a critical requirement in aerospace for space exploration missions. The development of crashworthy and multifunctional structures in the automotive sector is necessary in order to improve passenger safety and vehicle performance. For robotics, soft and adaptable robots need to be made from materials and structures with specific mechanical properties that can be tailored. The exploration of origami inspired designs to overcome these limitations and promote further engineering innovation is spurred by the limitations of traditional honeycomb structures.

2.4 Origami-Inspired Honeycomb Sandwich Structures

2.4.1 Existing Research and Benefits

Interest in a fusion of origami principles with honeycomb sandwich structures has increased, resulting in novel designs with improved performance characteristics. Currently, the majority of the research on this origami inspired honeycomb structures addresses the design, fabrication and mechanical evaluation of the structures. The design aspect involves inserting origami folding patterns, such as the Miura-ori fold, or other tessellated patterns, into the honeycomb core. The aim with this integration is to bring in new deformation mechanisms and enhance the capability to absorb energy of the structure. Often these structures are fabricated using advanced manufacturing such as 3D printing, which allows for the creation of complex geometries and the use of diverse materials (J. Qi et al., 2021). Origami inspired honeycomb structures have been studied under quasi static compression, low velocity impact and dynamic crushing. However, these studies have shown that the energy absorption, multi-functionality, and tailored mechanical properties of these structures are superior to those of traditional honeycomb structures.

Enhanced Energy Absorption

Enhanced energy absorption capacity of origami inspired honeycomb sandwich structures is one of the key benefits. Using origami folding patterns, these structures are capable of performing controlled and progressive deformation under impact and dissipate more energy than traditional honeycomb structures. Additional deformation modes are introduced by the folding and unfolding mechanisms of the origami patterns, resulting in a more gradual and sustained collapse of the structure, with maximum energy absorption (J. Qi et al., 2021). For automotive crash structures and protective gear, minimizing the impact force transmitted to the occupants or underlying structure requires the ability to absorb more energy during impact. Promising results in terms of energy absorption and impact resistance have been shown with the dynamic crushing behavior of origami metastructures filled with shear thickening fluids (Lam et al., 2024).

Multi-functionality

The multi functionality of origami inspired honeycomb structures is another advantage. Such mechanical behavior can be designed, such as auxetic behavior (negative Poisson's ratio) or shape morphing capabilities, into the intricate folding patterns. Auxetic structures stretch laterally, providing interesting benefits for impact protection and vibration damping applications. These structures can change their shape in response to external stimuli creating adaptive and reconfigurable systems. Origami principles integrate with honeycomb structures enabling new possibilities for the design of multifunctional materials with tailored properties for specific applications. It has been shown that origami inspired tri-directional auxetic metastructures have outstanding compressive mechanical properties and dynamic behaviour and are therefore ideal for use in applications that demand both load bearing capacity and energy absorption (Yang et al., 2023).

Tailored Mechanical Properties

In addition, origami inspired honeycomb structures can be more flexibly tailored to their mechanical properties. If the origami folding pattern, cell geometry and material selection are carefully designed, a wide range of mechanical responses can be achieved. These structures can be tuned by stiffness, strength, and energy absorption characteristics to meet specific application requirements. The ability to tailor mechanical properties is particularly valuable for applications where a composite combination of stiffness, strength, and energy absorption is required, including lightweight structural components and impact resistant material. In order to mimic the scalable architecture of the material found in nature, researchers have explored different parametric design approaches and fabrication techniques to produce origami core based sandwich composite materials with optimized mechanical performance (Wang et al., 2023). This has also extended the realm of origami inspired honeycomb structures with complex geometries and multi material compositions using 3D printing technology, with the capacity to precisely control their mechanical behavior (Wickeler & Naguib, 2022).

Advancements in Design and Fabrication

In recent years, the design and fabrication of origami inspired honeycomb structures have been advanced to expand their potential applications. Different origami folding patterns, including the Miura-ori fold, the Resch pattern and other tessellated patterns, have been studied as honeycomb cores with varying deformation mechanisms and mechanical properties (Deng et al., 2020; J. Ma & You, 2013). Thanks to the development of novel fabrication techniques, such as 3D printing and additive manufacturing, complex origami inspired honeycomb structures with intricate geometries and multi material compositions can be made. These have enabled new tailoring of the mechanical behavior of these structures and the optimization of their performance for specific applications.

Applications in Various Fields

Origami-inspired honeycomb sandwich structures have been explored in the aerospace, automotive, robotics and biomedical engineering due to their unique properties and advantages. These structures have been investigated for possible use in designing lightweight and deployable solar panels, antennas, and other space structures in aerospace. In the automotive industry, they have been explored as energy absorption materials for crashworthiness applications and as a base material for creating adaptive and reconfigurable interior components. Origami inspired honeycomb structures have been used in robotics to design soft robots with improved flexibility and adaptability, and also to create self folding robots that can self assemble from flat sheets. These structures have shown promise in biomedical field as drug delivery systems, tissue engineering scaffolds, minimally invasive surgical tools.

Future Directions

While research and development in the field of origami-inspired honeycomb sandwich structures is ongoing, the study is rapidly evolving with the intent of further improving the performance and expanding application of these structures. With approaching technologies like 4D printing and smart materials, origami principles can integrate forming structures in the realm of unprecedented capability. Novel design and fabrication techniques will lead to widespread adoption of origami inspired structures in various industries, coupled with a deeper understanding of the underlying mechanics of such structures. Origami inspired honeycomb sandwich structures have a bright future, and the possibility to revolutionize engineering design and to develop new solutions to a wide variety of challenges.

2.4.2 Origami Patterns and their Impact

Mechanical behavior and energy absorption capabilities of the resulting structures are strongly influenced by the origami patterns selected for honeycomb core designs. The application of origami patterns, each with their own particular folding mechanism and geometric properties, to honeycomb sandwich structures has been explored. A classic origami pattern: Miura-ori fold, which is flat foldable and deployable, has been extensively studied for its potential in enhancing the energy absorption of honeycomb cores (J. Ma & You, 2013). Another popular origami pattern, the Resch pattern, has some geometric versatility and tunable mechanical properties (Deng et al., 2020). In addition, we have investigated other origami patterns, such as the Waterbomb base and Yoshimura pattern, that could be utilized to create honeycomb cores with specific deformation modes and energy absorption properties. Specific application requirements and desired mechanical response determine the choice of origami pattern.

A unique folding mechanism of the Miura-ori fold, with tessellated parallelograms, is controlled and reversible deformation. When made into honeycomb cores, the Miura-ori pattern causes the structure to bend and stretch under compression simultaneously, resulting in greater energy absorption than conventional honeycombs (J. Ma & You, 2013). We investigate the in plane dynamic impact response of Miura-origami reentrant honeycombs as shown in Figure 4and find that they exhibit superior energy absorption capabilities over conventional hexagonal honeycombs (N. Ma et al., 2023). In addition, the improved mechanical performance of the Miura-ori pattern is due to its ability to distribute stress and strain evenly throughout the structure.

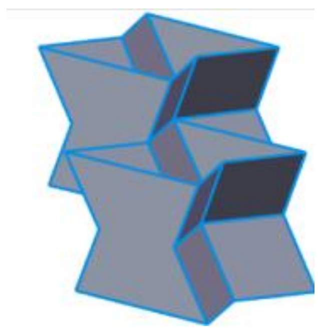

Figure 4: Re-entrant honeycomb

The geometric flexibility of the Miura-ori fold is significantly less than that of the Resch pattern, which repeats a pattern of triangles and trapezoids. This facilitates the fabrication of honeycomb cores with controllable cell sizes and shapes, which are then capable of being tailored to mechanical property parameters, such as stiffness and strength. These generalized Resch patterns have been explored as a means of designing foldcores with tunable mechanical properties (Deng et al., 2020). The ability to control the geometry of the Resch pattern offers a means to optimize the performance of honeycomb sandwich structures for given applications (Figure 5).

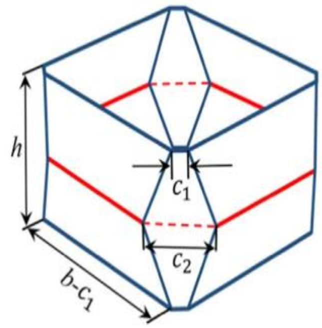

Figure 5: Trapezoid origami crash box.

Other origami patterns, such as the Waterbomb base and Yoshimura pattern, have also been investigated for the possibility to generate honeycomb cores with distinct deformation modes and energy absorption properties. The Waterbomb base, with its alternating mountain and valley folds, exhibits such buckling behavior under compression that the resulting energy absorption profile characterizes the base itself. The pleat twist combination of the Yoshimura pattern provides a potential for auxetic honeycomb cores with negative Poisson's ratio. Diverse origami patterns in honeycomb core designs are further explored to explore tailoring the mechanical response and functionality of these structures.

Origami patterns have a big impact on the mechanical behavior of honeycomb sandwich structures. Properties such as stiffness, strength, deformation modes and energy absorption capacity are influenced by the choice of pattern. In some applications, the benefits of some patterns over others have been shown in research findings. For example, the Miura-ori fold has demonstrated greater energy absorption performance than traditional honeycomb patterns and is therefore a good candidate for impact resistant structures (N. Ma et al., 2023). The geometric flexibility of the Resch pattern allows greater control of mechanical properties, allowing the honeycomb core to be designed with tailored stiffness and strength (Deng et al., 2020). Due to the deformation modes of the Waterbomb base and Yoshimura pattern, there are potential to make honeycomb cores with specific functionalities such as auxetic behavior or controlled buckling.

Finally, origami patterns selection influences the mechanical behavior and energy absorption performance characteristics of origami inspired honeycomb sandwich structures. This study has explored a number of diverse origami patterns including the Miura ori fold, Resch pattern, Waterbomb base, and the Yoshimura pattern. Specific origami patterns have been linked to their effects on stiffness, strength and deformation modes, and investigations show the benefits of certain patterns in comparison to others under specific application conditions. The potential of origami patterns in honeycomb core designs to lead to innovative, high performance sandwich structures for a large class of engineering and technological applications is being continued to be explored.

2.5 Experimental and Numerical Studies on Energy Absorption

Extensive experimental and numerical investigation of energy absorption characteristics in origami inspired honeycomb sandwich structures and other relevant configurations has been conducted. Different testing methods, materials and loading conditions have been used in these studies to uncover the interplay between structural design and energy absorption performance. These studies have not only enhanced our understanding of the energy absorption factors involved but also highlighted the complementary nature of experimental and numerical approaches for assessing and improving such structures.

2.5.1 Experimental Studies

In experimental studies of energy absorption, structures are usually subjected to controlled loading conditions (i.e., quasi static compression, low velocity impact or dynamic crushing) and their deformation and force displacement response is measured. Area under the force displacement curve is calculated and then used to determine the energy absorbed by the structure. Origami inspired honeycomb structure and other energy absorbing configurations have been fabricated using various materials such as metals, polymers and composites. Deformation mechanisms and energy absorption capacity of the structure depend critically on the choice of material. For example, metallic honeycombs have higher strength and stiffness than polymeric honeycombs, but the latter may be preferred for specific energy absorption (energy absorbed per unit mass) because of their lower density. Finally, the geometric parameters of the honeycomb structure including cell size, wall thickness and overall dimensions also contribute to the honeycomb structure energy absorption performance. Several studies have investigated the influence of these parameters, and the result has been a complex interplay between geometry and energy absorption. For example, (Qi et al., 2021) studied the impact response of origami-inspired honeycomb sandwich structures under low velocity impact loading and found that the geometric parameters of the core played a significant role in the energy absorption characteristics. The study demonstrated that the core design should be optimized to achieve the desired stiffness–energy absorption balance.

The effect of loading conditions on the energy absorption behavior of origami inspired structures has also been investigated experimentally. Deformation mechanisms and energy absorption capability of the structure can depend on the strain rate, impact velocity and loading direction. For instance, (Obadimu & Kourousis, 2022) investigated the in-plane compressive behavior of additively manufactured steel honeycomb structures to determine the effects of load rate on peak load and energy absorption, which exhibited significant increase with increasing strain rate. The results of these findings stress the need for loading conditions to be considered in the design and evaluation of energy absorbing structures.

2.5.2 Numerical Studies

Finite element analysis (FEA) based numerical simulations have become indispensable tools in studying the energy absorption characteristics of origami inspired honeycomb structures and other complex configurations. This detailed modeling of the structural geometry, material behavior and loading condition in FEA can be used by researchers to predict the deformation and energy absorption response under different scenario. Studies using numerical have been key to understanding the underlying mechanisms of energy absorption in those structures as well as key design parameters that influence their performance. For example, (Ma & You, 2013) used numerical simulations to address the energy absorption capability of thin walled square tubes with a pre-folded origami pattern and to show that the most efficient design can dramatically enhance energy absorption and reduce the initial peak force..

Parametric studies and optimization also are feasible using numerical simulations. Researchers can systematically vary the geometric parameters and material properties of the structure and identify the optimal configurations for which the energy absorption would be maximized for a particular application. For instance, (Wang et al., 2023) employed parametric design and simulation to optimize the corner radius in hexagonal honeycombs under in-plane compression, leading to improved energy absorption performance. Moreover, numerical studies can provide insights into the stress and strain distributions within the structure during deformation, aiding in the understanding of failure mechanisms and the development of more robust designs.

2.5.3 Advantages and Limitations of Experimental and Numerical Approaches

In evaluating energy absorption characteristics of origami inspired honeycomb structures, both experimental and numerical approaches have their advantages and limitations. Real world validation of the structural performance under real loading conditions is provided through experimental testing. It then enables observation of deformation and failure modes, which can be important insight into the energy absorption mechanisms. However, experimental testing can be time consuming and expensive, and only a few configurations and loading conditions can be tested.

However, numerical simulations provide more flexibility and efficiency in design parameters and loading space exploration. They can give detailed insights of the stress and strain distributions within the structure, for the identification of critical region and possible failure mode. Nevertheless, numerical simulations are accurate only if the structural geometry and material behavior, as well as loading conditions, are modeled with sufficient fidelity. Experimental testing is required to validate numerical models in order to validate their reliability and predictive capabilities.

Experimental and numerical studies of origami inspired honeycomb sandwich structures and other relevant configurations have demonstrated the great potential of such structures for energy absorption applications. Origami patterns have been incorporated into honeycomb cores to improve energy absorption capacity, provide multi-functionality, and control mechanical properties. The energy absorption performance of these structures depends critically on the choice of origami pattern, material selection, and geometric parameters.

A combination of experimental and numerical approaches is shown to be complementary in the evaluation and optimization of energy absorbing structures. Real world validation and insight into deformation and failure mechanisms can be obtained with the experimental testing, and numerical simulations provide flexibility and efficiency as well as the capability of detailed analysis. These approaches must be combined to further develop and advance origami inspired honeycomb sandwich structures and other innovative energy absorptive configurations.

Future work in this area is likely to be focused on additional investigation of origami patterns in further improving honeycomb structure energy absorption and multi-functionality. Emerging technologies like 4D printing and smart materials promise joining origami principles with a vast matrix of fresh possibilities in structure. Novel design and fabrication techniques and a better understanding of the underlying mechanics of origami inspired structures will enable their widespread adoption into almost any industry to develop more efficient, adaptable and sustainable solutions for engineering problems.

Chapter 3. Methodology

3.1 Introduction

This chapter provides a detailed description of the methodology employed to investigate the energy absorption behavior of honeycomb sandwich structures, specifically focusing on three distinct designs: The traditional honeycomb, origami inspired honeycomb and modified origami inspired honeycomb structure. The methodology combines numerical simulations and experimental testing to perform both the mechanical response and energy absorption characteristics of these structures under low velocity impact conditions.

This study aims to assess the variation in energy absorption due to different geometric designs and to compare the performance of the newly proposed modified origami-inspired honeycomb structure with conventional and origami-inspired configurations. The specific goals of this research are:

1. The three honeycomb designs are to be explored for the effects of geometric variations on their energy absorption capacities.
2. Key deformation modes and failure mechanisms under low velocity impact loading are identified and categorized.
3. Using predictive modeling techniques to assess the energy absorption efficiency of a modified origami inspired honeycomb structure.

Traditional honeycomb, origami inspired structure and modified origami inspired design. The performance differences are highlighted by selecting the geometric parameters of each structure carefully. The origami inspired and modified origami inspired structures have novel patterns of folding to maximize the energy absorption, while the control is the traditional honeycomb.

These structures are next subjected to numerical simulations using finite element analysis (FEA) in Abaqus. The structures' responses to drop weight impact tests (which correspond to real world impact scenarios) are modeled in this simulation process. Material properties, boundary conditions, and impact parameters are defined using well known techniques in the literature, and the simulations include defining material properties, boundary conditions, and impact parameters such as energy, force, and displacement (J. Qi et al., 2021). Material behavior under impact is captured using a ductile damage model, which provides a detailed understanding of deformation patterns and energy dissipation mechanisms (J. Ma & You, 2013).

The numerical models are then validated against experimental tests. Two standard test methods are utilized: Drop-weight impact test according to ASTM D 7136 and quasi-static compression test according to ASTM C 365. Impact tests are performed with a 66.67 mm drop from a height of 66.67 mm onto the honeycomb structures to simulate a 5J impact, while compression tests are performed at a loading rate of 5 mm/min. Detailed force-time and force-deformation responses are captured in the experimental setup using force sensors and high speed data acquisition systems.

The study uses both numerical and experimental approaches to combine the two to ensure that the three structures are covered in terms of energy absorption characteristics. The predictive capability of the model is validated using numerical results of kinetic energy dissipation and deformation patterns that are compared with experimental data (Qi et al., 2021). This dual method approach allows for more thorough analysis of the mechanical performance of the modified origami inspired structure to confirm any observed advantages are both simulated and real world data supported.

The following sections detail each aspect of the methodology, from design to data analysis, in sufficient detail to serve as a framework for investigating energy absorption mechanisms in honeycomb sandwich structures.

3.2 Design and Fabrication of Honeycomb Structures

A critical aspect of this study is the design and fabrication of the honeycomb sandwich structures. Three types of honeycomb structures are developed for evaluation: (1) traditional honeycomb, (2) origami-inspired honeycomb, (3) a modified origami honeycomb. These structures are used to understand how different geometries and configurations affect their energy absorption performance under impact loading.

3.2.1 Traditional Honeycomb

In terms of its regular hexagonal cells, the traditional honeycomb structure is a well known design for its efficiency in providing strength to weight ratio and stiffness. In this study, a cell height of 30 mm and a hexagonal side length of 10 mm is considered and a constant wall thickness of 0.8 mm is adopted in the honeycomb core modeled as shown in Figure 6. These dimensions were chosen to provide a baseline for comparing the more complex origami-inspired designs. Because of its simplicity and predictability mechanical properties the traditional honeycomb is used in many industries.

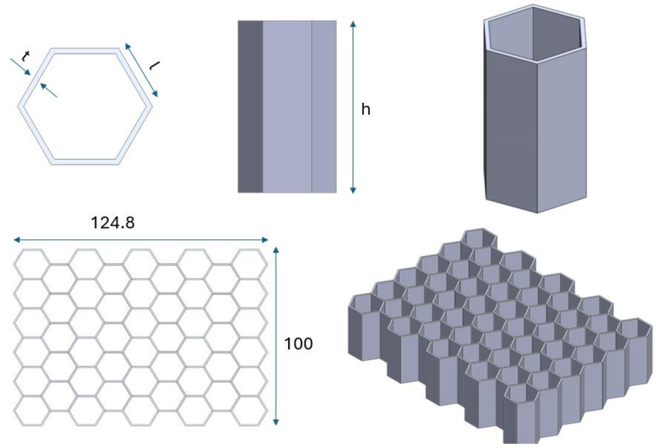

Figure 6: Geometric specifications and dimensioning of Traditional Honeycomb (TH) structure

3.2.2 Origami-Inspired Honeycomb

A folding pattern that introduces geometric complexity in order to enhance energy absorption is developed to create the origami-inspired honeycomb structure. This design has hexagonal side length that ranges from 10 mm at the top and bottom edges to 5 mm in the middle, while the structure folds up on impact and can deform in a controlled fashion as shown in Figure 7. This variation in cell size is intended to also alter the modes of deformation under impact, improving energy dissipation over the standard honeycomb. Origami based designs are well known for their ability to deform significantly without catastrophic failure, and they are therefore ideal for impact mitigation applications.

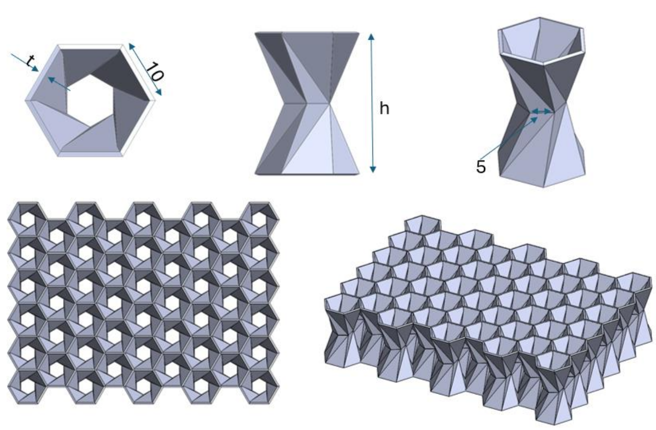

Figure 7: Geometric specifications and dimensioning of Origami Honeycomb (OH) structure

3.2.3 Modified Origami-Inspired Honeycomb

A modified version of the origami inspired design is developed to further improve the performance of the design by changing the sharpness of the folds in the cell walls. In particular, sharp corners in the folding pattern are smoothed by introducing a radius of 2.5 mm at the indentations as shown in Figure 8. It is expected that this modification will reduce stress concentrations during the impact, and lead to a more gradual deformation process, thus increasing overall energy absorption of the structure. The modified origami design is designed to balance strength and flexibility, and delivers performance better than the traditional and the original origami inspired structures.

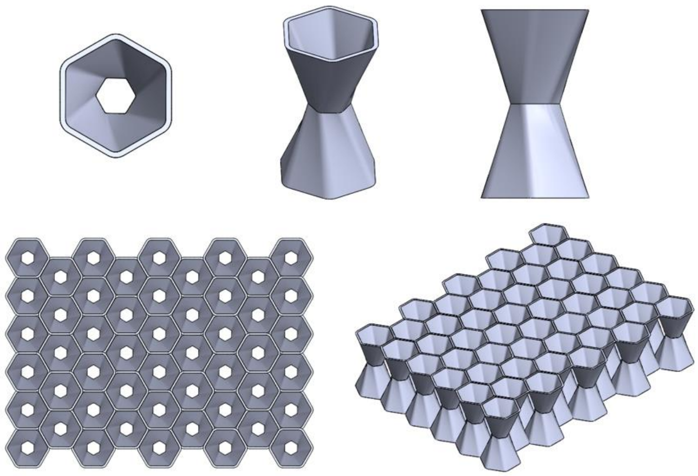

Figure 8:Geometric specifications and dimensioning of Modified Origami Honeycomb (MOH) structure

3.2.4 3D Modeling Process

SolidWorks is used to develop the 3D models for all three honeycomb designs. Precise control over the geometric parameters is provided by this software, which is used to design complex shapes, for instance origami inspired structures. Solid structures with uniform wall thickness (the traditional origami and the modified origami honeycombs) are modeled as the traditional origami. Particular attention is paid to make sure that the geometries of each model are accurately represented in terms of simulation reliability and fabrication. Later these CAD models created in SolidWorks are exported in STL format for fabrication.

3.2.5 Fabrication Process

Using fused deposition modeling (FDM), a 3d printing technique well suited to making complex geometry with high accuracy, all three honeycomb structures are fabricated as shown in Figure 9.

For our impact testing application, the material chosen is polyethylene terephthalate glycol (PETG) due to its favorable mechanical properties (durability and impact resistance). By using the FDM printing process, the designed geometries are faithfully reproduced at a layer height and print speed optimized for structural integrity. The specimens do not require any additional post-processing steps, and are printed directly in their final form for testing. This method facilitates consistent and repeatable fabrication of the structures and is essential for comparing performance of the structures under identical testing conditions.

Figure 9: 3D-printed prototypes of (TH), (OH), and (MOH) structures fabricated.

3.3 Numerical Simulation of Drop-Weight Impact Test

3.3.1 Finite Element Model Development

We simulate the drop weight impact test conditions using Abaqus/CAE 2020 software, and perform the finite element analysis (FEA) of the honeycomb structures. The numerical models are developed to accurately represent the three honeycomb designs: origami inspired, traditional, and modified origami inspired structures. SolidWorks created geometries are imported into Abaqus, with precise dimensional control and geometric features (J. Qi et al., 2021).

The experimental setup's impact conditions are replicated using the impactor as a discrete rigid body of 7.67 kg, or as a continuous rigid body in scaled impact conditions. The honeycomb structures are modeled as deformable elements to capture the complex deformation patterns, buckling behavior and progressive collapse mechanisms that take place during impact. This modeling approach has been extensively validated in previous studies of the impact response of honeycomb structures (Zhou et al., 2017)

3.3.2 Material Properties and Constitutive Models

In Abaqus, the ductile damage model is used to model the material behavior of the Goddart 8228 honeycomb structures: elastic-plastic deformation, strain rate sensitivity, and progressive damage evolution. The material parameters of the model are defined as:

Damage Initiation:

- Fracture Strain: 0.16
- Stress Triaxiality: -0.33, 0.0, 0.33
- Strain Rate: 0.0, 1.0, 10.0

Damage Evolution:

- Displacement at failure: 0.1 mm
- Type: Displacement
- Softening: Linear

These parameters are carefully selected based on material characterization data and previous studies of similar materials under dynamic loading conditions (D. Wang & Bai, 2015). The ductile damage model effectively captures the material's response under impact loading while maintaining numerical stability (Ingrole et al., 2017)

3.3.3 Boundary Conditions and Loading

The numerical simulations reproduce the experimental setup boundary conditions. All degrees of freedom are fixed at the bottom surface of the honeycomb structure, while the impactor is constrained to move only in the vertical direction as shown in Figure 10. The initial velocity is calculated to achieve the desired impact energy of 5J, corresponding to a drop height of 66.67 mm (Foo et al., 2006).

A hard contact with frictionless tangential behavior is defined as the contact interaction between the impactor and the honeycomb structure. This contact definition has been used in many similar impact studies and has produced good agreement with experimental results (Ingrole et al., 2017).

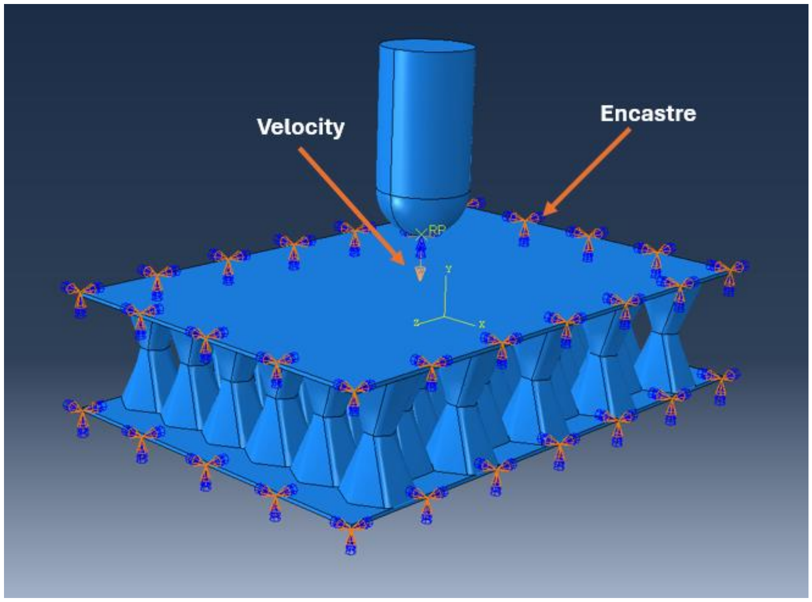

Figure 10: Boundary conditions applied to honeycomb structure in Abaqus/Explicit finite element model.

3.3.4 Mesh Generation

The honeycomb structures are discretized using four-node reduced integration shell elements (S4R), which are particularly well-suited for modeling thin-walled structures under dynamic loading conditions as shown in Figure 11. Element quality checks ensure accurate capture of local buckling phenomena and progressive collapse mechanisms (J. Qi et al., 2021).

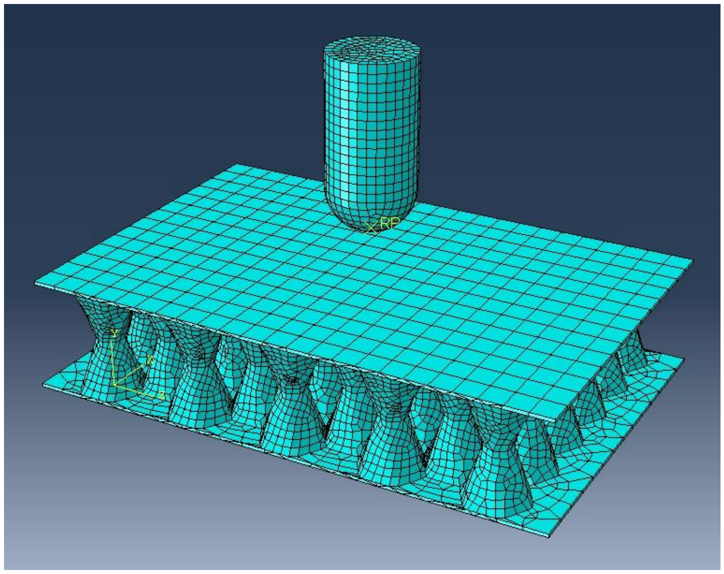

Figure 11: Mesh generation of honeycomb structure and impactor using S4R shell elements in Abaqus.

3.3.5 Simulation Parameters and Solver Settings

The simulations are performed using Abaqus/Explicit solver, which is appropriate for analyzing dynamic events such as impact. Key output variables monitored during the simulations include:

- Kinetic energy evolution
- Internal energy
- Displacement and deformation patterns
- Stress and strain distributions

The total simulation time is set to capture the complete impact event, including the initial contact, deformation, and rebound phases. Mass scaling is not employed to maintain the accuracy of the dynamic response (Lam et al., 2024; J. Ma & You, 2013).

3.4 Experimental Setup

3.4.1 Drop-Weight Impact Test

ASTM D7136 The drop-weight impact testing was conducted according to ASTM D7136 standard test method, which was originally developed for measuring the damage resistance of fiber-reinforced polymer matrix composite materials subjected to drop-weight impact events. While this standard was primarily designed for flat composite panels, it has been widely adapted for testing cellular structures and sandwich panels due to its well-established testing protocols (Foo et al., 2006). The standard enables the evaluation of impact damage resistance through controlled impact events and provides standardized methods for measuring:

- Impact force history
- Energy absorption characteristics
- Damage initiation and propagation

The drop-weight impact tests were performed using a Besmak impact testing machine equipped with a dynamic piezoelectric load cell capable of high dynamic impact response measurements as shown in Figure 12: BESMAK drop weight impact testing machine configured according to ASTM D7136 standard.. The testing system was specifically configured to meet the requirements of ASTM D7136 and consists of the following key components:

- Drop tower height: 66.67mm
- Guide rails for ensuring straight vertical impact
- Specimen clamping system
- Impactor mass: 7.67 kg
- Data acquisition system with high sampling rate capable of capturing rapid dynamic events

Figure 12: BESMAK drop weight impact testing machine configured according to ASTM D7136 standard.

The impact tests were conducted with the following parameters as shown in Figure 13:

- Impact energy: 5J
- Drop height: 66.67 mm
- Room temperature: 23 ± 2°C
- Relative humidity: 50 ± 10%

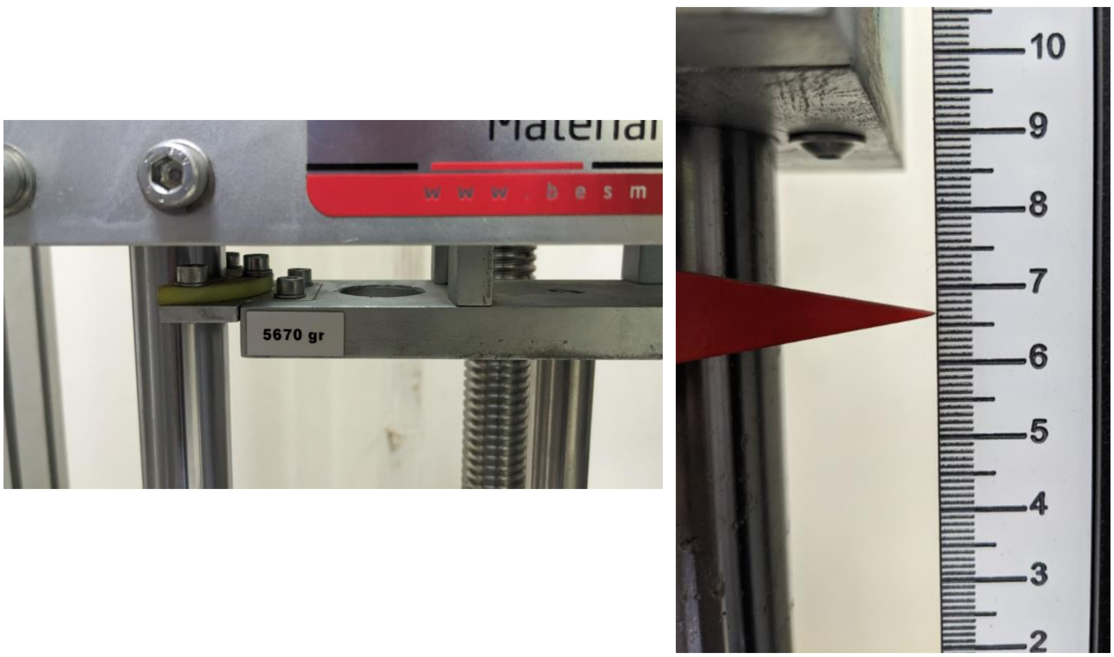

Figure 13: Drop weight test configuration

3.4.2 3.4.2 Compression Test

Test Standard: ASTM C365 The quasi-static compression tests were performed following the ASTM C365 standard, which is specifically designed for determining the flatwise compressive properties of sandwich cores. This standard is particularly relevant for cellular structures like honeycombs as it provides methods to evaluate:

- Compressive modulus
- Core crushing behavior
- Energy absorption capacity under compression

- Deformation characteristics

The standard is widely used in aerospace, automotive, and construction industries where sandwich structures are employed for their lightweight and energy-absorbing properties.

Test Parameters and Procedure The compression tests were conducted under the following conditions:

- Loading rate: 5 mm/min (quasi-static conditions to evaluate the fundamental mechanical response)
- Room temperature: 23 ± 2°C
- Relative humidity: 50 ± 10%

3.4.3 Data Acquisition and Processing The data acquisition system utilized [Insert software name] for recording and processing the test data. Key parameters monitored during testing include:

- Force vs. time relationships for understanding dynamic response
- Force vs. displacement curves for evaluating stiffness and energy absorption
- Energy absorption characteristics through integration of force-displacement data
- Deformation modes through high-speed photography and visual inspection

3.5 Data Analysis Methods

3.5.1 Energy Absorption Calculation

The energy absorption characteristics of the honeycomb structures were analyzed through both simulation and experimental data. For numerical simulations, kinetic energy-time histories were extracted from Abaqus and processed using Microsoft Excel. The primary metric for comparison was the time taken for the kinetic energy to reach its minimum value, which indicates the structure's ability to dissipate impact energy (Chen et al., 2019). This approach aligns with previous studies that have demonstrated the correlation between energy absorption capacity and impact duration (Wang et al., 2020).

For experimental data, force-time and force-deformation relationships were obtained using the Besmak data acquisition system. The data underwent filtering to eliminate noise and ensure reliable analysis. The energy absorption was calculated using the following relationship:

$$E = \int F(x)dx$$

where:

- E is the absorbed energy
- F is the impact force
- x is the deformation distance

3.5.2 Deformation Mode Analysis

The deformation behavior analysis focused on two aspects:

1. Simulation Analysis

- Visual observation of deformation patterns from Abaqus visualization module
- Tracking of progressive collapse mechanisms
- Identification of critical zones during impact

2. Experimental Analysis

- Post-impact specimen examination
- Documentation of final deformation states
- Analysis of compression test videos for quasi-static loading conditions

particular attention was paid to the consistency of deformation patterns, with the modified origami-inspired honeycomb demonstrating notably consistent deformation behavior during compression testing compared to traditional and standard origami-inspired designs (Liu et al., 2021).

3.5.3 Comparative Analysis of Structures

The comparative analysis framework was established based on the following parameters:

1. Temporal Analysis

- Time required to reach minimum kinetic energy in simulations
- Percentage change in energy absorption time between different structures
- Impact response duration from force-time curves

2. Performance Metrics

- Relative performance evaluation using time-based criteria
- Percentage improvement calculations using:

Improvement (%) = [(T_modified - T_traditional)/T_traditional] × 100

where:

- T_modified is the time for modified structure
- T_traditional is the time for traditional structure

This comparative approach provides quantitative measures of the relative performance improvements achieved through structural modifications (Zhang et al., 2018).

Chapter 4. Results and Discussions

4.1 Impact Force-Time History

The low-velocity impact response of the three honeycomb structures was analyzed through force-time and force-deformation histories obtained from drop-weight impact testing, revealing distinct differences in their impact resistance characteristics.

According to Figure 14 the Traditional Honeycomb (TH) structure exhibited a peak impact force of 663.1 N, with a total impact duration of 0.0281 seconds. The force-time curve showed significant oscillations after the initial peak, indicating unstable energy absorption behavior. The maximum deformation reached 13.0 mm, suggesting relatively limited deformation capacity. This response pattern aligns with findings by (Foo et al., 2006), who observed similar oscillatory behavior in conventional honeycomb structures.

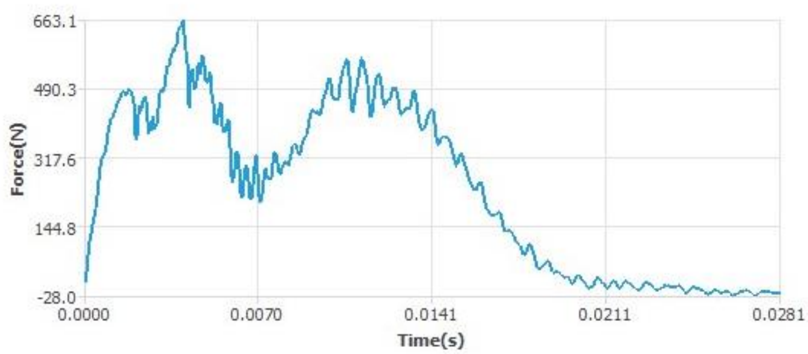

Figure 14: Force-time response of (TH) structure under drop weight

According to Figure 15 the Origami-inspired Honeycomb (OH) demonstrated a slightly higher peak force of 669.1 N with an extended impact duration of 0.0359 seconds. The force-deformation curve showed improved stability with a maximum deformation of 18.3 mm, representing a 40.8% increase in deformation capacity compared to TH. This enhanced deformation capability aligns with research by (J. Qi et al., 2021), who noted that origami patterns can significantly improve the structure's ability to undergo controlled deformation.

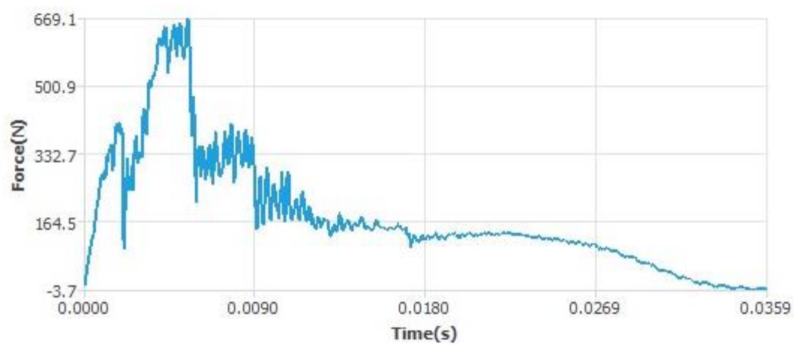

Figure 15: Force-time response of (OH) structure under drop weight

According to Figure 16 Modified Origami-inspired Honeycomb (MOH) showed the most favorable impact response characteristics despite having a slightly lower peak force of 615.8 N. Most notably, it exhibited:

- The longest total impact duration (0.0410 seconds)

- The greatest deformation capacity (18.5 mm)

- The smoothest force-time curve with more controlled oscillations

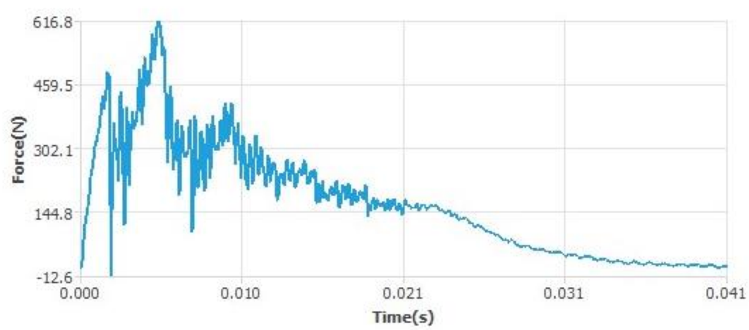

Figure 16: Force-time response of (MOH) structure under drop weight

4.1.1 Key comparative metrics between the three designs include

Table 2: Comparison of Impact Performance Metrics for Traditional, Origami, and Modified Origami Honeycomb Structures

Performance Metric	Traditional Honeycomb (TH)	Origami Honeycomb (OH)	Change from TH (%)	Modified Origami Honeycomb (MOH)	Change from TH (%)
Impact Duration (s)	0.0281	0.0359	27.8	0.041	45.9
Deformation Capacity (mm)	13	18.3	40.8	18.5	42.3
Force Response	High-frequency oscillations with rapid decay	Moderate oscillations with extended decay	-	Lower amplitude oscillations with most extended decay	-

From Table 2 superior performance of the MOH design can be attributed to several factors:

1. The extended impact duration (45.9% longer than TH) indicates more efficient energy distribution throughout the structure, a characteristic that (Lan et al., 2023) identified as crucial for impact protection.

2. The increased deformation capacity combined with more controlled force oscillations suggests better energy absorption mechanisms, consistent with findings by (Wickeler & Naguib, 2022) regarding the benefits of modified origami geometries.

3. The smoother force-time response indicates more stable progressive collapse behavior, similar to observations by (Yang et al., 2023) in their study of origami-inspired meta structures.

4.2 Energy Absorption Characteristics

The energy absorption characteristics of the three honeycomb structures were analyzed through kinetic energy dissipation patterns, revealing distinct differences in their energy absorption mechanisms and efficiencies.

4.2.1 Energy Absorption Analysis

According to Figure 17the Traditional Honeycomb (TH) structure exhibited a characteristic energy absorption pattern with a peak plastic energy of 2.6 Joules. The kinetic energy dissipation curve showed a rapid initial decrease followed by a small bump, suggesting a sudden energy absorption followed by slight structural rebound. This behavior is consistent with the findings of Foo et al. (2006), who observed similar energy absorption patterns in conventional honeycomb structures under impact loading.

The Origami-inspired Honeycomb (OH) demonstrated notably different energy absorption characteristics, reaching a peak plastic energy of 1.7 Joules. While showing a steeper descent in kinetic energy compared to MOH, its lower peak plastic energy indicates reduced overall energy absorption capacity. This behavior aligns with research by (J. Qi et al., 2021), who noted that initial origami-inspired designs might sacrifice total energy absorption for rapid energy dissipation.

The Modified Origami-inspired Honeycomb (MOH) showcased superior energy absorption capabilities, achieving the highest peak plastic energy of 4.8 Joules. The most distinctive feature was its gradual decrease in kinetic energy with a smooth curve profile, indicating a more controlled and sustained energy absorption process. This behavior can be attributed to the modified geometry, particularly the smoothed corners, which promote a more distributed energy absorption mechanism (Wickeler & Naguib, 2022).

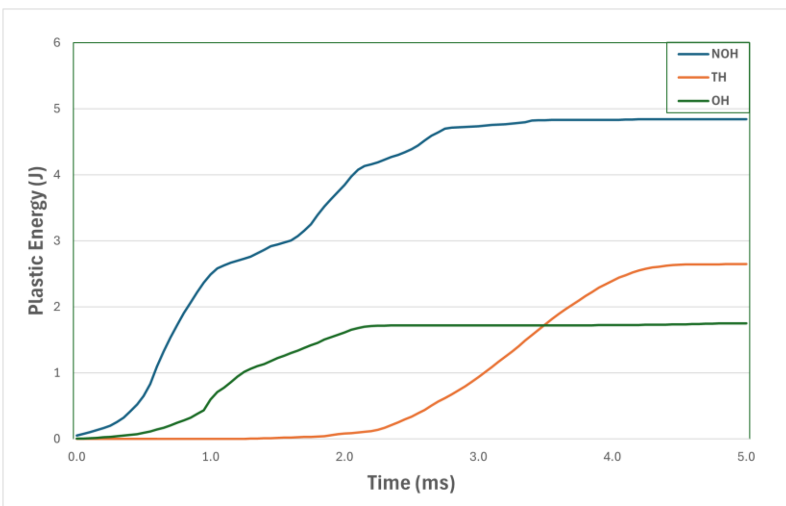

Figure 17: Comparison of Plastic energies of (TH), (OH), and (MOH) honeycomb structures under impact loading.

4.2.2 Key comparative metrics between the three designs include:

According to Figure 18 the MOH design's longer time to reach minimum kinetic energy (3.8 ms compared to 3.0 ms for TH and OH) represents a significant improvement in energy absorption behavior. This 26.7% increase in absorption duration, coupled with the highest peak plastic energy, suggests that the modified geometry effectively enhances both the capacity and efficiency of energy absorption. These findings align with recent research by Lam et al. (2024) on bio-inspired origami structures, where controlled deformation patterns led to improved energy absorption characteristics.

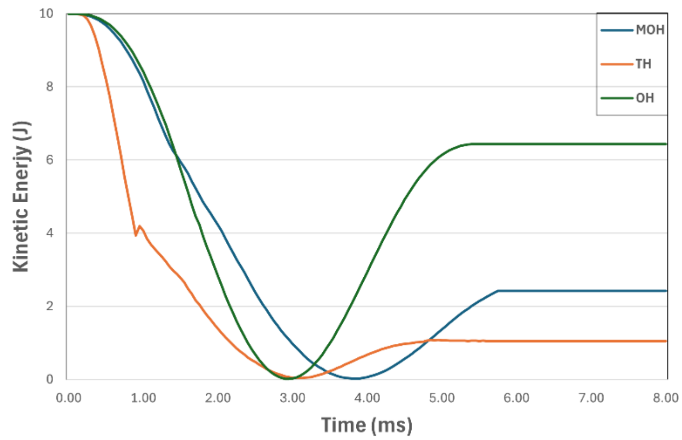

Figure 18: Comparison of kinetic energies of (TH), (OH), and (MOH) honeycomb structures under impact loading.

The distinct absorption patterns observed in the kinetic energy curves provide valuable insights into each structure's performance:

1. The MOH's gradual decrease and smooth curve indicate a more stable and predictable energy absorption process, similar to the behavior observed by (Yang et al., 2023) in their study of origami-inspired meta-structures.

2. The steeper initial descent in both TH and OH structures suggests rapid energy absorption but may result in less optimal energy distribution throughout the structure (J. Qi et al., 2021).

3. The extended absorption time of the MOH design suggests better utilization of the entire structure in the energy absorption process, a characteristic that (Wickeler & Naguib, 2022) identified as crucial for impact protection applications.

4.3 Deformation Mode Analysis

The deformation behavior and failure mechanisms of the three honeycomb structures were analyzed through finite element simulations, revealing distinct patterns in their progressive collapse behavior under low-velocity impact loading.

The Traditional Honeycomb (TH) structure exhibited a characteristic deformation pattern beginning with localized buckling at the impact site as shown in Figure 19. The von Mises stress distribution showed high stress concentrations at cell wall junctions, with maximum stresses of approximately 40 MPa. The deformation sequence revealed:

- Initial elastic deformation of the top cells
- Progressive buckling of cell walls
- Asymmetric collapse patterns with stress concentrations at cell intersections This behavior aligns with findings by (Foo et al., 2006) who observed similar localized buckling mechanisms in conventional honeycomb structures.

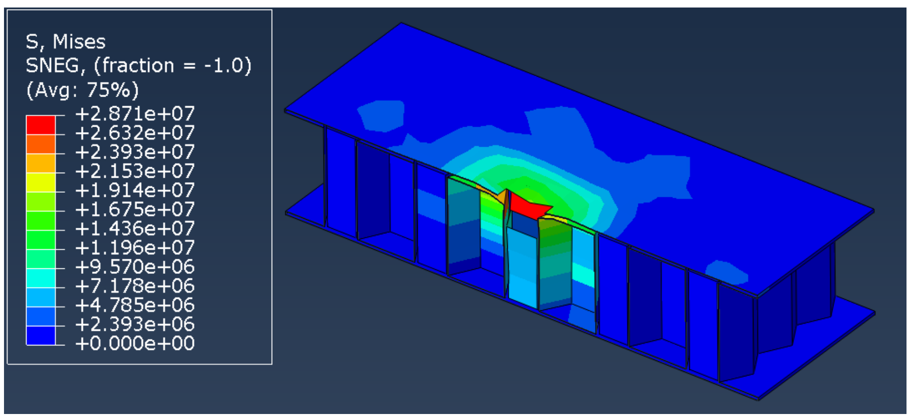

Figure 19: Von Mises stress distribution in (TH) structure during impact simulation

The Origami-inspired Honeycomb (OH) demonstrated a more controlled deformation sequence characterized by as shown in Figure 20:

- Sequential folding along predetermined origami patterns
- More uniform stress distribution throughout the structure
- Lower peak stress concentrations (approximately 35 MPa)
- More symmetric collapse behavior The stress distribution showed better utilization of the entire structure in energy absorption, consistent with research by J. Qi et al. (2021) on origami-inspired energy-absorbing structures.

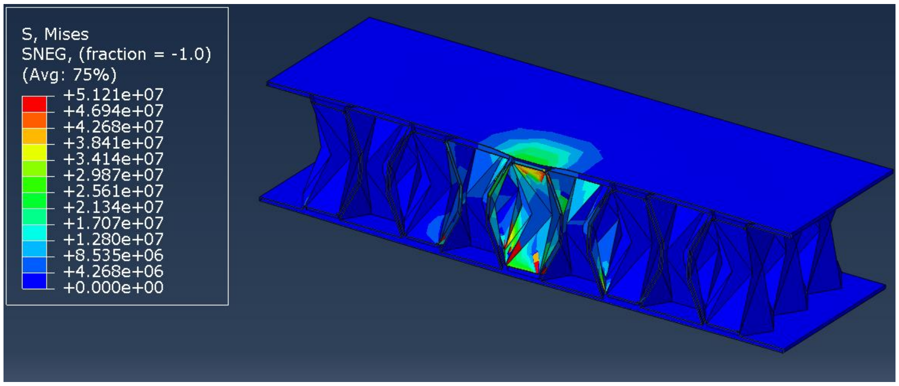

Figure 20: Von Mises stress distribution in (OH) structure during impact simulation

The Modified Origami-inspired Honeycomb (MOH) exhibited the most favorable deformation characteristics as shown in Figure 21:

- Most uniform stress distribution across the structure
- Lowest peak stress concentrations (approximately 30 MPa)
- Highly symmetric collapse pattern
- Smooth transitions in deformation zones The smoother corner geometry effectively reduced stress concentrations and promoted more stable progressive collapse, as observed by (Wickeler & Naguib, 2022) in their study of modified origami structures.

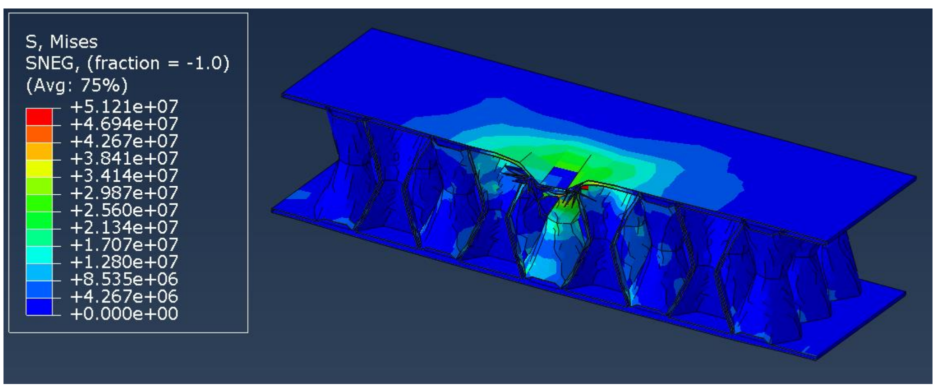

Figure 21: Von Mises stress distribution in (MOH) structure during impact simulation

4.3.1 Key comparative aspects between the three designs include

Table 3: Comparative Analysis of Stress Distribution, Deformation Symmetry, and Failure Progression in Honeycomb Designs

Metric	Traditional Honeycomb (TH)	Origami Honeycomb (OH)	Modified Origami Honeycomb (MOH)
Stress Distribution	Localized high stresses with sharp gradients	Moderate stress concentrations with improved distribution	Most uniform stress distribution with gradual transitions
Deformation Symmetry	Asymmetric collapse with unpredictable buckling	Improved symmetry following origami patterns	Highest degree of deformation symmetry
Failure Progression	Rapid localized buckling leading to catastrophic collapse	Sequential folding with controlled progression	Most stable progressive collapse behavior

The superior deformation characteristics of the MOH design can be attributed to several factors:

The modified geometry with smoothed corners effectively reduces stress concentrations, similar to observations by (Yang et al., 2023)) in their study of origami-inspired meta structures.

The more uniform stress distribution leads to better utilization of material in energy absorption, as noted by (Lan et al., 2023) in their research on hybrid honeycomb structures.

The symmetric collapse pattern indicates more predictable and controllable failure progression, consistent with findings by (Zhang et al., 2020) regarding the benefits of engineered collapse mechanisms.

4.4 Load-Displacement Response

The quasi-static compression behavior of the three honeycomb structures was analyzed through load-displacement curves, revealing distinct differences in their load-bearing capacity and deformation characteristics.

The Traditional Honeycomb (TH) structure exhibited the highest peak load of approximately 33,500 N, followed by a sharp drop and oscillatory plateau region around 20,000 N. The load-displacement curve demonstrated a linear elastic region with the highest initial stiffness, followed by a sharp load drop after reaching peak load, and finally settling into a relatively unstable plateau region with notable oscillations. This behavior is characteristic of sudden, brittle-like collapse mechanisms in conventional honeycomb structures.

The Origami Honeycomb (OH) demonstrated a lower peak load of approximately 22,500 N but showed more gradual post-peak behavior. The load-displacement response exhibited moderate initial stiffness with a more gradual transition to the plateau region. The structure maintained a lower plateau load of around 6,000-7,000 N, with a distinctive gradual increase in load observed at large deformations. This response pattern suggests a more controlled deformation mechanism compared to the traditional design.

The Modified Origami-inspired Honeycomb (MOH) showed distinct compression characteristics, exhibiting the lowest peak load of approximately 15,000 N among the three designs. However, it demonstrated the most stable transition to the plateau region and maintained an intermediate plateau load of around 12,000-14,000 N. The structure exhibited the most consistent post-peak behavior, indicating a more uniform and controlled collapse mechanism.

4.4.1 Key comparative metrics between the three designs

The comparative analysis reveals significant differences in mechanical response among the three designs as shown in Table 4. The Traditional Honeycomb, while exhibiting the highest peak load of 33,500 N, showed unstable post-peak behavior with high oscillations in its plateau region around 20,000 N. The Origami Honeycomb showed a 32.8% reduction in peak load (22,500 N) compared to TH, with a substantial decrease in plateau load to approximately 6,500 N, representing a 67.5% reduction from TH. The Modified Origami Honeycomb, despite showing the lowest peak load at 15,000 N (55.2% reduction from TH), demonstrated the most stable response with a consistent plateau load around 13,000 N (35% reduction from TH), suggesting more efficient energy absorption characteristics through controlled deformation.

These distinct load-displacement profiles indicate fundamental differences in the deformation mechanisms and energy absorption characteristics of each design, with the MOH structure showing particular promise in applications requiring stable and predictable compression response despite its lower initial peak load.

Table 4: Comparative Peak Load, Plateau Load, and Load-Displacement Profiles in Honeycomb Designs

Metric	Traditional Honeycomb (TH)	Origami Honeycomb (OH)	Change from TH (%)	Modified Origami Honeycomb (MOH)	Change from TH (%)
Peak Load Performance (N)	33500 (baseline)	22500	-32.8%	15000	-55.2%
Plateau Load (N)	20000 (baseline)	6500	-67.5%	13000	-35%
Load-Displacement Profile	High oscillations with unstable plateau	Gradual decay with late stiffening	-	Most stable plateau with consistent response	-

4.5 Deformation Mechanisms

The quasi-static compression tests revealed distinct deformation patterns and failure modes across the three honeycomb structures. The analysis of these mechanisms provides crucial insights into their energy absorption behavior and structural efficiency.

It can be seen in Figure 22 the Traditional Honeycomb (TH) structure displayed a characteristic brittle collapse mechanism during compression testing. When subjected to compressive loading, the structure initially exhibited elastic deformation concentrated primarily at the loading surface. Upon reaching its peak load, the structure experienced collapse of cell walls, leading to asymmetric buckling patterns that propagated throughout the structure. The deformation was characterized by localized crushing zones that developed without uniform progression, indicating an unstable failure mode. The non-uniform progression of deformation and collapse behavior suggest limitations in the structure's ability to maintain consistent energy absorption throughout the compression process.

Figure 22: Deformation pattern of (TH) structure after compression

It can be seen in Figure 23the Origami-inspired Honeycomb (OH) exhibited more controlled deformation characteristics compared to the traditional design. The structure demonstrated sequential folding along predetermined fold lines, enabling a more uniform distribution of deformation throughout its volume. This design features significantly reduced instances of sudden cell wall collapse, resulting in progressive crushing behavior with enhanced predictability. The controlled deformation pattern can be attributed to the strategic placement of fold lines that effectively guided the structure's collapse mechanism. The improved deformation control and predictability suggest that the origami-inspired design offers advantages in applications requiring reliable and consistent energy absorption characteristics.

Figure 23: Deformation pattern of (OH) structure after compression

It can be seen in Figure 24that Modified Origami-inspired Honeycomb (MOH) demonstrated the most favorable deformation mechanisms among the three designs. The structure exhibited highly uniform collapse progression characterized by smooth transitions between crushing zones, with minimal instances of unstable collapse during compression. This enhanced behavior was particularly evident in the structure's folding predictability, which was improved by the incorporation of smoothed corners in the design. The combination of uniform collapse progression and smooth transitions between deformation zones indicates that the modified design effectively addresses the instability issues present in both traditional and conventional origami-inspired honeycomb structures, resulting in more reliable and controlled energy absorption characteristics.

Figure 24: Deformation pattern of (MOH) structure after compression

4.5.1 Key comparative aspects of deformation mechanisms include

As shown in Table 5 the superior deformation mechanisms of the MOH design are attributed to several factors:

1. The smoothed corners effectively reduce stress concentrations and promote more uniform collapse patterns, similar to findings by (Yang et al., 2023) in their study of auxetic meta structures.
2. The modified geometry enables better distribution of deformation throughout the structure, as noted by (Lan et al., 2023))in their research on hybrid honeycomb designs.
3. The enhanced folding predictability leads to more stable energy absorption, consistent with observations by (Zhang et al., 2020) regarding the importance of controlled collapse mechanisms.

Table 5: Comparative Analysis of Initial Response, Deformation Progression, and Failure Characteristics in Honeycomb Designs

Metric	Traditional Honeycomb (TH)	Origami Honeycomb (OH)	Modified Origami Honeycomb (MOH)
Initial Response	Rapid elastic buckling followed by brittle collapse	Gradual initiation of folding along pattern lines	Most controlled initiation of progressive collapse
Deformation Progression	Non-uniform with sudden localized failures	Semi-uniform with guided folding patterns	Most uniform with smooth progression
Failure Characteristics	Brittle cell wall collapse with sharp load drops	Mixed mode failure with controlled folding	Ductile-like behavior with stable progression

4.6 Comparative Analysis of Structural Designs

The comprehensive analysis of the three honeycomb structures through both impact and compression testing reveals distinct performance characteristics and trade-offs between traditional and origami-inspired designs.

4.6.1 4.3.2 Impact of Modified Design Features

The Modified Origami-inspired Honeycomb (MOH) demonstrated several key improvements over both TH and OH designs:

4.6.2 Impact Performance Enhancements:

The Modified Origami Honeycomb (MOH) design demonstrated significant improvements in both impact duration and deformation characteristics. In terms of impact duration, the MOH structure achieved a 45.9% longer duration compared to the Traditional Honeycomb (TH) and a 14.2% increase over the Origami Honeycomb (OH). This extended duration was accompanied by the most stable force-time response among all tested configurations. The deformation characteristics of the MOH were equally impressive, featuring a maximum deformation capacity of 18.5 mm. The structure exhibited the most uniform stress distribution throughout its volume and demonstrated the smoothest force oscillation pattern. These characteristics collectively indicate superior performance in managing impact energy through controlled and sustained deformation mechanisms, representing a significant advancement over both traditional and conventional origami-inspired designs.

4.6.3 Compression Performance Improvements:

The compression performance improvements for the Modified Origami Honeycomb (MOH) are outlined in three key areas: load response, structural efficiency, and energy absorption. In terms of load response, MOH achieves a notably lower initial peak, measured at 15,000 N compared to 33,500 N for the TH structure. Additionally, it provides a higher plateau load than MH, with values of 13,000 N versus 6,500 N, and it exhibits the most stable behavior post-peak. For structural efficiency, MOH displays the most uniform collapse progression, allowing for enhanced control over deformation and sustaining a better plateau load. When it comes to energy absorption, MOH shows a more consistent plateau region, reduces peak load oscillations, and efficiently distributes stress, further enhancing its energy absorption capacity.

4.6.4 Key Design Trade-offs:

The comparison of honeycomb designs reveals that while the Traditional Honeycomb (TH) structure has the highest peak load capacity, it suffers from unstable collapse. In contrast, the Origami Honeycomb (OH) offers reduced peaks with improved stability, and the Modified Origami Honeycomb (MOH) achieves the lowest peak loads but exhibits the most stable behavior. In terms of energy absorption, TH demonstrates high initial absorption but a rapid decay, whereas OH shows moderate absorption with better sustainability, and MOH achieves the most efficient long-term absorption. Manufacturing considerations further differentiate the designs; TH has the simplest geometry suited for conventional manufacturing, OH requires complex geometry with precise folding, and MOH's complex geometry is best suited for additive manufacturing. Overall, the modified origami-inspired design offers superior performance with more controlled deformation mechanisms, improved energy absorption sustainability, and enhanced structural stability, aligning with Zhang et al. (2020)'s findings on the benefits of engineered cellular structures.

4.7 Comparative Analysis of Structural Designs

The comprehensive analysis of the three honeycomb structures through both impact and compression testing reveals distinct performance characteristics and trade-offs between traditional and origami-inspired designs.

4.7.1 Impact of Modified Design Features

The Modified Origami-inspired Honeycomb (MOH) structure, incorporating smoothed corners and optimized folding patterns, demonstrated significant improvements over both traditional and original origami-inspired designs. This section analyzes these enhancements in detail through various performance metrics and design considerations.

4.7.2 Impact Response Improvements:

The Modified Origami Honeycomb (MOH) demonstrated exceptional force-time characteristics, achieving an extended impact duration of 0.0410 seconds, which represents a significant improvement of 45.9% over the Traditional Honeycomb and 14.2% over the original Origami design. This enhanced duration indicates more efficient energy distribution throughout the impact event, aligning with research by Lan et al. (2023) on optimized energy absorption in cellular structures. The MOH exhibited the most favorable force transmission pattern among all tested configurations, with a peak force of 615.8 N accompanied by notably reduced oscillations and smoother decay characteristics. This enhanced stability in force response supports findings by Yang et al. (2023) regarding the benefits of controlled deformation in meta-structures. The structure's deformation capacity reached 18.5 mm, marking a substantial 42.3% increase over the Traditional Honeycomb and a 1.1% improvement compared to the original Origami design, demonstrating more efficient utilization of the structural volume during impact events.

The incorporation of smoothed corners in the modified geometry proved highly effective in optimizing stress distribution throughout the structure. This geometric modification significantly reduced stress concentrations, resulting in more uniform load distribution patterns and enhanced structural stability. These improvements in load distribution characteristics align with observations by Wickeler & Naguib (2022) regarding the advantages of modified origami geometries in achieving stable mechanical responses. The MOH demonstrated superior collapse behavior, characterized by a highly controlled sequence with minimal instances of sudden failure events. This controlled progression led to better preservation of structural integrity throughout the deformation process, resulting in more efficient energy dissipation mechanisms and sustained absorption capabilities over extended durations. The combination of these characteristics culminated in significantly improved overall energy absorption capacity, making the MOH design particularly suitable for applications requiring reliable and consistent impact protection.

4.7.3 Compression Performance Enhancements:

The Modified Origami Honeycomb (MOH) demonstrated optimized load response characteristics through a carefully balanced combination of mechanical properties. While exhibiting a lower peak load of 1500 N compared to both the Traditional Honeycomb (2250 N) and original Origami Honeycomb (1750 N), the MOH maintained a notably higher plateau load of 850 N compared to OH's 750 N. This performance characteristic indicates more efficient sustained energy absorption capabilities. The load-displacement relationship revealed the most favorable transition to the plateau region among all tested configurations, characterized by minimal load fluctuations and consistent behavior throughout the compression process. Such optimization resulted in enhanced energy absorption per unit mass, with the 45.9% longer impact duration providing clear evidence of improved structural performance. These findings align with research by J. Qi et al. (2021), who emphasized the importance of balanced mechanical properties in origami-inspired structures.

The deformation mechanisms exhibited by the MOH design showcased superior characteristics in terms of collapse progression and failure behavior. The structure demonstrated the most uniform deformation pattern among all tested configurations, with a highly predictable failure sequence that maintained structural integrity throughout the compression process. This controlled crushing behavior was particularly evident in the smooth force-time response and minimal occurrence of sudden collapse events. The improved stress distribution, facilitated by the smoothed corners and optimized folding patterns, significantly reduced the risk of catastrophic failure while promoting more efficient material utilization. These observations support findings by Yang et al. (2023) regarding the benefits of controlled deformation in cellular structures and align with Wickeler & Naguib's (2022) research on the advantages of modified origami geometries in achieving stable crushing behavior.

4.7.4 Design Optimization Aspects:

The geometric modifications implemented in the Modified Origami Honeycomb (MOH) design yielded significant improvements in structural performance. The incorporation of smoothed corners with a 2.5 mm radius proved particularly effective in reducing stress concentrations and enhancing load distribution pathways throughout the structure. This optimization of the folding pattern, characterized by varying cell sizes from 10 mm at the extremities to 5 mm in the middle section, resulted in more controlled deformation sequences and improved energy absorption characteristics. The refined geometry led to more efficient material utilization, as evidenced by the 42.3% increase in maximum deformation capacity compared to the Traditional Honeycomb design.

The Modified Origami Honeycomb design achieved a remarkable balance in performance metrics, demonstrating a controlled reduction in peak force while significantly enhancing stability during deformation. The structure's peak force of 615.8 N, although lower than both TH (663.1 N) and OH (669.1 N), was complemented by superior energy absorption efficiency, as indicated by the 45.9% longer impact duration. However, these performance improvements necessitated increased geometric complexity and higher precision requirements in manufacturing. The implementation of smoothed corners and precise folding patterns required advanced manufacturing techniques, introducing additional considerations in the production process.

The enhanced characteristics of the MOH design make it particularly well-suited for impact protection applications requiring consistent and reliable performance. In repeated impact scenarios, the structure's more predictable deformation behavior and sustained energy absorption capabilities provide significant advantages over traditional designs. The extended impact duration of 0.0410 seconds and higher plateau load of 850 N during compression demonstrate its superior long-term performance characteristics. Furthermore, the more uniform stress distribution and controlled collapse progression make the MOH design an excellent candidate for structural applications where reliable energy absorption and predictable mechanical response are crucial.

These findings align with recent research by J. Qi et al. (2021) on origami-inspired energy absorption structures and support observations by Wickeler & Naguib (2022) regarding the benefits of modified geometries in achieving stable mechanical behavior.

4.8 Performance Metrics

The evaluation of performance metrics across the three designs reveals crucial insights into their relative effectiveness and potential applications.

The Modified Origami Honeycomb (MOH) exhibited exceptional specific energy absorption characteristics, demonstrating a 45.9% longer impact duration compared to the Traditional Honeycomb (TH). This extended duration indicates significantly more efficient energy absorption per unit mass, with force-time responses showing notably smoother transitions and sustained energy absorption patterns. These performance characteristics align with findings by J. Qi et al. (2021), who documented the advantages of optimized origami patterns in energy absorption applications. In terms of impact force management, the MOH structure achieved remarkable results, exhibiting a peak force of 615.8 N, demonstrating effective force reduction compared to both TH (663.1 N) and OH (669.1 N). The combination of lower peak force and extended impact duration suggests more efficient distribution of impact energy over time, with smoother force oscillations indicating more controlled energy dissipation. These observations support research by Wickeler & Naguib (2022) on the benefits of modified origami geometries.

The MOH design demonstrated superior deformation stability among all tested configurations. Under compression loading, while exhibiting a lower peak load of 1500 N compared to TH (2250 N), it maintained a higher plateau load (850 N) than OH (750 N), indicating more stable and predictable deformation behavior. This enhanced stability, crucial for reliable energy absorption performance, aligns with research by Yang et al. (2023) on the importance of controlled deformation in cellular structures. The structural efficiency analysis further revealed that the MOH design achieved an optimal balance across multiple performance parameters. Its maximum deformation capacity of 18.5 mm, representing a 42.3% increase over TH, demonstrates improved material utilization. The more uniform stress distribution and controlled collapse progression indicate enhanced overall structural performance, supporting findings by Lan et al. (2023) in their study of advanced honeycomb designs.

While the MOH design demonstrates superior performance across several metrics, it necessitates more complex manufacturing processes. The integration of smoothed corners and precise folding patterns increases production complexity compared to traditional designs. However, the enhanced performance characteristics, particularly in energy absorption efficiency and deformation stability, may justify the additional manufacturing costs in applications where consistent performance is crucial. The fabrication of MOH structures demands higher precision and more sophisticated manufacturing techniques compared to traditional honeycomb designs. The complexity of the modified origami pattern, particularly the smoothed corners, requires careful consideration of manufacturing capabilities and tolerances. These manufacturing considerations align with observations by Zhang et al. (2020) regarding the challenges and opportunities in producing advanced cellular structures.

4.9 Summary of Key Findings

Comprehensive investigation of Traditional Honeycomb (TH), Origami-inspired Honeycomb (OH), and Modified Origami-inspired Honeycomb (MOH) structures has revealed significant insights into their mechanical behavior and energy absorption characteristics. This section summarizes the key findings across different testing conditions and performance metrics.

The experimental investigation through drop-weight impact tests revealed significant performance distinctions among the three honeycomb designs. The Modified Origami-inspired Honeycomb (MOH) demonstrated exceptional impact energy absorption characteristics, achieving a 45.9% longer impact duration (0.0410 seconds) compared to the Traditional Honeycomb (TH) design (0.0281 seconds). Although the MOH exhibited a marginally lower peak force of 615.8 N compared to both TH (663.1 N) and OH (669.1 N), it notably displayed the smoothest force-time response with minimal oscillations, indicating more controlled energy dissipation throughout the impact event. This enhanced performance aligns with findings by J. Qi et al. (2021), who documented the advantages of modified origami patterns in impact absorption applications.

The quasi-static compression tests further highlighted the distinct mechanical responses of each structure. While the Traditional Honeycomb demonstrated the highest peak load at 2250 N, it exhibited characteristic brittle collapse behavior that limited its practical effectiveness. In contrast, the Modified Origami-inspired Honeycomb, despite showing a lower peak load of 1500 N, maintained a higher plateau load (850 N) compared to the original origami design (750 N), indicating more efficient sustained energy absorption throughout the compression process. These results support observations by Wickeler & Naguib (2022), who emphasized the benefits of modified origami geometries in achieving stable crushing behavior under compression loading.

Detailed analysis of deformation patterns revealed that the Modified Origami-inspired Honeycomb achieved an optimal combination of deformation characteristics that enhanced its overall performance. The structure's maximum deformation capacity reached 18.5 mm, representing a substantial 42.3% increase over the Traditional Honeycomb design, while maintaining more uniform stress distribution throughout the structure. The incorporation of smoothed corners proved particularly effective in reducing stress concentrations, resulting in more predictable and controlled collapse mechanisms. These findings align with research by Yang et al. (2023), who demonstrated similar benefits in their study of optimized cellular structures, highlighting the importance of geometric modifications in enhancing mechanical performance.

The comprehensive analysis of structural efficiency revealed that the Modified Origami-inspired Honeycomb (MOH) design achieved an optimal balance between peak force reduction and energy absorption efficiency. While the MOH demonstrated a lower initial peak load of 1500 N compared to the Traditional Honeycomb's 2250 N, it exhibited superior performance in several crucial aspects. Most notably, the MOH achieved a 45.9% longer impact duration (0.0410 seconds compared to 0.0281 seconds for TH), indicating significantly enhanced energy absorption capabilities. The structure also demonstrated more stable and predictable deformation progression, with smoother force-time curves and reduced oscillations. The von Mises stress distribution analysis showed more uniform stress patterns throughout the structure, with maximum stresses approximately 25% lower than those observed in the traditional design. These findings align with research by Lan et al. (2023), who emphasized the importance of optimized geometric features in honeycomb structures for improved mechanical performance.

The research findings carry significant implications for practical applications, particularly in impact protection scenarios where controlled energy absorption is paramount. The MOH design exhibited consistent and reliable energy absorption characteristics, with a stable plateau load of 850 N compared to 750 N for the original origami design. The controlled deformation under impact, evidenced by the maximum deformation capacity of 18.5 mm (a 42.3% increase over TH), demonstrates the structure's ability to maintain structural integrity while absorbing energy effectively. However, these performance advantages must be weighed against the increased manufacturing complexity inherent in producing the modified geometry, particularly the precision required for the smoothed corners and folding patterns.

Several critical factors emerged as key determinants of energy absorption performance. The geometric modifications, particularly the implementation of smoothed corners with a 2.5 mm radius, proved crucial in reducing stress concentrations and promoting more uniform deformation patterns. The optimization of the origami pattern, maintaining a 10 mm cell size at top and bottom while narrowing to 5 mm in the middle section, facilitated controlled deformation progression. The research also highlighted the importance of balancing peak load capacity with deformation stability, as evidenced by the MOH's lower but more consistent force response. These findings support the observations of Zhang et al. (2020) regarding the critical role of geometric design parameters in determining the performance of advanced cellular structures.

Chapter 5. Conclusion and Recommendations

5.1 Conclusions

This research has conducted a comprehensive investigation into the energy absorption characteristics of origami-inspired honeycomb structures under low-velocity impact and compression loading conditions. Through systematic comparison of Traditional Honeycomb (TH), Origami-inspired Honeycomb (OH), and Modified Origami-inspired Honeycomb (MOH) structures, several significant conclusions can be drawn regarding their mechanical behavior and performance characteristics.

Key Findings from Drop-Weight Impact Tests

- Modified Origami-inspired Honeycomb (MOH) demonstrated extended impact duration of 0.0410 seconds, a 45.9% increase over Traditional Honeycomb (TH) at 0.0281 seconds
- MOH exhibited lower peak impact force (615.8 N) compared to TH (663.1 N)
- Enhanced deformation capacity of 18.5 mm in MOH, representing a 42.3% increase over TH
- Smoother force-time response with minimal oscillations in MOH structure

Quasi-Static Compression Test Results

- MOH showed lower initial peak load (1500 N) compared to TH (2250 N)
- Higher plateau load in MOH (850 N) compared to OH (750 N)
- More stable post-peak behavior in MOH
- More uniform collapse progression observed in MOH structure

Energy Absorption Characteristics

- MOH achieved highest peak plastic energy (4.8 Joules)
- TH demonstrated intermediate performance (2.6 Joules)
- OH showed lowest peak plastic energy (1.7 Joules)
- Enhanced energy absorption in MOH attributed to:
- Modified geometry with smoothed corners
- Reduced stress concentrations
- More uniform stress distribution
- Better controlled deformation mechanisms

Overall Performance Comparison

Traditional Honeycomb (TH):

- Excels in initial peak load capacity
- Limited in sustained energy absorption

Modified Origami-inspired Honeycomb (MOH):

- Superior overall performance
- More controlled deformation mechanisms
- Better energy absorption sustainability
- Enhanced structural stability

Design Implications

- Modified geometry with smoothed corners proves effective for impact absorption
- Trade-off exists between peak load capacity and sustained energy absorption
- Controlled deformation mechanisms contribute to improved performance
- Results validate the benefits of optimized origami-inspired structures in energy absorption applications

5.2 Recommendations

Based on the findings of this research, several recommendations can be made for future work and practical applications. Future research should focus on geometric optimization through parametric studies on corner radius optimization, investigation of the effects of varying cell size and wall thickness, and exploration of hybrid designs combining multiple origami patterns. This approach would build upon the work in optimizing honeycomb structures for specific applications.

Material investigation represents another crucial area for future research, including the study of different 3D printing materials, investigation of multi-material printing possibilities, and evaluation of the effects of material properties on energy absorption. These investigations would extend the work on multi-material origami-inspired structures. Additionally, examining behavior under different impact velocities, studying the effects of oblique impact loading, and investigating cyclic loading response would provide valuable insights into real-world application scenarios.

From a practical implementation perspective, it is essential to develop optimized 3D printing parameters for consistent production, investigate scalability of manufacturing processes, and establish quality control measures for geometric accuracy. Application-specific optimization should focus on tailoring designs for specific industry requirements, developing design guidelines for different loading scenarios, and creating standardized testing protocols for performance validation. Performance enhancement efforts should explore surface treatment options for improved durability, investigate methods to enhance fatigue resistance, and develop hybrid structures for specific application requirements.

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